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Energy consumption and CO_2 emissions in buildings: a bibliometric review of trends, challenges, and future directions

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Research Paper - Subject review

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Energy consumption and CO_2 emissions in buildings: a bibliometric review of trends, challenges, and future directions

This bibliometric review aims to systematically analyze the evolving research landscape on the relationship between energy consumption and CO_2 emissions in buildings. Using the PRISMA methodology and Scopus database, 1,969 relevant publications were identified and analyzed through bibliometric tools, particularly VOSviewer. The review highlights significant trends, prolific authors, influential institutions, and key research themes over the past decade. Findings reveal a strong global focus on energy efficiency, the integration of renewable energy, and emissions reduction, with notable contributions from China, Italy, Spain, and the United States. Despite technological progress, critical gaps remain - especially regarding behavioral factors, socio-economic dimensions, and the affordability of energy solutions in developing regions. The study concludes by identifying emerging research directions such as AI-driven energy optimization, circular economy applications, and interdisciplinary approaches to policy and design. These insights are essential for guiding future academic efforts and informing practical strategies to mitigate climate change impacts through sustainable building practices.

Key words:
energy efficiency, energy consumptions, CO_2 emissions, energy utilizations, energy policy, climate change

Pregledni rad

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Potrošnja energije i emisije CO_2 u zgradama: bibliometrijski pregled trendova, izazova i budućih smjernica

Cilj je ove bibliometrijske analize sustavno analizirati razvojno znanstveno okružje o odnosu između potrošnje energije i emisija CO_2 u zgradama. Primjenom metodologije PRISMA i baze podataka Scopus, identificirano je 1969 relevantnih publikacija koje su analizirane bibliometrijskim alatima, posebno VOSviewerom. Pregled ističe ključne trendove, najproduktivnije autore, utjecajne institucije i glavne istraživačke teme tijekom posljednjeg desetljeća. Rezultati otkrivaju snažan globalni fokus na energetsku učinkovitost, integraciju obnovljivih izvora energije i smanjenje emisija te znatne doprinose Kine, Italije, Španjolske i Sjedinjenih Američkih Država. Unatoč tehnološkome napretku i dalje postoje ključne praznine, osobito u pogledu ponašanja korisnika, socioekonomskih aspekata i dostupnosti energetskih rješenja u zemljama u razvoju. Studija završava identificiranjem novih smjerova istraživanja poput optimiranja potrošnje energije pomoću umjetne inteligencije te primjene načela kružnoga gospodarstva te interdisciplinarnih pristupa politikama i oblikovanju. Ti uvidi ključni su za usmjeravanje budućih akademskih napora i oblikovanje praktičnih strategija za ublažavanje utjecaja klimatskih promjena kroz održivu gradnju.

Ključne riječi:
energetska učinkovitost, potrošnja energije, emisije CO_2, korištenje energije, energetska politika, klimatske promjene

1. Introduction

The energy consumption of buildings has been continuously increasing due to population growth and urbanization [1]. This rise in energy demand leads to higher CO_2 emissions in the atmosphere, thereby contributing to climate change [2, 3].

The construction sector plays a crucial role in increasing energy consumption. According to the Global Status for Buildings and Construction 2024 report, the construction sector is the largest energy consumer in the world. In 2022, it accounted for 30 % of the final energy demand, primarily for operational needs such as heating and cooling. Including the energy required for the production of building materials, this figure increases to 34 % [4].

Globally, the construction sector is responsible for more than 40 % of global energy use and contributes to approximately 30 % of global greenhouse gas (GHG) emissions [2] and CO_2 emissions from building operations. In 2022, construction reached new heights, representing 37 % of the total global CO_2 emissions, i.e., nearly 10 gigatonnes (Gt) of CO_2. This reflects a growth in indirect emissions related to electricity use, which reached 6.8 $GtCO_2$, while direct emissions from buildings slightly decreased to 3 $GtCO_2$ (Global Alliance for Buildings and Construction) [4].

There are many strategies for reducing energy consumption and greenhouse gas emissions. These include improving the energy efficiency of buildings through various modifications to the building envelope, such as using thermal insulation for walls and installing double or triple glazing systems. The use of energy-efficient heating, ventilation, and air conditioning (HVAC) systems, as well as the adoption of energy-saving equipment, is crucial as well. The introduction of information and communication technologies (ICT) in buildings can further optimize energy consumption [5-10].

A fundamental aspect of these efforts is the behavior of occupants. Eco-responsibility on their part is essential for these measures to be truly effective. By adopting more responsible energy consumption habits, occupants can significantly contribute to reducing energy consumption and CO_2 emissions [11, 12].

This framework helps to better understand how the elements of a building's energy system, despite their diversity and complexity, can be integrated to achieve effective management of energy consumption and CO_2 emissions.

The need for a comprehensive understanding of the intricate relationship between energy consumption and CO_2 emissions is paramount in this era. The objective of this bibliometric analysis is to provide a thorough investigation of the many impacts of energy consumption in buildings on CO_2 emissions, focusing specifically on detecting trends, patterns, and shortcomings in the current body of research. The main aim of this research is to conduct a comprehensive bibliometric analysis of academic literature [13] related to building energy consumption and CO_2 emissions. Rather than directly measuring the physical impact of energy consumption on emissions, this study seeks to synthesize and map the existing body of research over the past decade (2013–2023), offering insight into the structure, trends, and key contributors in this field. By identifying influential publications, prominent authors, leading institutions, and evolving research themes, this analysis supports a deeper understanding of how the topic has been addressed in the literature and where gaps remain.

Therefore, the objective of this bibliometric evaluation is to provide responses to the following research inquiries:

- What are the distributions of publications on energy consumption in building and CO_2 emissions in the years 2013-2023?
- What are the most relevant journals and authors in the field of energy consumption in building and CO_2 emissions?
- Which countries publish the most research on energy consumption in building and CO_2 emissions?
- What are the key educational institutions involved in research on the energy consumption in building and CO_2 emissions?
- What are the primary research keywords for energy consumption in building and CO_2 emissions within the last decade?

2. Methods

2.1. Research design

The present bibliometric investigation adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [14], which ensures transparency and rigor in the systematic review process. The primary aim of this comprehensive analysis is to delineate the body of research that explores the correlation between energy consumption and CO_2 emissions in buildings. This includes an exhaustive examination of leading nations, academic institutions, publications, and authors contributing to this field. Additionally, the study seeks to identify emerging patterns, research gaps, and key terminologies within this domain.

