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Hot Topics and Trends in Zero-Energy Building Research—A Bibliometrical Analysis Based on CiteSpace

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Abstract: With the development of a low-carbon economy, zero-energy structures will become prevalent and take center stage in the construction industry. This paper uses the CiteSpace software to create knowledge maps of authors, institutions and keywords, and then examined and commented on research publications regarding zero-energy buildings in order to understand the research state and development trends of zero-energy buildings. The findings demonstrate that: (1) Since its inception in 2000, research on zero-energy buildings has advanced significantly; (2) A subject analysis approach is used to identify development trends and research emphasis, and the four research areas with the most papers published are energy fuels, construction building technology, civil engineering and green sustainable science technology; (3) China, the United States and Italy are the countries with the most activity in zero-energy building research; (4) Out of the eight most prominent keywords for the study subjects, the design of zero-energy buildings, the estimation of the carbon emissions of zero-energy buildings, the technical challenges of zero-energy buildings and the follow-up energy-saving measures of zero-energy buildings are the four fundamental topics covered in the most cited papers; (5) There are three obstacles to the development of zero-carbon buildings: unclear standards, immature technology and insufficient development momentum. The following three problems should receive more attention in the future: how to develop a widely accepted zero-carbon building standard; how to coordinate national support to achieve technological breakthroughs; and the establishment of an effective incentive mechanism at the international and national levels to promote the development of zero-carbon buildings.

Keywords: zero-energy building; bibliometrics; CiteSpace; carbon dioxide emissions; development trends; energy efficiency

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1. Introduction

Global warming is a concern of the international community [1]. According to statistics [2], in 2020, the construction industry accounted for 36% of the global end-use energy consumption and 37% of energy-related CO_2 emissions. The 2020 Global Construction and Construction Industry Status Report [3], released by Global Architecture Alliance (Global ABC) and sponsored by United Nations Environment Programme (UNEP,) pointed out that, in 2019, carbon emissions from the construction sector reached their peak, and the development of the construction industry deviated from the 2 °C temperature-control target of the Paris Agreement. The construction sector's energy consumption and carbon emissions are among the major drivers of global energy use and emissions of greenhouse gases. Despite this, the sector has strong cost advantages for emission reduction and has a significant potential to reduce emissions. The construction industry will have a more considerable impact on the worldwide plan to reduce carbon emissions as a result of the

influence of the expansion of decarbonization initiatives and the adoption and promotion of energy-saving and emission-reduction policies and programs.

In recent years, a number of nations have viewed the building industry as one of the most important sectors for reducing emissions and conserving energy. They have released a number of policies to direct and encourage the implementation of carbon emission reductions in the construction sector. These policies note that being guided by ecological priorities, green development action plans and quality improvement action plans can vigorously promote building energy conservation and emission reduction while also accelerating the development of green buildings. Building energy conservation and green buildings are facing new challenges and requirements as a result of the implementation of mandatory standards, which have been made possible by the comprehensive development of green building technology, green building materials and building energy conservation. In the realm of green buildings, the construction and promotion of "low-carbon buildings", "net zero energy buildings" and "zero-carbon buildings" have become popular. As the "ultimate goal" and "highest pursuit" of carbon reduction in buildings, zero-energy buildings, which is the ultimate goal of zero-energy buildings, refuse to use conventional polluting energy sources (coal, gas, oil, and wood) as the basis and, instead, place a premium on sustainable development, which has positive cross-era significance [4,5]. Zero-energy structures will eventually take center stage in the construction industry's development under the conditions of a low-carbon economy.

The world's first "zero-carbon community" and "zero-carbon dwellings" were constructed in the UK in 2002, where the idea of zero-carbon buildings was first introduced. After examining the previous research, it was discovered that academics from different nations had carried out several useful investigations on the conceptual boundaries of zero-energy buildings from various perspectives. According to Sartori [6], the term "net zero energy building" refers to a building with zero net carbon emissions. That is, the annual energy consumption of the building is no greater than the annual energy output. At the same time, the paper emphasized that only meeting the annual balance is not enough to fully describe the characteristics of an NZEB (net zero energy building), and a specific analysis should be carried out to achieve a systematic balance based on national political goals and specific situations. Deng [7] explained that an NZEB is a comprehensive solution to achieve building energy conservation, environmental protection and carbon-dioxide-emission reductions. Wells [8] argues that an NZEB is an ambiguous term used to describe a building that has the characteristics of equal power generation and use, significantly reduced energy demand, zero energy cost or net zero greenhouse gas emissions (GHG). The construction life-cycle refers to the full-cycle process from material and component production (including raw material mining), planning and design, construction and transportation, operation and maintenance, demolition and treatment. The term "zero-energy buildings" refers to structures with absolutely no systematic carbon emissions at any point in their entire life-cycle. Although there is no universally accepted definition of a zero-energy building, experts generally agree that it produces zero-carbon emissions and that the carbon emissions produced by the building for a year should not exceed the carbon emissions reduced by using technology to reduce carbon emissions.

Figure 1 shows the logical relationship between zero-carbon communities and zero-carbon buildings. In the process of building zero-carbon communities, more consideration is granted to social policies and the surrounding environment to ensure their adaptation to the social environment. Zero-carbon buildings are more self-contained, including building materials, system construction and technology improvement. A net zero energy building is a building that produces as much (or more) renewable energy on site as that which the building uses each year. A variety of tools and technologies are available to achieve this net zero energy goal, such as radiative cooling, green walls, heat exchange systems and solar energy. In the last decade alone, technology has been able to make NZEB practices more efficient and achievable.