The study followed a structured bibliometric workflow encompassing four key phases: identification, screening, eligibility, and inclusion. These phases are clearly illustrated using the PRISMA flow diagram (see Figure 1). In conjunction with the PRISMA framework, this study extensively utilized VOSViewer (version 1.6.19) for data visualization and analysis. VOSViewer is a software tool specifically developed to streamline the construction and observation of bibliometric networks, which may include journals, publications, researchers, or individual works. These networks are based on co-authorship, citation, co-citation, and bibliographic coupling links.

The mapping and analysis of the complex networks in energy consumption and CO_2 emissions research were greatly facilitated by VOSViewer. It enabled the identification of interconnections between various academic disciplines, the most influential journals, publications, and authors, and the visualization of trends. VOSViewer's clustering algorithm also helped categorize publications into thematic clusters, enabling the identification of research hotspots and trends. This, in turn, led to the identification of the most relevant trends and patterns in the field of energy consumption and CO_2 emissions research.

By using VOSViewer, a more comprehensive understanding of the global impact and research dynamics around energy consumption and CO_2 emissions was achieved. This was accomplished through the geographical organization of publications and collaborations between institutions and authors [15].

Table 1. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Energy consumption and CO_2 emissions in building	Any other subject was excluded
2013 – 2023	All publications before 2013 were excluded and 2024 publications were excluded
English language	Any others languages
Articles, conference paper	Thesis, books, book chapters, blogs
Journals, conference proceedings	Any other source was excluded

2.2. Identifications

2.2.1. Database selections

This review was conducted on June 26, 2024, using Scopus as the primary database. Scopus was chosen for its advanced analytical capabilities, extensive multidisciplinary coverage, and robust citation tracking features. This comprehensive database includes a wide range of articles, conference papers, and books, making it an invaluable resource for researchers. The database was accessed via institutional login, and export options were configured to include metadata such as title, authors, affiliations, abstracts, keywords, source titles, document types, and citations. Scopus's Top of Formhigh-quality sources and detailed bibliometric tools facilitate thorough analysis, supporting a wide array of research fields. As one of the most prestigious databases for analyzing scientific papers, Scopus is considered a key resource for academic research [16, 17].

2.2.2. Search strings

To ensure the retrieval of relevant studies, the researchers used specific keywords, such as "energy consumption of building AND CO2 emissions," for instance, TITLE-ABS-KEY (energy AND consumption AND of AND building AND CO2 AND emissions). Publications from the last decade, specifically from 2013 to 2023, were selected using the criteria AND PUBYEAR > 2012 AND PUBYEAR < 2024. The subject areas were limited to energy, environment, and engineering, for instance, (LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENGI")). Publications in English were selected for this review AND (LIMIT-TO (LANGUAGE, "English")). The document types were limited to articles and conference papers AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")). The sources included journals and conference proceedings (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p")). The full export included 2,634 documents initially retrieved through this comprehensive search query.

2.2.3. Inclusion and exclusion criteria

To ensure the quality and consistency of the literature selected for this bibliometric analysis, clear inclusion and exclusion criteria

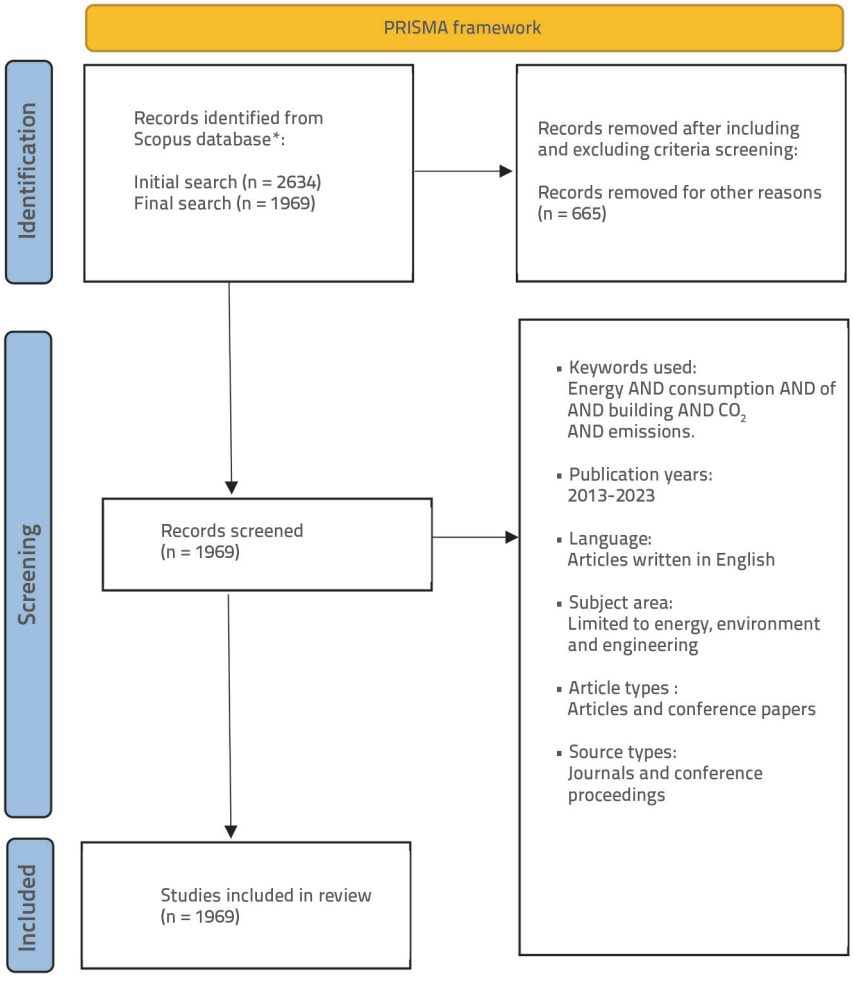

Figure 1. Prisma framework of this review (Source: The PRISMA 2020 statement: An updated guideline for reporting systematic reviews)

were applied. These criteria were designed to narrow down the relevant sources and ensure that the analysis focused on the most significant and recent studies on energy consumption and CO_2 emissions in buildings. Table 1 outlines the specific inclusion and exclusion criteria used in this study.
The criteria listed in Table 1 were used to select publications that were directly relevant to energy consumption and CO_2 emissions in buildings. These criteria ensured that the literature analyzed was current, in English, and from reputable sources such as journal articles and conference proceedings. By applying these specific filters, the study was able to focus on high-quality and relevant research that contributes meaningfully to understanding the connection between building energy consumption and CO_2 emissions.

Screening and selection
The main keywords used were "ENERGY CONSUMPTION IN BUILDING AND CO_2 EMISSIONS." The initial search yielded 2,634 publications. Duplicate records were automatically filtered out by Scopus's export function. After applying the inclusion and exclusion criteria, as shown in Table 1, the number of relevant publications was reduced to 1969, with 665 publications being excluded.

Inclusion and reporting
The final set of 1969 studies was analyzed using VOSViewer, and findings are reported according to the PRISMA 2020 [14] guidelines (see Figure 1). The visual representation of bibliometric networks is organized around the key research questions concerning the volume, impact, and trends in publications related to energy use and CO_2 emissions in buildings.

3. Results

In this section, we address the research questions based on the analysis of data retrieved from the Scopus database. A comprehensive search using the specified keywords and criteria resulted in a refined dataset of 1969 relevant documents. The findings are organized as follows:

3.1. The distributions of publications on energy consumptions in building and CO_2 emissions

In this section, we explore the temporal distribution of publications related to energy consumption in building and CO_2 emissions over the past decade (2013-2023). This section will answer the following question:
Question 1: What are the distributions of publications on energy consumption in building and CO_2 emissions in the years 2013-2023?

In this section, we explore the temporal distribution of publications related to energy consumption in buildings and CO_2 emissions from 2013 to 2023. This analysis provides valuable insights into how research interest and output in this area have evolved over the past decade, and highlights the growing academic and practical focus on sustainability in the built environment.

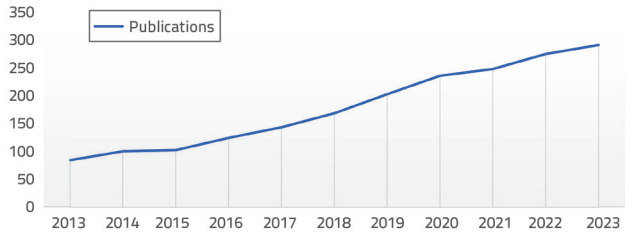

Figure 2. Distribution of publications by years

The data indicates a notable increase in the number of publications over the years. For example, in 2023, there were 290 publications, and in 2022, there were 274 publications. This surge suggests a robust and expanding interest in the field, likely driven by increasing global awareness of climate change and the urgent need to reduce carbon emissions. Several factors may explain this trend, including advancements in energy-efficient technologies, the adoption of international sustainability frameworks, and the rising demand for more environmentally friendly building practices.
In contrast, the number of publications was relatively lower at the beginning of the decade. In 2013, there were only 96 publications, and in 2014, there were 100 publications. The slow initial pace of publications may reflect earlier stages of research, when the focus on energy consumption in buildings was still developing. However, the gradual increase in publications each year reflects growing concern and urgency surrounding the environmental impact of the built environment. This shift likely coincided with the global push for more sustainable urban planning, stricter environmental regulations, and increased funding for green building research.

3.2. Top 10 countries that publish the most about energy consumption in building and CO_2 emission and their most significant academic institutions

The analysis is based on the number of publications attributed to researchers from each country over the last ten years. Additionally, we identify the most significant academic institutions contributing to this field of research.
This section will answer the following questions:
Question 2: Which countries publish the most research on energy consumption in building and CO_2 emissions?
Question 2: What are the key educational institutions involved in research on the energy consumption in building and CO_2 emissions?

The analysis in this section provides an overview of the countries with the highest number of publications on energy consumption in buildings and CO_2 emissions over the past decade. The data

highlights China as the leading contributor, with a staggering 314 publications. This is indicative of China's growing commitment to addressing climate change and enhancing energy efficiency in the built environment. China's extensive use of renewable energy solutions and policies aimed at reducing CO_2 emissions play a crucial role in this trend.

In contrast, Italy's 204 publications reflect the country's efforts to address climate change, driven by the lack of fossil resources and a focus on energy-efficient building technologies. Spain's substantial contribution (170 publications) can be linked to the country's comprehensive research policies, fostering collaboration between universities and industry to improve energy efficiency in buildings.

Iran and India, with 69 and 59 publications respectively, show a growing interest in energy efficiency, but they are still catching up in comparison to other nations. This indicates that while these countries recognize the importance of sustainable energy practices, their research output has been limited by factors such as available funding and technological infrastructure.

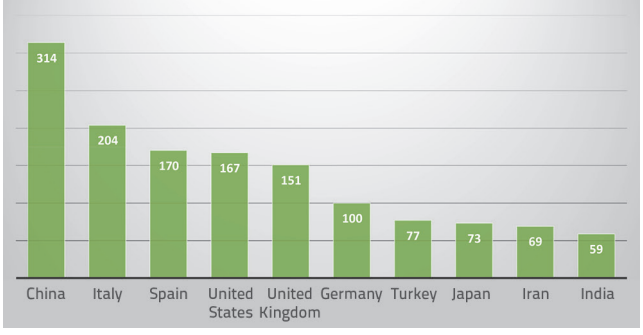

Figure 3. Top 10 countries publishing the most research on energy consumption in building and CO_2 emissions (2013-2023)

Figure 3 provides a visual representation of the top 10 countries publishing research in the field of energy consumption in buildings and CO_2 emissions. The contrast between China's dominance and other countries highlights the significant gap in research outputs. It is important to critically examine why certain countries, such as China, have been able to scale their research efforts in this area. This success can be largely attributed to factors like government incentives, substantial funding, and the presence of active research institutions. These elements have played a key role in enabling China to lead in publication volume while also driving innovation and advancements in energy efficiency and sustainability research.