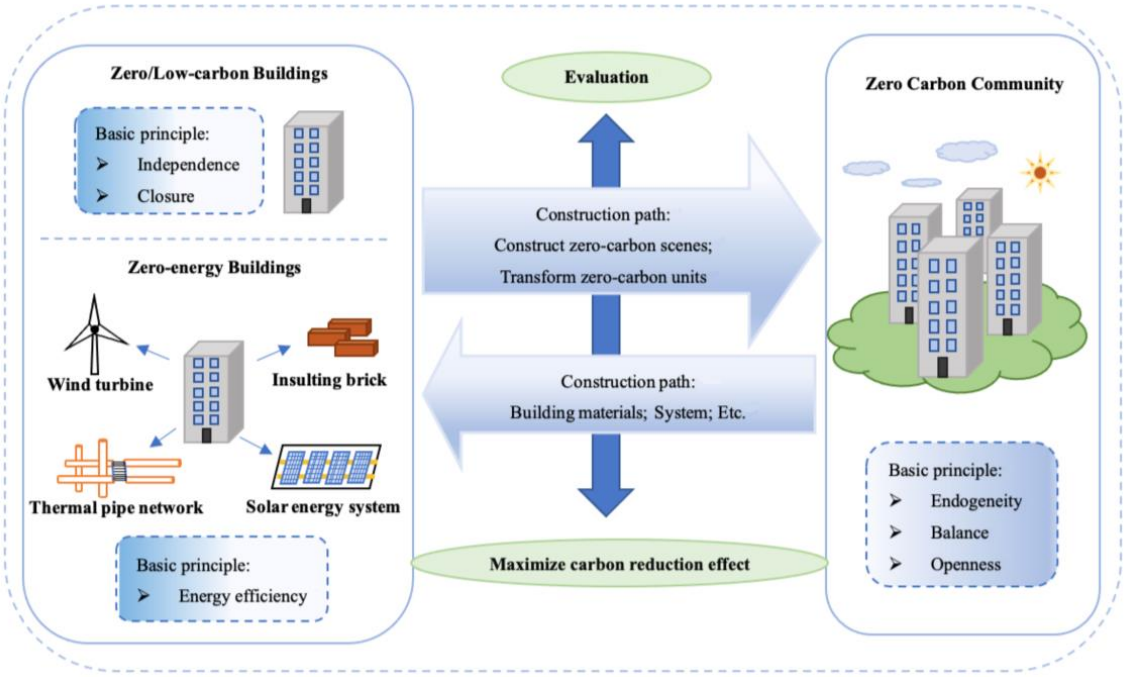


Figure 1. Relationship and difference between zero/low-carbon buildings, zero-energy buildings and zero-carbon community.

Zero-energy buildings are a model where the carbon source minus the carbon sink equals zero, and buildings with net or near-zero energy are essential to achieving climate neutrality. To help scholars and practitioners to gain an in-depth understanding of the current status and future trends of zero-energy building research, it is necessary to conduct a systematic analysis of the current research. To date, zero-energy building research has involved many different disciplines, and scholars have systematically explored the definition, goals and specific technical optimization of zero-energy buildings from different perspectives, including case studies of zero-energy buildings, multi-objective optimization of zero-energy buildings and technical issues in the development of zero-energy buildings. In general, zero-energy buildings are favored by more and more local governments, enterprises and the public considering the high carbon emissions in the construction sector and the residents' multiple demands for improvements in the environment and health. However, although existing studies have conducted relevant analyses on zero-energy buildings from multiple perspectives, a systematic analysis of zero-energy buildings has not been conducted. In some studies, the concept of zero-energy building is not clearly defined, and the research boundary of similar concepts, such as a low-carbon building, is blurred and confused. The case study of zero-energy buildings is still relatively isolated or concentrated in a specific region or country. Although there are many articles related to the field of zero-carbon buildings, the number of review articles in this field is low. In addition, the analysis period is relatively long, and recent research on this subject is not covered. This paper offers a more complete and referential analysis both in terms of the coverage of the published articles and the research years of this topic.

As a result, from the standpoint of time sequence, the current research's objectives are to identify the essential literature, investigate novel research subjects and directions, characterize the growth pattern of the field of research on zero-energy buildings and establish a worldwide knowledge network structure.

Therefore, the following research issues are addressed in this paper:

- What was the relationship between the research area and the zero-energy building theory as it emerged between 2000 and 2021? What are the yearly trends in publishing?
- Which publications and essays in the field of zero-energy buildings have the greatest impact?

- What are the disciplinary organization, research hotspots and research frontiers of zero-energy buildings at the various stages of development from various research perspectives?
- What potential barriers can stand in the way of the construction of zero-energy structures?

To answer these questions, literature metrology and visual analysis methods were used to systematically determine the basis, development and hot spots of zero-energy building research, and the relevant literature was reviewed, revealing the development trends of future research. In this regard, this work has heuristic guiding significance for the study of zero-energy buildings and has some bearing on how such structures will be developed in the future.

2. Research Tools and Data Sources

2.1. Research Tools

It has become more urgent to use visualization software to build knowledge graphs in order to mine the association between data due to the rapid development of social information, the advent of the big data era, the exponential growth of the literature and the shift in scientific research from being technology-driven to data-driven. Pajek (1996), CiteSpace (1999), HistCite (2004), Gephi (2006), SciTool (2009), VOSviewer (2010) and CitNetExplorer (2017) are the mainstream visualization analysis software at present. Compared with other software, CiteSpace has a higher proportion in the computer science, environmental science, ecology and engineering disciplines, which is the best match for our research object "zero-energy building". At the same time, the visualization software CiteSpace is one of the literature visualization analysis tools widely used by scholars and has been widely applied in the field of the energy economy and low-carbon economy and management [9].

The CiteSpace application's operation process is systematic and scientific, focusing on the definition of terms and keywords, data gathering, term extraction, time zone segmentation, threshold selection, network simplification and merger, visual knowledge map display, visual knowledge map editing and detection and key node verification. Chen stated that CiteSpace has obvious advantages over other software in mining mutant words in the atlas, exploring research hotspots and understanding research directions. This algorithm can easily find mutant words in the literature, which is more conducive for users to understand research hotspots in this field. In addition, CiteSpace provides three visualization methods, and the default setting is cluster view (Cluster), which focuses on the structural characteristics of clusters, highlighting key nodes and important connections. The timeline focuses on delineating the relationship between clusters and the historical span of documents in a cluster. The timezone view focuses on the temporal dimension of knowledge evolution, which can clearly show the update and interaction of the literature. CiteSpace provides automatic clustering based on the spectral clustering algorithm.

The first algorithm to extract cluster tag words is the MI algorithm (mutual information algorithm).

MI algorithm (mutual information algorithm) formula:

Suppose for a set of articles {C}, the total number of articles is N, where the total number of articles containing the word **X** is Nx, the total number of articles containing the word **Y** is Ny, and the total number of articles containing {**X** + **Y**} is Nxy. Then, the correlation is calculated as follows.

$$Corr(X,Y) = Math.\log 10\left(\frac{N}{Nx}\right) * Math.\log 10\left(\frac{N}{Ny}\right) * Nxy/(Nx + Ny - Nxy) \quad (1)$$

$$MI = \log\left(\frac{f(x,y)}{N}\right) - \log\left(\left(\frac{f(x)}{N}\right) * \left(\frac{f(y)}{N}\right)\right) \quad (2)$$

where $f(x,y)$—times of co-occurrence within the current search scope;

$f(x)$—number of occurrences of keywords in the whole corpus;

$f(y)$—number of occurrences of the word in the context of the whole corpus;

N—corpus size.

The second algorithm to extract cluster tag words is the ***LLR*** algorithm (log-likelihood ratio algorithm).