As shown in Table 2, the countries with the most significant academic contributions to the field of energy consumption in buildings and CO_2 emissions are as follows:

- China leads with 314 total publications (TP), with Tianjin University being the most prominent academic institution in this domain. This underscores China's significant investment in both research and innovation in energy efficiency and sustainability, driven by its national policies focused on climate change and environmental management.
- Italy, with 204 publications, ranks second. Genoa University stands out as the most significant academic institution in Italy in this area, contributing substantially to the body of knowledge. It reflects Italy's dedication to improving energy efficiency and its architectural heritage, focusing on retrofitting and optimizing building performance.
- Spain, contributing with 170 publications, ranks third, with Lleida University playing a major role. Spain's increasing research in energy consumption within buildings is part of its broader efforts to improve energy use in the built environment and tackle CO_2 emissions through efficient building practices.
- United States, with 167 publications, comes in fourth, with Purdue University being its leading institution. The U.S. has been at the forefront of energy research for

Table 2. Top 10 countries in energy consumption in building and CO_2 emissions and their most significant academic institutions

Rank	Country	TP	The most significant academic institutions
1	China	314	Tianjin University
2	Italy	204	Genoa University
3	Spain	170	Lleida University
4	United states	167	Purdue University
5	United Kingdom	151	Heriot-Watt University
6	Germany	100	Helmholtz Centre for Environmental Research
7	Turkey	77	University of Gaziantep
8	Japan	73	Middle East Technical University
9	Iran	96	Islamic Azad University
10	India	59	Indian Institute of Science
TP = total publications			

decades, supported by governmental policies and large-scale initiatives for sustainable buildings and low-carbon technologies.

- United Kingdom ranks fifth with 151 publications, and Heriot-Watt University is identified as a key contributor. The UK's commitment to achieving net-zero carbon emissions by 2050 is reflected in its academic outputs focusing on energy efficiency and sustainable construction.
- Germany, with 100 publications, is home to the Helmholtz Centre for Environmental Research, which is a leader in environmental research, including energy efficiency in buildings and the reduction of CO_2 emissions.
- Turkey, contributing with 77 publications, sees University of Gaziantep as its most influential institution. Turkey's research efforts align with its goal of improving building performance in terms of energy consumption and environmental impact.
- Japan, with 73 publications, has Middle East Technical University (a notable institution despite being located outside Japan, in Turkey) making significant contributions in the field.
- Iran, with 96 publications, lists Islamic Azad University as its leading institution. Iran has steadily increased its research focus on energy conservation within the built environment as part of its national sustainability efforts.
- India, contributing with 59 publications, lists Indian Institute of Science as its most prominent institution in energy consumption and CO_2 emissions research. India's increasing urbanization and focus on energy-efficient building solutions contribute to this growing area of research.

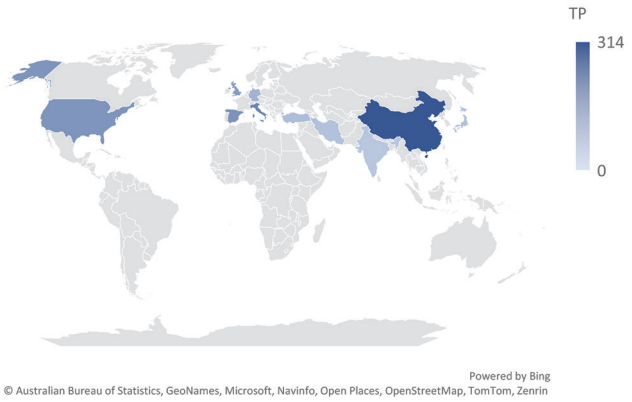

Figure 4. Top 10 countries in publishing about energy consumption in building and CO_2 emissions (2013-2023)

Figure 4 illustrates the top 10 countries in terms of publications related to energy consumption in
building and CO_2 emissions. The color intensity represents the number of publications, with darker shades indicating a higher number of publications. Countries with darker shades on the map reflect a higher number of publications, showcasing their active participation and leading role in research on energy consumption in buildings and CO_2 emissions. The prominence of countries like China, Italy, and Spain on the map further emphasizes the strong academic collaborations in these regions. However, there is a visible gap in the number of publications from regions like Africa and parts of the Middle East, which reflects the limited research funding and infrastructure in those areas.

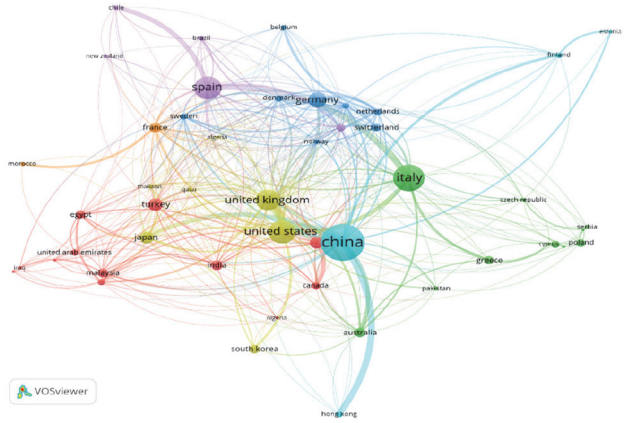

Figure 5. Analysis results of productive countries on energy consumption in building and CO_2 emissions.

Figure 5 illustrates the analytical results of productive countries in the field of energy consumption in buildings and CO_2 emissions. The most productive country is China, followed by Italy and Spain. Additionally, the United States, United Kingdom, Germany, Turkey, Japan, Iran, and India are listed as the top 10 countries in this research field.

The trend shown by these figures suggests that countries with established research institutions and strong governmental support for climate change policies tend to dominate the field. Collaboration between countries in Europe and Asia is also noteworthy, especially in terms of shared research on energy-efficient building technologies. These joint efforts have led to innovative technologies and energy systems that significantly reduce energy consumption and CO_2 emissions. Moreover, such collaborations have influenced governmental policies, prompting updates to building regulations and energy efficiency standards based on shared research findings. However, further collaboration with emerging economies is essential to ensure a more balanced and inclusive approach to addressing global challenges in energy consumption and CO_2 emissions.

3.3. The most relevant journals and authors in the field of energy consumption in building and CO_2 emissions

This section identifies the most influential journals that publish research on energy consumption in building and CO_2 emissions, highlighting their impact on the field. It also recognizes the leading authors who have significantly contributed to this area of study. By pinpointing these key sources and contributors, we can better understand the central hubs of knowledge and innovation in this research area.