The log-likelihood ratio is used as the similarity in an association rule.

$$\begin{aligned} \boldsymbol{LLR} &= -\mathbf{2log}\left(\frac{\boldsymbol{L(H0)}}{\boldsymbol{L(H1)}}\right) \\ &= \mathbf{2}(\boldsymbol{k_{11}}\mathbf{log}(\boldsymbol{p_1}) + \boldsymbol{k_{21}}\mathbf{log}(\mathbf{1}-\boldsymbol{p_1}) + \boldsymbol{k_{12}}\mathbf{log}(\boldsymbol{p_2}) + \boldsymbol{k_{22}}\mathbf{log}(\mathbf{1}-\boldsymbol{p_2}) - (\boldsymbol{k_{11}}+\boldsymbol{k_{12}})\mathbf{log}(\boldsymbol{p}) \\ &-(\boldsymbol{k_{21}}+\boldsymbol{k_{22}})\mathbf{log}(\mathbf{1}-\boldsymbol{p})) \end{aligned} \quad (3)$$

where:

$\boldsymbol{k_{11}}$—the number of items that both A and B like;
$\boldsymbol{k_{12}}$—the number of items that A likes but B does not;
$\boldsymbol{k_{21}}$—the number of items that A does not like but B likes;
$\boldsymbol{k_{22}}$—the number of items that neither A nor B likes;
***H*0**—preferences of A and B are not related;
***H*1**—preferences of A and B are related.

$$\boldsymbol{p_1} = \frac{\boldsymbol{k_{11}}}{(\boldsymbol{k_{11}}+\boldsymbol{k_{21}})}; \quad (4)$$

$$\boldsymbol{p_2} = \frac{\boldsymbol{k_{12}}}{(\boldsymbol{k_{12}}+\boldsymbol{k_{22}})}; \quad (5)$$

$$\boldsymbol{p} = (\boldsymbol{k_{11}}+\boldsymbol{k_{12}})/(\boldsymbol{k_{11}}+\boldsymbol{k_{21}}+\boldsymbol{k_{12}}+\boldsymbol{k_{22}}). \quad (6)$$

The third algorithm to extract cluster tag words is the LSI algorithm (Latent Semantic Indexing algorithm).

LSI uses SVDS to decompose the word–document matrix. SVDS finds unrelated index variables (factors) from the word–document matrix and maps the original data into the semantic space. Two documents that are not similar in the word–document matrix may be similar in the semantic space.

SVD, also known as singular value decomposition, is a method of matrix decomposition. A t* D-dimensional matrix (word–document matrix)X can be decomposed into T*S*DT, where T is t* m-dimensional matrix, each column of T is called left singular vector (S) and S is m* m-dimensional diagonal matrix. Each value is called a singular value, D is a d* m-dimensional matrix and each column in D is called a right singular vector. After the SVD decomposition of the word–document matrix X, we save only the largest K singular values in S and the corresponding K singular vectors in T and D. The K singular values form a new diagonal matrix S′, and the K left singular vectors and right singular vectors form a new matrix T′ and D′: X′ = T′* S′* D′t forms a new t*d matrix.

Therefore, the software can provide methodological support for exploring the research hotspots, discipline structure and the development trends of zero-carbon buildings. For the above reasons, CiteSpace was selected as the analysis tool in this article.

2.2. Data Sources and Processing Process

This literature review summarized and analyzed the existing zero-energy building research based on key themes. Data for this document were obtained from the Web of Science Core Collection. In Web of Science, "Subject" was selected for retrieval. In this study, Web of Science was selected as the retrieval database to retrieve journal papers from 2000 to 2021. The main reason for the selection of data from 2000 is that, although the first zero-carbon building was built in 2002, the discussion about zero-carbon building had already started before that occurence. In 2000, there were conceptual discussions and technical ideas about "zero-carbon building", and relevant articles were published. In addition, limited by the development of modern science and technology, zero-carbon buildings were not achieved until 2000, and relevant research articles exploded after 2011. The retrieval conditions were the following subjects, including "zero-energy building", "nearly-zero

energy building", "zero-carbon building", "zero carbon building", "zero carbon homes", "zero carbon house", "zero carbon housing", "zero-energy house", "zero-energy housing", "net-zero-energy house", "net-zero-energy housing", "zero (net) energy housing" and "zero (net) energy house".

In order to fine-tune the early retrieval records and ensure that high score literature information was included in CiteSpace (5.8.R3 SE 64-bit) analysis (Chaomei Chen. Philadelphia, PA, USA; Download address:https://citespace.podia.com/), we first selected articles, reviews, proceedings and other types of the literature in the Web of Science Core Collection database (4153 items in total). We gathered 2869 records, comprising 2640 articles and 229 reviews, after excluding invalid literature types, such as letters, conference abstracts and news. Additionally, we preserved 2869 entries after using CiteSpace to remove duplicates from the improved records of this literature material. To create the sample database for this paper, CiteSpace was used to export and transcode the target literature in accordance with its reference standards. This paper's entire body of literature data was compiled in English on 12 December 2021.

3. Data Analysis

3.1. Zero-Energy Building Publication Status

To show the basic state of research on zero-energy buildings, a detailed analysis of the number of papers, nations and research organizations was conducted.

In Figure 2, the number of published research articles on global zero-energy buildings and the number of authors over time are depicted. Only the first author and the corresponding author of the article were maintained in the TXT text when we downloaded the article information as TXT-text-processing data from WOS, as can be seen in Figure 1.

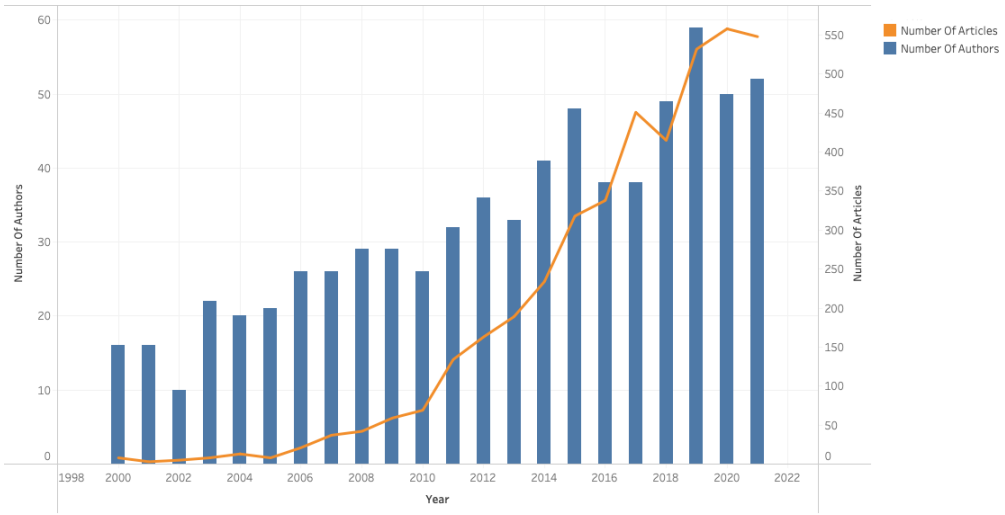


Figure 2. Number of published papers and the chronological distribution of authors of zero-energy building research.

As can be observed in Figure 2, even though there were more papers published each year between 2000 and 2010, the total number of articles was still relatively modest (less than 100), and research was still in its early stages of development of zero-energy buildings. Although the total number of publications published on zero-energy buildings increased from 2011 to 2016, the number of articles published each year remained low. We identified it as the expansion stage of the construction of zero-energy buildings. Since 2017, there have been more than 400 papers published per year on zero-energy buildings, with a sharp increase in that number. This is what we refer to as the era of zero-energy buildings. It is clear that researchers across the world have considerable concerns about zero-energy buildings. Two aspects can be mentioned as possible explanations for this occurrence. On the one hand, there has been a significant and further advancement after several years

of development and the utilization of hybrid energy systems has become more extensive, such as in rural and other remote areas around the world. On the other hand, the explicit concept of zero-energy buildings and their methodologies still need to be improved, which in turn inspires more research.