Question 4: What are the most relevant journals and authors in the field of energy consumption in building and CO_2 emissions?

Table 3. Top 10 journals in energy consumption of building and CO_2 emissions research

Journal	TP	TC	Cite score	Most cited article	Times cited	Publisher
Energy And Buildings	3320	42.306	12,7	Ultra-short term power load forecasting based on CEEMDAN-SE and LSTM neural network [18]	71	Elsevier
Energies	32.416	201.848	6,2	Electrochemical Impedance Spectroscopy: A New Chapter in the Fast and Accurate Estimation of the State of Health for Lithium-Ion Batteries [19]	102	Multidisciplinary Digital Publishing Institute (MDPI)
Sustainability (Switzerland)	55.991	381.357	6,8	Chatbots in Education and Research: A Critical Examination of Ethical Implications and Solutions [20]	123	Multidisciplinary Digital Publishing Institute (MDPI)
IOP Conference Series: Earth and Environmental Science	66.209	68.990	1,0	Investments in green business and corporate governance by Ukraine's cooperation with the European Union [21]	24	IOP Publishing
Journal of Cleaner Production	19.382	394.597	20,4	Green technological innovation, green finance, and financial development and their role in green total factor productivity: Empirical insights from China [22]	252	Elsevier
Applied Energy	6362	134.584	21,2	Wind power forecasting considering data privacy protection: A federated deep reinforcement learning approach [23]	106	Elsevier
Journal of Building Engineering	7051	70.200	10,00	Predictive models for concrete properties using machine learning and deep learning approaches: A review [24]	106	Elsevier
Energy	12.098	184.935	15,3	Investment in renewable energy and electricity output: Role of green finance, environmental tax, and geopolitical risk: Empirical evidence from China [25]	140	Elsevier
Sustainable Cities and Society	67.666	3072	22	Algorithmic urban planning for smart and sustainable development: Systematic review of the literature [26]	64	Elsevier
Energy Conversion and Management	4686	89.091	19	A comprehensive review of primary strategies for tar removal in biomass gasification [27]	82	Elsevier

Note: TP = total publications, TC = total citations

As shown in Table 3, the most prolific journals in the field energy consumption in building and CO_2 emissions was Sustainable Cities and Society with 22 cite score, followed by Applied Energy with 21.2 cite score.

Based on the most prolific journal in accordance with the most total publications (TP), Sustainable Cities and Society has the most amount of publications with 67 666 publications in the area of research. On the other hand, Energy and Buildings journal has only 3 320 publications, i.e., it has the least amount of publications.

From the total citations (TC) view, Journal of Cleaner Production was the first with 394 597 citations, while Sustainable Cities and Society had the least citations, i.e., 3072.

The most cited papers in this field often explore critical challenges and present solutions for reducing energy consumption in buildings and minimizing CO_2 emissions. These papers receive significant citations because they contribute with valuable insights or innovative methodologies that are applicable to both academic research and practical applications in the industry. A key factor in their high citation rates is the relevance of the topics addressed, such as energy efficiency strategies, carbon-neutral building design, and the integration of renewable energy into building systems.

For instance, the paper published in *Energy and Buildings* titled "Ultra-short term power load forecasting based on CEEMDAN-SE and LSTM neural network" is highly cited because it offers a cutting-edge approach to load forecasting, which is crucial for optimizing energy consumption in buildings. This methodological innovation is critical for smart grid technologies, hence its widespread adoption in the research community.

Table 4. Top 10 authors in research on the energy consumption in building and CO_2 emissions

Author	Year of first publication	TP (total number of publications)	h-index	TC (total number of citations)	Current affiliations	Contrary
Fabrizio Ascione	2009.	135	41	4941	Università degli Studi di Napoli Federico II	Italiy
Nicola Bianco	1997.	241	45	6213	Università degli Studi di Napoli Federico II	Italiy
Juha Jokisalo	2004.	119	28	2414	Aalto University	Finland
Jesús Las-Heras-Casas	2014.	33	15	558	Universidad de La Rioja	Spain
Luis María López-Ochoa	2007.	64	21	1033	Universidad de La Rioja	Spain
Luisa F. Cabeza	1997.	634	92	39.732	Universitat de Lleida	Spain
Taehoon Hong	2005.	289	47	7459	Yonsei University	South Korea
Risto Kosonen	1991.	220	30	3745	Aalto University	Finland
L. M. López González	1997.	67	26	1601	Universidad de La Rioja	Spain
Gerardo Maria Mauro	2014.	92	27	2793	Università degli Studi del Sannio	Italiy

Table 4 highlights the top 10 prolific authors in the research area of energy consumption in building and CO_2 emissions. The most prolific author is Luisa F. Cabeza from Universitat de Lleida, Spain, with 634 total publications, 39,732 total citations, and an h-index of 92. Following her is Taehoon Hong from Yonsei University, Seoul, with 289 total publications, 7,459 total citations, and an h-index of 47.

Notably, a significant number of top authors are from Spain. For example, López González, L. M. from Universidad de La Rioja, Logrono, has 67 total publications, 1,601 total citations, and an h-index of 26. Similarly, López-Ochoa, Luis María from the same institution has 64 total publications, 1,033 total citations, and an h-index of 21. Finally, Las-Heras-Casas, Jesús from Universidad de La Rioja has 33 total publications, 558 total citations, and an h-index of 15.

This data underscores the substantial contributions from Spanish researchers to the field of energy consumption in building and CO_2 emissions.

3.4. Subject area

This section will explore the primary subject areas in research on energy consumption in building and CO_2 emissions. By categorizing the research into various subject areas, we can better understand the multidisciplinary nature of these studies and the diverse approaches used to address this complex issue. This analysis will also help in identifying gaps in the current research and potential areas for future investigation, answering the following question:

Question 5: What are the primary research keywords for energy consumption in building and CO_2 emissions within the last decade?

Figure 6 illustrates the distribution of research publications in energy consumption in building and CO_2 emissions across various scientific disciplines. Energy leads the contributions, followed closely by Engineering and Environmental Science. Social Science also plays a significant role, while Mathematics, Computer Science, and Materials Science contribute to a lesser extent but are still vital in providing a comprehensive understanding and management strategies to reduce energy consumption in buildings and CO_2 emissions.

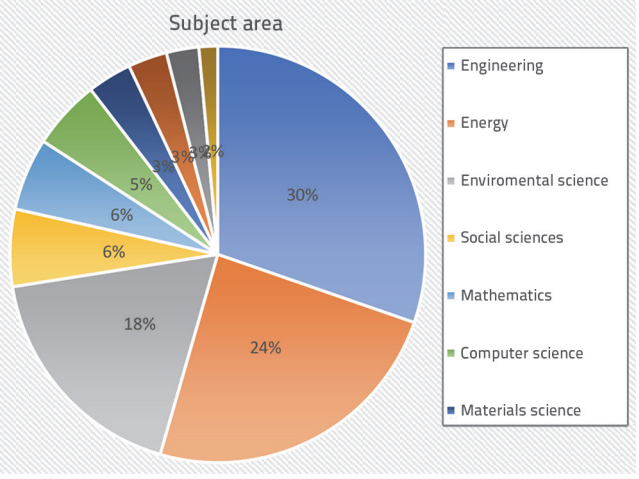

Figure 6. Subject area

Figure 7 presents the analysis results of publications based on keyword co-occurrence. For this bibliometric analysis, "Co-occurrence" was selected as the analysis type, with "Author Keywords" marked as the unit of analysis. The visualization reveals a rich, interconnected research landscape in the field of reducing energy consumption in building and CO_2 emissions.

Central themes that were identified include energy utilization, carbon dioxide, emissions control, energy consumption, buildings, and technologies. These themes highlight the multi-dimensional nature of this research area. Additionally, the prominence of international collaborations and the diverse geographical focus underscore the global importance and collaborative efforts

needed to advance knowledge and develop effective strategies for reducing energy consumption and CO_2 emissions.

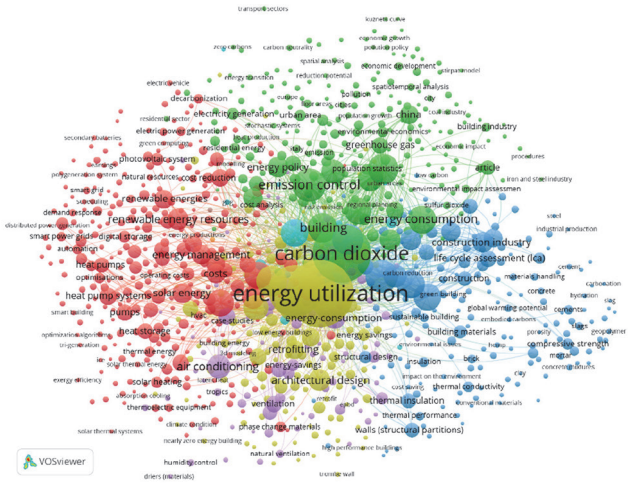

Figure 7. Analysis results of publications by keywords

The distribution of research across multiple disciplines indicates that solving the challenges of energy consumption and CO_2 emissions in buildings will require not just technological solutions but also social, economic, and political approaches. The rising focus on international collaborations, as reflected in the keyword analysis, also suggests that collective global action is critical to achieving sustainable energy solutions.

4. Discussion

With regard to the dynamic realm of energy consumption in building and CO_2 emissions, the bibliometric study detailed in this article provides a comprehensive viewpoint. The findings illustrate the growth and progress of an academic discipline characterized by diverse contributions from various nations and organizations, as well as a growing focus from scholars.

4.1. Trends in publications and geographic distributions

The significant increase in scholarly articles related to the correlation between energy consumption in buildings and CO_2 emissions indicates an expanding academic focus on this field, as evidenced by the growing number of publications over the years, as shown in Figure 2. While the war in Ukraine did disrupt global energy supplies and led to heightened urgency regarding energy policies [28], the linear nature of the increasing publications suggests that other factors, such as the global push for renewable energy adoption, climate change mitigation efforts [29], and technological advancements in energy efficiency, have played a significant role as well. The war may have amplified these issues, particularly in Europe, by increasing energy prices and accelerating the transition to sustainable energy solutions. However, the broader trend of growing interest in energy consumption and CO_2 emissions likely results from a complex interplay of global environmental concerns, economic pressures, and scientific advancements aimed at improving energy efficiency in buildings and reducing greenhouse gas emissions [30].

Many researchers are dedicated to finding solutions to reduce energy consumption and CO_2 emissions, as well as to enhance energy efficiency in buildings and the utilization of renewable energy sources [32-37].

The prominence of countries such as China, Italy, and Spain in the field of energy consumption in buildings and CO_2 emissions can be attributed to a combination of factors, including their research output, government policies, and investment in renewable energy technologies. Table 4 highlights the top 10 prolific authors in this domain, whose work has made significant contributions to advancing our understanding of energy-efficient buildings and CO_2 emissions reduction.

China, with 314 publications over the last decade, leads in the sheer quantity of research output. However, while China's publications are numerous, their citation impact does not match that of countries like Italy and Spain, where researchers consistently produce high-impact studies. The lower citation count of Chinese publications might be indicative of several factors, such as the early-stage development of the research in China, emerging research networks, or the focus of some studies on nationally relevant rather than globally applicable topics.

Despite the relatively lower citation count, China's leadership in publication volume is not without merit. The country's growing commitment to energy efficiency is reflected in aggressive government policies, such as the 13th Five-Year Plan for Ecological and Environmental Protection, which prioritizes energy-efficient buildings and the reduction of CO_2 emissions. These policies drive national research efforts and contribute to the country's leading role in addressing its energy consumption challenges.

In contrast, Italy and Spain produce fewer publications compared to China but boast significantly higher citation counts, indicating that their research is widely recognized and influential. For instance, Luisa F. Cabeza (634 publications) from Spain has received 39,732 citations, while Fabrizio Ascione (135 publications) from Italy has garnered 4,941 citations. These high citation counts suggest that the research conducted in Italy and Spain is of global relevance, often influencing energy policies and practices beyond their national borders.

The relatively higher citation impact of Italian and Spanish research can also be attributed to their strong academic networks, collaboration with international research initiatives, and significant contributions to European Union regulatory frameworks on climate action. Both countries are deeply invested in the transition to renewable energy, and their research is aligned with EU policies on energy efficiency and carbon reduction, providing them with strong funding opportunities and avenues for cross-border collaboration.