As can be seen from Figure 2, the variation trend of the number of authors is consistent with the variation law of the number of published articles. We can see from Figure 2 that, between 2010 and 2021, the number of scholars studying zero-energy buildings has increased.

A further in-depth analysis of the spatial distribution of zero-energy building research countries revealed that China published a total of 417 papers during 2000–2021, followed by the United States with 411 papers and Italy with 330 papers. In other words, scholars in China, the United States and Italy are paying more and more attention to and studying zero-energy buildings. A detailed ranking of papers published on zero-energy buildings is shown in Table 1.

Table 1. Top 20 countries with zero-energy building studies, 2000–2021.

Order	Country	Number	Order	Country	Number
1	China	417	11	Belgium	80
2	USA	411	12	Netherlands	77
3	Italy	330	13	Greece	76
4	England	268	14	India	74
5	Spain	185	15	Norway	73
6	Germany	140	16	Portugal	72
7	Australia	130	17	France	68
8	Canada	121	18	Denmark	66
9	South Korea	98	19	Iran	62
10	Finland	93	20	Japan	62

Additionally, the top 20 research institutions in the field of zero-energy buildings were examined in this study (as shown in Table 2). The findings reveal that the top 20 research institutes for zero-energy buildings have published 571 publications, with Aalto University coming in first and City University Hong Kong coming in second.

Table 2. Top 20 institutions and countries conducting zero-energy building research.

Order	Research Institutions	Country	Number	Order	Research Institutions	Country	Number
1	Aalto University	Finland	56	11	Aalborg University	Denmark	24
2	City University of Hong Kong	China	53	12	University of Salento	Italy	22
3	Hong Kong Polytechnic University	China	39	13	Aristotle University of Thessaloniki	Greece	22
4	Politecnico di Torino	Italy	39	14	University of Liege	Belgium	21
5	Norwegian University of Science and Technology	Norway	36	15	Chinese Academy of Sciencess	China	21
6	Politecnico di Milan	Italy	36	16	University of Naples Federico II	Naples	21
7	Chinese Academy of Sciences	China	31	17	Shanghai Jiao Tong University	China	20
8	Concordia University	Canada	25	18	University of Colorado	USA	19
9	Tallinn University of Technology	Estonia	25	19	University of Sannio	Italy	19
10	University of Seville	Spain	24	20	Delft University of Technology	Finland	18

3.2. Analysis of Research Hotspots of Zero-Energy Buildings

3.2.1. Keyword Analysis

The keywords and quantitative traits of every article on zero-energy buildings from 2000 to 2021 are represented visually in Figure 3. The word cloud's size corresponds to a

word's frequency of occurrence. The term "performance", followed by "design" and "system", can be easily found in the center of Figure 3. This demonstrates that researchers who investigate zero-energy buildings pay careful consideration to the design of these structures as well as the realization of their entire systems and final performance. Additionally, "building", "optimization", "energy efficiency" and similar terms are other most frequently used keywords. This demonstrates that, after zero-energy buildings are constructed, researchers pay close attention to their energy efficiency and optimization route.



Figure 3. Keyword word cloud.

Only the top 20 high-frequency terms are shown in this paper (see Table 3), and 8 of them—performance, system, design, optimization, zero energy building, building, residential building and energy efficiency—have a frequency of more than 200.

Table 3. Top 20 high-frequency keywords in zero-energy building research.

Order	Keywords	Number	Order	Keywords	Number
1	performance	549	11	model	179
2	system	377	12	efficiency	171
3	design	344	13	renewable energy	168
4	optimization	240	14	simulation	167
5	zero-energy building	225	15	energy	142
6	building	215	16	thermal comfort	123
7	residential building	209	17	life-cycle assessment	119
8	energy efficiency	208	18	technology	99
9	impact	194	19	climate change	96
10	consumption	190	20	storage	94

- Cross-analysis of keywords and countries

Table 4 shows the keywords in the published research from the over 100 nations that we chose. The keywords and source of the cross-analysis showed that, although China is the country with the greatest number of zero-energy buildings, with a total of 413 distinct keywords, the broader field of research involves 475 different keywords. In all nations, research on zero-energy buildings is a common topic. Environmental performance is among the top 10 high-frequency terms to which countries pay close attention, and in all seven countries, performance is the research topic that causes the most concern. The second keyword, system, is a popular high-frequency keyword in ten different countries.

Table 4. Keyword analysis of the 8 key countries.

Country	Article Number	Numbers of Keywords	Top 10 Keywords
China	417	413	performance, system, design, optimization, zero-energy building, simulation, efficiency, model, impact, storage
USA	411	475	system, performance, design, energy efficiency, climate change, residential building, model, optimization, simulation, life-cycle assessment
Italy	330	356	performance, design, system, zero-energy building, residential building, simulation, energy efficiency, model, optimization, building
England	268	378	performance, energy, design, system, building, energy efficiency, renewable energy, climate change, optimization, technology
Spain	185	283	performance, system, residential building, energy efficiency, building, consumption, optimization, design, impact, efficiency
Germany	140	395	performance, consumption, building, zero-energy building, design, efficiency, climate, simulation, system, emission
Australia	130	282	performance, building, system, design, energy, energy efficiency, impact, model, efficiency, renewable energy
Canada	121	326	performance, system, simulation, design, building, model, impact, consumption, energy efficiency, optimization

- Cross-analysis of keywords and research fields

The distribution of papers published in the research field is quite straightforward, as shown in Table 5. The four fields with the most papers published (more than 500) are energy fuels, construction building technology, civil engineering and green sustainable science technology, particularly energy fuels and construction building technology with more than 1000 articles published. Performance, system and design are some of the zero-energy building research's most popular keywords, and they all have a centralized tendency.

Table 5. High-frequency subject and keywords.

Discipline	Number	High-Frequency Keywords					
		Keywords	Number	Keywords	Number	Keywords	Number
Energy fuels	1766	performance	335	system	229	design	225
Construction building technology	1248	performance	187	design	124	system	104
Civil engineering	719	performance	144	design	94	system	78
Green sustainable science technology	716	performance	115	design	86	system	63
Environmental science	470	performance	59	system	47	design	36

3.2.2. Published Journals and Citations Analysis

Table 6 shows that the top three journals regarding the outcomes of zero-energy buildings in the subject of energy fuels are *Energy and Buildings*, *Applied Energy* and *Renewable and Sustainable Energy Reviews*. *Applied Energy*, *Renewable and Sustainable Energy Reviews* and *Energy and Buildings* are also among the top three economics journals.

Applied Energy, *Renewable and Sustainable Energy Reviews* and *Energy and Buildings* have significantly higher citation rates than other journals, according to a follow-up analysis of the top ten highly productive journals without subject classification (Table 7). These journals also have the highest non-self-cited impact factors (14.280 and 8.276, respectively). With regards to the number of citations, *Energy and Buildings* has the most (1774), followed by *Applied Energy* and *Renewable and Sustainable Energy Reviews*, with 1334 and 1256 citations, respectively. In conclusion, these are the most widely read and quoted journals on the subject of zero-energy buildings.

Table 6. High-yield subject classification and high-frequency journals.

Discipline	Number	High-Frequency Journal					
		Journal	Number	Journal	Number	Journal	Number
Energy fuels	1766	*Energy And Buildings*	1062	*Applied Energy*	871	*Renewable and Sustainable Energy Reviews*	765
Construction building technology	1248	*Energy And Buildings*	657	*Buildings And Environment*	456	*Applied Energy*	413
Civil engineering	719	*Energy And Buildings*	496	*Buildings And Environment*	341	*Applied Energy*	317
Green sustainable science technology	716	*Energy And Buildings*	372	*Renewable and Sustainable Energy Reviews*	297	*Applied Energy*	280
Environmental science	470	*Energy And Buildings*	210	*Applied Energy*	160	*Renewable and Sustainable Energy Reviews*	159

Table 7. Most frequently cited journals and their related information.

Journal	Reference Number	Centricity	Impact Factor	JCR Partition
Energy And Buildings	1774	0.01	5.010	Q1
Applied Energy	1334	0.01	8.276	Q1
Renewable and Sustainable Energy Reviews	1256	0.01	14.280	Q1
Energy	1135	0	6.118	Q1
Buildings And Environment	1094	0.02	5.032	Q1
Renewable Energy	883	0.02	6.881	Q1
Solar Energy	834	0.01	4.846	Q2
Energy Policy	830	0.07	5.521	Q1
Proceedings Of the Institution of Civil Engineers-Energy	713	0	0.909	Q4
Energy Conversion and Management	668	0.01	7.758	Q1

In addition to looking at the correlation between highly cited journals and literary works, we also analyzed the top 10 articles on zero-energy buildings. The results are displayed in Table 8. We can see that most highly cited literature comes from journals.

Table 8. Top ten cited articles from 2000 to 2021.

Year	Article	Author	Journal	Reference Number
2016	The ecoinvent database version 3 (part I): overview and methodology	Gregor Wernet	*International Journal of Life Cycle Assessment*	1381
2014	A review on simulation-based optimization methods applied to building performance analysis	Anh-Tuan Nguyen	*Applied Energy*	647
2014	Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review	Luisa Fernanda Cabeza	*Renewable and Sustainable Energy Reviews*	608
2011	Zero Energy Building—A review of definitions and calculation methodologies	Anna Joanna Marszal	*Energy and Buildings*	605
2012	Net zero energy buildings: A consistent definition framework	Igor Sartori	*Energy and Buildings*	465

Table 8. *Cont.*

Year	Article	Author	Journal	Reference Number
2016	Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade	Xiaodong Cao	*Energy and Buildings*	408
2015	A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings	Chi Kwan Chau	*Applied Energy*	331
2013	Zero energy buildings and sustainable development implications—A review	Danny Hin Wa Li	*Energy*	285
2010	From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB)	Patxi Hernandez	*Energy and Buildings*	276
2013	A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010	Mohamed Hamdy	*Energy and Buildings*	267

The following four topics are primarily covered in highly referenced works on the subject of zero-energy buildings, as shown in Table 8:

- An explanation of zero-energy structures

Hernandez drew attention to the fact that "zero energy" and "net zero energy" buildings have distinct definitions, which only refer to the energy consumed in the building's operation and disregard the parts of energy use associated with the building's construction and delivery [10]. In an effort to further the creation of uniform ZEB definitions and reliable energy calculation techniques, Marszal analyzed the majority of ZEB (zero-energy building) definitions and several potential ZEB calculation methods [11]. According to Sartori, resolving the connection between buildings and energy networks is necessary in order to completely characterize the characteristics of net zero energy buildings because merely meeting the annual balance is insufficient [6]. The study makes the point that alternative definitions may exist depending on the political goals and unique circumstances of a nation.

- The potential use of zero-energy structures

Anh-Tuan recommended the study and use of optimization methods based on simulation in the field of architecture in recent years due to the advancement of computer science and severe standards for "green" building design [12]. In his discussion of the zero-energy building's (NZEB) most affordable solution, Hamdy suggested the potential fusion of numerous energy-saving techniques and energy delivery systems (including renewable energy) [13]. Building energy conservation, in Cao's opinion, can play a significant role in addressing the substantial environmental risks posed by carbon emissions, energy scarcity and other factors [14].

- Calculation of the idea of a zero-energy building based on the life-cycle

In his study of the three life-cycle research facets used to evaluate the environmental effects of building development, Chau [15] primarily examined whether they could be applied to decision-making. LCA, Life-Cycle Assessment, and LCEA, Life-Cycle Energy Analysis, were created by Cabeza [16] for the environmental assessment of the building and construction-related industries. The research analysis, life-cycle cost analysis and other components were compiled and organized. According to Chastas, the proportion of embodied energy increases when buildings transition from traditional to passive, low-

carbon and zero-energy designs. As a result, a life-cycle energy study of buildings is required to ascertain the true carbon emissions of a building [17].

- Sustainable construction of zero-energy structures

Buildings, in Li's opinion, contribute significantly to the world's total energy use and carbon emissions and are crucial in the formulation of plans for sustainable development [18]. To reduce energy use and environmental damage, certain nations have adopted or proposed zero-energy buildings as the future building energy aim.

3.3. Analysis of Research Hotspots of Zero-Energy Buildings

3.3.1. The Evolution Trend of Keywords

When analyzing the frequency of keywords, we set the CiteSpace (5.8.R3 SE 64-bit) parameter settings as follows: Time span Period to 2021, the Time Slice as a Time partition every year, the analysis object as the keyword and the filtering criteria of the analysis object as the TOP50. The Pathfinder algorithm was used to trim the graph and run to obtain eight clusters of keywords, including energy storage, thermal comfort, life-cycle assessment, carbon dioxide levels, carbon nanotube, energy efficiency, PCM and climate change. Furthermore, this study used the cluster number as the Y-axis and the publication year as the X-axis, and finally obtained the time axis visualization of the keyword co-occurrence network (Figure 4).