While China leads in the quantity of publications, the quality and global impact of research from Italy and Spain highlight the complexity of assessing research leadership in this field.

Research impact, measured by citations, relevance to global energy policy, and interdisciplinary collaboration, is equally important in understanding a country's commitment to addressing climate change.

In addition to government policies and national energy strategies, other factors such as the availability of fossil energy resources, technological innovation, and industry-driven research play a role in determining a country's research output. For example, countries like Italy and Spain, which have fewer fossil fuel resources, are more likely to invest in research focused on energy-efficient buildings as part of their efforts to meet climate action goals. On the other hand, China, with its vast energy demands driven by urbanization and industrialization, emphasizes energy-efficient solutions as a critical strategy to reduce its carbon footprint.

Ultimately, the prominence of countries like China, Italy, and Spain in energy consumption in buildings and CO_2 emissions research reflects a combination of quantitative and qualitative factors. While China dominates in terms of publication volume, countries like Italy and Spain lead in research impact as measured by citations, underscoring the importance of both research output and global influence in shaping the field of energy efficiency and climate change mitigation.

4.2. Influential journals and educational institutions

The study identifies prominent academic institutions and publications that are conducting significant research on energy consumption and CO_2 emissions in buildings. These institutions are recognized for their contributions to advancing energy efficiency and sustainability in the built environment. For example, research at Universitat de Lleida in Spain has led to breakthroughs in the integration of renewable energy systems in buildings, while studies from Università degli Studi di Napoli Federico II in Italy focus on innovative building materials that enhance energy performance. These specific contributions exemplify how these institutions are shaping the future of energy-efficient buildings.

However, while these academic establishments play a pivotal role in disseminating knowledge and promoting sustainable practices, there are also limitations. For instance, the focus on established institutions from developed countries may overlook emerging research from institutions in developing regions, where different energy challenges and solutions may be found. Additionally, the practical application of some cutting-edge research may be hindered by economic, regulatory, or technological barriers in certain countries, potentially slowing the implementation of research findings on a global scale.

In summary, while these academic institutions are leading the way in energy research, it is important to acknowledge that the full impact of their contributions depends on broader global collaboration, including engagement with emerging economies and overcoming practical challenges in applying new technologies.

4.2.1. Policy and funding influence:

The dominant position of journals like *Sustainable Cities and Society*, *Applied Energy*, and *Energy and Buildings* reflects their critical role in shaping the discourse on energy efficiency and CO_2 emissions. These journals serve as platforms for disseminating policy recommendations and best practices in the energy sector. The influence of these publications is directly tied to their accessibility and focus on publishing high-impact research that informs policy decisions worldwide.

National energy strategies significantly influence the research landscape in energy consumption and CO_2 emissions. Countries with robust energy policies and substantial funding mechanisms (such as the European Union, China, and the U.S.) naturally foster research excellence in this domain. Conversely, countries with limited energy-focused policies may not witness the same intensity of research output, underscoring the role of government investment in promoting academic and practical research.

4.2.2. Practical implications for policymakers and urban planners

The findings of this study offer valuable insights for policymakers, urban planners, and engineers. Policymakers should leverage this research to refine building regulations and energy efficiency policies. They can incorporate energy consumption and CO_2 emissions reduction measures into building codes, incentivize the adoption of renewable energy solutions, and push for the integration of smart building technologies that optimize energy use. Urban planners, in collaboration with architects and engineers, can design energy-efficient buildings that adhere to these updated regulations, prioritizing sustainable practices such as passive design, renewable energy integration, and the use of green materials. Practical steps that can be taken include:

- Enhanced building regulations: Revising building codes to mandate energy-efficient designs, renewable energy integration, and smart technologies that monitor and optimize energy use.
- Incentive programs: Introducing financial incentives for retrofitting existing buildings with energy-efficient technologies.
- Cross-disciplinary collaboration: Encouraging collaboration between architects, engineers, urban planners, and policymakers to design and implement holistic, sustainable solutions that address both energy consumption and CO_2 emissions.

.4.3. Prolific authors and research keywords

The work of prolific authors such as Fabrizio Ascione, Nicola Bianco, and Juha Jokisalo has been instrumental in shaping the understanding of energy consumption and CO_2 emissions in buildings. Their contributions highlight the interdisciplinary nature of this field, where engineering, environmental science, and social science converge to address complex issues. The analysis of the

most common keywords, such as "energy utilization," "carbon dioxide emissions," and "energy policy," reveals a strong emphasis on technological solutions for energy efficiency, alongside the socio-economic factors that drive energy consumption behaviors.

Emerging topics and gaps in research

Over time, there has been a noticeable shift in the types of research being conducted. Topics related to renewable energy integration, smart building technologies, and advanced materials are gaining prominence. However, there remain unexplored or underexplored areas that warrant further investigation. For instance, while energy consumption in buildings is a widely researched topic, there is limited focus on the intersection of energy consumption with the social aspects of building use. How human behaviors and cultural practices affect energy consumption in different regions remains a significant gap in the literature. Additionally, while technological advancements are being explored, research on the affordability and accessibility of energy-efficient solutions in developing countries remains underrepresented.

Future research directions

Future research should explore several emerging areas, including:

- Integration of artificial intelligence and big data: Using AI and data analytics to optimize energy use in buildings through predictive modeling and real-time monitoring systems.
- Circular economy in building materials: Investigating the role of circular economy principles in reducing the environmental footprint of building materials and waste.
- Social and behavioral aspects: Understanding how human behavior, cultural norms, and socioeconomic factors influence energy consumption in buildings, particularly in different geographical and cultural contexts.

4.4. Subjects areas and their implications

The research covers a wide array of subject matters, highlighting the multidisciplinary nature of energy consumption and CO_2 emissions. This is evident from the prevalence of fields like computer science and social science, which have increasingly merged. The use of an interdisciplinary approach is critical because it enables the integration of diverse methodologies and perspectives, ensuring that both technological innovations and social considerations are addressed. This approach is crucial in developing engaging and effective strategies to reduce energy consumption and CO_2 emissions, accommodating a wide range of methods for achieving these reductions.