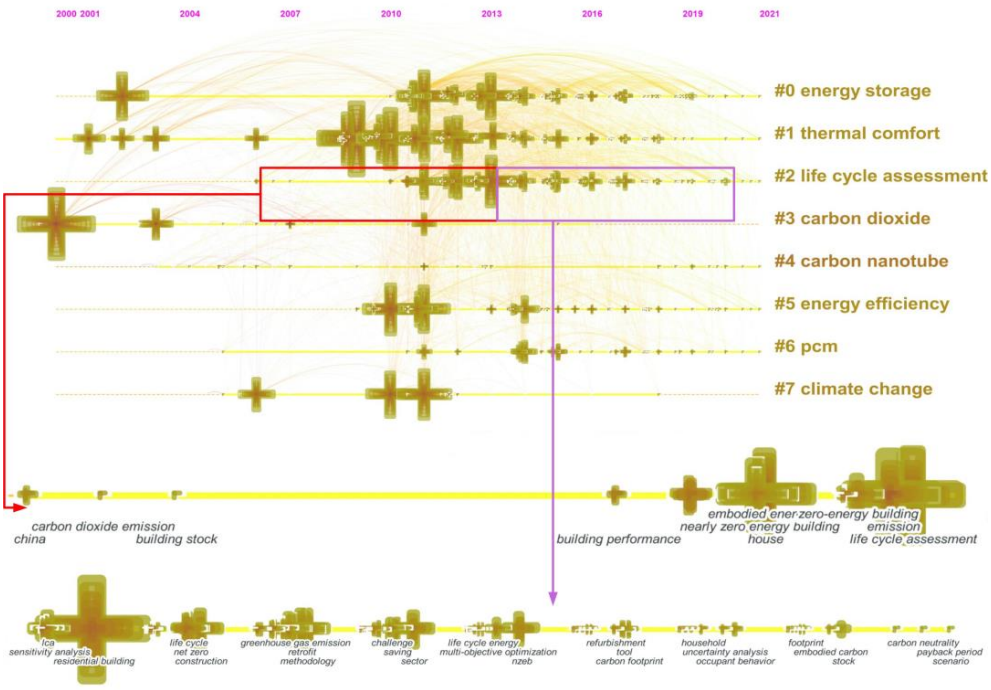


Figure 4. Timeline visualization of the keywords (2000–2021).

The brown mark "+" represents "burst", which represents the keywords with the highest fluctuation frequency in a certain period, namely, the high-frequency keywords, which indicate the research trends. It should be noted that the frequency of high-frequency keywords is not completely uniform. That is, in general, the larger the shape of the brown marker "+", the higher the frequency of high-frequency keywords at a certain time. Combining keywords with time can accurately reveal the research trend and research results within a certain period of time.

For instance, a number of important study findings in the area of carbon dioxide emissions were published between 2000 and 2007 with keywords such as climate, systems and climate change. The definition of a zero-energy building in its infancy only refers to the energy used in the building's operation, ignoring the energy use aspects related

to the building's construction and delivery, as well as the energy use of the building's components. In contrast, the concept of "net zero energy building", which is used in the field of ecological economics, considers the energy used in the production of building materials and is widely used in fields such as agriculture and transportation. In addition, from Figure 4, we can see that the keyword node of cluster #2 life-cycle assessment shows that, in 2006, the carbon emission levels of building stock in China began to be considered a problem. In 2011, a number of zero-energy buildings appeared in the field, and resarchers began to make a connection between the life-cycle of buildings and zero-energy buildings. From 2012 to 2021, the impact of the carbon footprint on the life-cycle of buildings was noticed, and further research has been conducted to develop zero-energy buildings.

The burst terms in Figure 5 were paired with the aforementioned results to explore the boundaries and difficulties of zero-energy construction research. Words that are likely to change often over a short period of time are referred to as "Burst Terms" and may represent the direction of current scientific inquiry. CiteSpace can be used to find and display academic material of common interest as well as the frequency of citations over a specific time period by applying burst detection methods. Keywords will draw more attention in the time period under consideration the more sudden they are, which in some ways reflects the research frontier and hot area of an academic field. The time period for "Burst Terms" to occur is indicated in red in Figure 5.

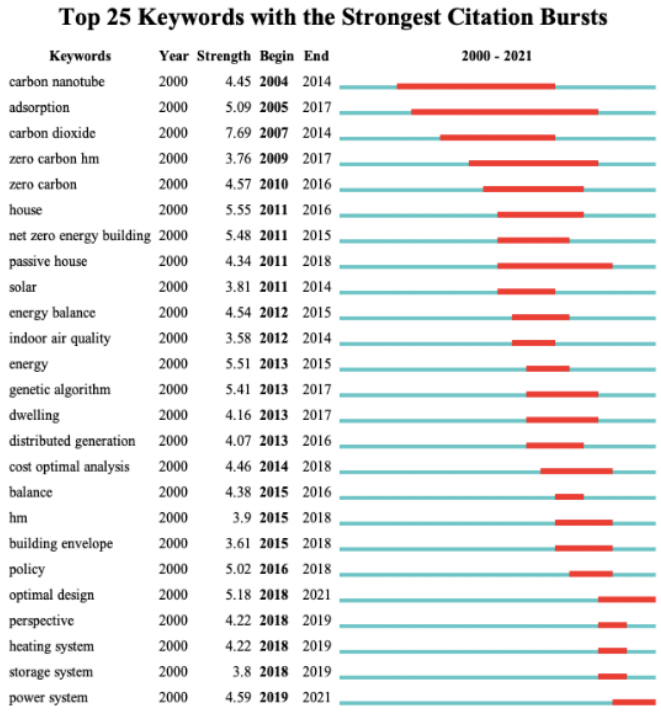


Figure 5. Keywords sorted by emergence time.

As can be seen from Figure 5, carbon nanotube is the first keyword to be highly valued by scholars in the field of zero-energy building research and has received attention since 2004. Bent is the keyword that has received attention for the longest time in the field of zero-energy construction, attracting wide attention from researchers for 12 years, from 2005 to 2017. There is a close connection between carbon nanotube and bent. Carbon adsorption materials have become the most representative type of air purification materials due to their large specific surface area, stable physical and chemical properties, and strong adsorption performance. Carbon nanotubes have unique properties, such as special electrical conductivity, mechanical properties, and physical and chemical properties, and have attracted attention and been widely used in many scientific fields since their emergence. The issue of carbon emission reduction has been widely discussed since 2007 and continued to be a major source of concern throughout 2014. In 2018, we can see that researchers started to

study and explore zero-energy buildings from the perspectives of heating system, power system, storage system and others, paying more attention to the exploration of technologies conducive to the realization of zero-energy buildings. This means that scholars have more specific research priorities.

3.3.2. Cluster and Evolution Trend of Co-Citation Network

In this section, CiteSpace (5.8.R3 SE 64-bit) software was used for the co-citation analysis. Firstly, we chose the node type "cited journal" and extracted the Top50 cited in each time slice. We selected "cosine" as the connection strength and used "Pathfinder + Pruning the Merged network" for the cluster analysis. The results are shown in Figure 6. The color change in the co-citation network represents the distance in time. The warmer the color, the closer the time; the colder the color, the longer the time. Network clustering analysis can reveal changes in knowledge base topics in each stage, which is an important reference for this study.



Figure 6. Co-citation clustering of co-cited journals of zero-energy buildings.

The concept of literature co-citation was first proposed in 1973. Co-citation can be defined as the situation when both articles A and B are cited by article C at the same time. Therefore, we can say that there is a co-citation relationship between A and B. Co-citation analysis and visual measurement are common methods to study the spatial structure and relationship between different pieces of literature. The purpose of co-citation analysis is to distinguish high-impact journals in the field from authors who have made considerable contributions to the research topic, and to help scholars to quickly locate influential articles in the field. At the same time, it can reflect the connections between different journals and disciplines, and show the basic distribution of existing research in a certain field.

In order to show the co-cited journals in the field of zero-energy buildings more clearly, based on Figure 6, this study selected the top 10 co-cited journals according to the principle of the center value from high to low and analyzed their country, impact factor and JCR partition. The results are shown in Table 9. As can be seen from Table 9, as a whole, British journals have a strong influence in the field of zero-energy buildings. The co-cited journals were listed as *Atmospheric Environment*, *Nature* and *Energy Policy* by influence.

Table 9. Journals cited for high centricity and related information.

Journal	Country	Centricity	Impact Factor	JCR Partition
Atmospheric Environment	England	0.12	4.304	Q1
Nature	England	0.09	49.315	Q1
Energy Policy	England	0.07	5.521	Q1
Solar Energy Materials and Solar Cells	Netherland	0.07	6.595	Q1
Carbon	USA	0.07	8.979	Q1
Journal of Environmental Management	England	0.05	6.393	Q1
Journal of Power Sources	Netherland	0.05	8.447	Q1
Ashrae Journal	USA	0.04	0.367	Q4
Journal of the American Chemical Society	USA	0.04	13.621	Q1
Building Simulation	China	0.04	2.763	Q2

This study employed CiteSpace to depict the time axis of co-cited literature in order to further investigate the development trends of co-cited literature in the temporal dimension. The Top50 references in each time slice were extracted using the "cited reference" node type. We chose "cosine" as the link strength and performed a cluster analysis using "Pathfinder + Pruning Sliced Networks". Finally, a co-citation network yielded 1107 nodes and 2471 connections (Figure 7). The network's clustering effect is good, its density is 0.004 and its modularity Q value is 0.8289. To achieve the timeline representation of the network of literature citations, we further used the Timeline view (Figure 7).

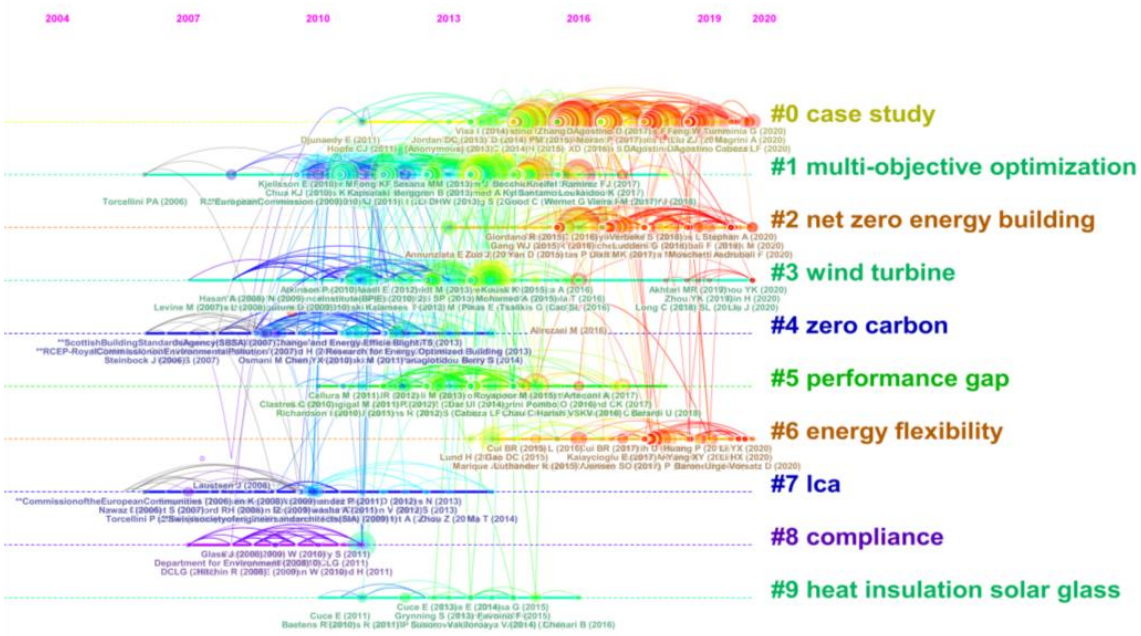


Figure 7. Co-citation clustering related to the zero-energy building literature.

The relationship between clusters and the chronological range of the literature within a cluster is mostly shown in the timeline view in Figure 7. The timeline view allows for the analysis listed below: (1) The year that the cluster first appeared, or the year that the cluster's initial reference point was found; (2) The year that the cluster's achievement begins to rise; and (3) The year that the cluster's growth begins to decline. (4) During the entire cluster formation process, key texts (such as widely cited works of literature and highly mediated texts, as revealed in Table 10) and their effects on the overall cluster's trend were taken into consideration. The evolution tendency of each cluster in the field of zero-energy buildings can be clearly seen through the above-detailed study of clusters and significant nodes in the co-citation network.

Table 10. Co-cited references with high frequency and high centrality.

References (High Frequency)		References (High Centrality)	
Frequency	**Co-Cited References**	**Centrality**	**Co-Cited References**
98	Marszal AJ, 2011, ENERGY BUILDINGS, V43, P971, DOI 10.1016/j.enbuild.2010.12.022 [11]	0.05	Mohamed A, 2014, APPLIED ENERGY, V114, P385, DOI 10.1016/j.apenergy.2013.09.065 [19]
98	Sartori I, 2012, ENERGY BUILDINGS, V48, P220, DOI 10.1016/j.enbuild.2012.01.032 [6]	0.05	Lu YH, 2015, ENERGY BUILDINGS, V89, P61, DOI 10.1016/j.enbuild.2014.12.032 [20]
65	Attia S, 2017, ENERGY BUILDINGS, V155, P439, DOI 10.1016/j.enbuild.2017.09.043 [21]	0.05	Becchio C, 2015, ENERGY BUILDINGS, V90, P173, DOI 10.1016/j.enbuild.2014.12.050 [22]
62	Deng S, 2014, ENERGY, V71, P1, DOI 10.1016/j.energy.2014.05.007 [7]	0.04	Deng S, 2014, ENERGY, V71, P1, DOI 10.1016/j.energy.2014.05.007 [7]
60	Hamdy M, 2013, ENERGY BUILDINGS, V56, P189, DOI 10.1016/j.enbuild.2012.08.023 [13]	0.04	Hamdy M, 2013, ENERGY BUILDINGS, V56, P189, DOI 10.1016/j.enbuild.2012.08.023 [13]

As can be seen from Figure 7, 2011 is the key node of co-cited literature. Before 2011, the co-cited literature cluster mainly included clusters #7 and #8, when the zero-energy building research was still in its infancy. At this stage, the co-cited literature of researchers could be clustered into two categories, namely, #7 life-cycle assessment and #8 compliance. After 2011, compliance-related co-cited pieces of literature no longer appeared. On the contrary, co-citation studies based on the case study, multi-objective optimization, net-zero-energy building, wind turbine and other aspects show a diversified trend.

The definition, concept, calculation and viability of zero-energy buildings are primarily discussed and analyzed in the co-cited literature that was published before 2011, according to the literature's network of co-citations, and these works have much in common with the highly cited works on the subject. According to the majority of academics, a zero-energy building should be outlined as one that has an output that is more than or equal to its input of energy [23], also referred to as a self-sufficient building [24]. By examining the energy calculation techniques used in nations with zero-energy buildings, researchers have calculated the energy performance level of buildings with the lowest cost and net-zero energy [25]. Leckner [26] showed the viability of using current solar technology to create at least as much energy as the primary energy needed by the residents year-round. According to Kolokotsa [27], zero-energy structures have more stringent and complex performance standards in addition to being environmentally responsible and grid-friendly.