By incorporating insights from various disciplines, interdisciplinary research fosters solutions that are not only technologically advanced but also socially acceptable and environmentally sustainable. This comprehensive approach ensures that solutions are not only technologically advanced but also socially acceptable and environmentally sustainable. By incorporating insights from various disciplines, researchers can design more holistic and resilient strategies that address the complex challenges associated with energy consumption and CO_2 emissions. This collaboration across fields is essential for creating impactful and long-lasting solutions that can adapt to the diverse needs and contexts of different communities and industries. In this way, interdisciplinary collaboration is essential for creating impactful and long-lasting solutions that can effectively address the complex and evolving challenges of energy consumption and CO_2 emissions.

In summary, the findings of this bibliometric study provide an all-encompassing depiction of the present condition and future direction of scholarly inquiry concerning energy consumption and CO_2 emissions. In addition to being crucial for academic objectives, this expanding body of knowledge has practical implications for practitioners, policymakers, and technologists. It is essential to stay updated on ongoing advancements in energy consumption and CO_2 emissions to ensure that strategies to reduce energy consumption and CO_2 emissions in buildings are productive, comprehensive, and favorable for environmental conservation and the preservation of natural energy resources.

4.5. Study limitations

Despite the comprehensive nature of this study, there are certain limitations that must be acknowledged:

- Database coverage: The study relies on specific bibliometric databases, which may exclude certain articles, especially those published in non-English languages or in regional journals. This limitation could introduce a bias toward English-language publications and those in high-impact journals.
- Potential language bias: A predominance of English-language publications may not fully represent the global diversity of research, particularly in non-English-speaking regions.

In future studies, expanding the scope to include non-English publications and utilizing additional bibliometric databases could help mitigate these biases and provide a more comprehensive view of global trends in energy consumption and CO_2 emissions in buildings.

4.6. Summary of the results of the review

The following table presents a consolidated summary extracted from this research article, which conducts an exhaustive analysis of the development, consequences, and potential future of reducing energy consumption and CO_2 emissions in buildings, with a specific focus on their impact on climate change. The data is categorized into significant domains, including discoveries, ramifications, trends, and future plans. These classifications provide a comprehensive overview of the importance of reducing energy consumption and CO_2 emissions, highlighting attention to geographic distribution, primary authors, and subject-specific emphasis in the field. The objective of the research is to delineate the current state of affairs and forecast future directions in this rapidly evolving domain, as seen in Table 5.

Table 5. A thorough examination of energy consumption and CO_2 emissions and its influence on climate change: principal discoveries and prospects for the future

Aspect	Findings	Implications	Trends	Future agenda
Publication	Significant increase in publications over the last decade	An increased focus on reducing energy consumption and CO_2 emissions has emerged due to the impact of the Ukraine war and the global commitment of countries to mitigate climate change by cutting energy use and emissions.	The trend of publications continues to rise annually	Continued expansion in research efforts, with a focus on increasing interdisciplinary studies such as the integration of engineering, environmental science, architecture, social science, and data analytics aimed at enhancing energy efficiency and reducing CO_2 emissions. These studies are particularly important for addressing complex challenges like optimizing building design, developing smart energy systems, and formulating effective policy frameworks. Including social science also allows researchers to better understand and influence occupant behavior, which plays a key role in actual energy performance
Journals	*Sustainable Cities and Society, Applied Energy, and Energy and Buildings, are all significant periodicals.*	For beneficial strategies, policies, and methodologies aimed at reducing energy consumption and CO_2 emissions, it is essential to consult these periodicals	Extensive contributions from a variety of periodicals.	Support for open access; higher citation rates.
Countries	Leading countries include China, Italy, Spain, and the United States.	Highlights international effort in energy consumption and CO_2 emissions research.	Geographic expansion in research.	Enhance global techniques to reduce energy consumption and CO_2 emissions through more collaborative international research.
Educational institutions	Tsinghua University, Sapienza Università di Roma, Universidad de Sevilla, are notable contributors to this cause.	These institutions lead in innovative research and influence global strategies for energy reduction.	Energy consumption and CO_2 emissions reduction research is being produced in significant quantities by several countries, including China, Italy, and Spain.	It is crucial to encourage additional educational institutions around the globe to participate in research on energy consumption and CO_2 emissions.
Authors	The subject features a blend of established and emerging scholars, evidenced by contributions from notable authors such as Fabrizio Ascione, Nicola Bianco, and Juha Jokisalo.	Their research forms the foundation for current and future developments in the field.	There is a combination of seasoned researchers and newcomers contributing to the area.	It is important to provide researchers with support and recognition to encourage further advancements in reducing energy consumption and CO_2 emissions.
Keywords	The following are some the most important keywords: energy utilization, carbon dioxide energy, consumption, energy, emissions control, energy policy.	Keywords indicate a strong focus on energy utilizations, CO_2 energy, consumptions, energy, building	This reflects the emphasis that energy consumption and CO_2 emissions put on aspects such as energy utilization, carbon dioxide management, energy consumption in buildings, and overall energy efficiency.	In the realm of energy consumption and CO_2 emissions, future investigations should focus on cutting-edge tools for reducing energy consumption and CO_2 emissions.

5. Conclusion

Due to population growth and urbanization, energy consumption in buildings has been steadily increasing. This paper presents a bibliometric and content analysis of 1,969 publications focused on energy consumption in buildings and CO_2 emissions, aiming to identify key research topics and their dynamics. The analysis reveals a dramatic increase in the number of publications over the years, indicating a growing interest in this research area. Interdisciplinary journals are at the forefront of exploring the connection between building energy consumption and CO_2 emissions, as they provide a platform for integrating diverse perspectives to engineering, environmental science, social science, etc., in order to address complex challenges. However, it is important to acknowledge that interdisciplinary journals represent only one segment of the broader scholarly landscape. Specialized journals in energy engineering, architecture, and environmental policy also play a critical role in advancing focused research and technical innovation in this field. Tsinghua University is recognized as the leading institution in this field in terms of publication output. The study emphasizes that international collaborations significantly enhance scientific performance. Commonly occurring phrases in the publications include energy utilization, carbon dioxide, energy consumption, emissions control, and energy policy. The predominant research topics in literature cover areas such as technology integration, blended learning, and educational technology. Research areas that have seen increasing attention from scholars include energy, engineering, environmental science, social science, and computer science. This trend highlights the growing interdisciplinary nature of research on the relationship between building energy consumption and CO_2 emissions, emphasizing its increasing relevance across various fields.

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