The co-citation network of the literature indicates that, after 2011, topics including case studies, multi-objective optimization, performance gap and energy flexibility have received an increasing amount of attention, and the topics that researchers are interested in have gradually assumed a more definite form. Three levels of the zero-energy building research process are shown in Figure 8.

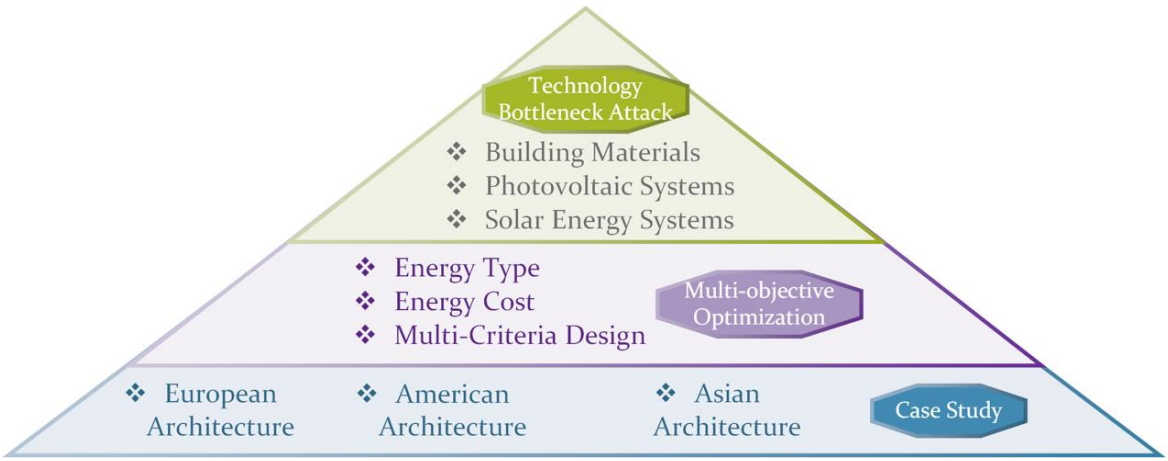


Figure 8. Three levels of the zero-energy building research process.

Scholars have studied the development status or problems of zero-energy buildings in different regions [28]. Western countries developed zero-energy buildings earlier. Some scholars evaluated the implementation progress of an NZEB in Europe and compared the definitions of EU-NZEB and US-NZEB [29]. TRNSYS (Transient System Simulation Program) dynamic energy simulation software and GenOpt general optimization program were used to find the optimal level of cost to reduce building energy consumption for single buildings in France [30]. In contrast, the development of zero-energy buildings in Asia is relatively late and there are more problems. In Malaysia, there are barriers in cost, skill and technology and government policy in the development of zero-energy buildings [31].

Some academics hold the opinion that, while assessing the implementation of zero-carbon buildings, multi-objective optimization should be used and that four indexes, namelym primary energy (PE), site energy, CO2 equivalent emission and energy cost, should be taken into account [19]. Similar multi-criteria RES design optimization techniques were proposed by several researchers [32], and they effectively supported an architectural design [33]. They also used examples to examine the "zero-energy" buildings' operational performance, emphasizing the significance of multi-objective optimization for zero-carbon structures [34]. A building's energy efficiency can be improved by determining the appropriate mix of design techniques [35]. There is no precise way to accomplish or approach the net zero energy aim, however, in fully integrated buildings with complex interactions between energy production, consumption and storage systems and automatic and manual control systems/elements [36].

The most fundamental technical aspects of attaining zero-energy buildings, as far as we can tell, are building materials, window size [37] and orientation [38], the possible window design scheme of office buildings [39] and the importance of photosynthetic materials in zero-carbon buildings [40]. Additionally, some researchers have demonstrated that photovoltaic systems, solar energy systems and their combination will significantly affect zero-carbon structures in terms of energy savings, grid interaction and financial considerations [41]. Climate and energy targets, as well as decreasing costs, have led to the increased use of solar PV in residential buildings [42], with the additional costs of zero-carbon buildings being mainly for the installation of PV systems [43]. Additionally, there are issues with estimating non-dispatchable electrical energy consumption in zero-energy buildings [44], and high insulation and large PV systems play a key role in the energy balance of near-zero and net-zero buildings [22]. Some scholars pointed out that one of the most potential competitive solutions is based on potential energy efficiency measures and is sensitive to the energy storage system for energy consumption control [45]. Only the family and active citizen who use a photovoltaic (PV) grid power system is responsible for participating in the solution of reducing carbon and energy challenges, in an attempt to achieve zero-carbon buildings [46].

Finding the important literature was the subsequent step after examining the knowledge base and advancement of zero-energy buildings. We principally emphasized two aspects: (2) The similarity in the centrality node is high, and the references establish a co-citation link with many studies, having a relationship with many studies. (1) High-frequency nodes signify widely cited literature, which provides an essential knowledge base on a particular topic. These nodes serve as "transportation hubs", which to some extent serve as research hotspots. The results are displayed in Table 10.

A few significant studies can be found by analyzing the co-citation relationship with other studies, as shown in Table 10. There are differences between article centrality and citation frequency. The frequency with which a node serves as a short-circuited bridge between the other two nodes is known as mediation centrality. A node's mediation centrality will increase with the frequency of its "intermediary" roles. A larger mediating role is played by articles with a higher centrality in this field's research process, which can more accurately reflect their influence. However, there is not a direct link between citation frequency and mediating centrality. The study with the most citations is that of Marszal [11], which presented and discussed potential responses to the aforementioned

problems while focusing on the majority of zero-energy building definitions in use at present and a variety of potential calculation methodologies. To encourage the development of a standard concept of zero-energy buildings and reliable energy calculation methodologies, Sartori [6] presented a unified framework to determine the definition of net-zero-energy buildings. The definition of a zero-energy building was established systematically through the evaluation of standards and the selection of pertinent choices in the definition framework. Building energy design introduces the idea of grid interaction flexibility as an ideal objective. In the cross-comparison of the social and technological impediments to the implementation of net-zero-energy buildings in seven southern European nations, Attia [21] compiled the findings and investigated and analyzed the current state of net-zero-energy buildings in Southern Europe. Due to a lack of adequate technical support for retrofitting older structures, the majority of southern European nations are not ready to execute the net-zero-energy building. Mohamed's [19] essay, which thoroughly examined the impact of several indicators on the achievement of zero-energy buildings under various definitions, had the greatest centrality. Through a review of the literature, Deng [7] created a guide to the evaluation of net-zero-energy buildings, outlined the definition and energy-saving practices of zero-energy buildings, and made clear the purpose of the study and the technical limitations of zero-energy building evaluation.

4. Discussion

4.1. Researching the History of Zero-Energy Buildings

According to the data, studies on zero-energy buildings started in earnest in 2000, but it was only in 2011 that the subject became a hot topic in academic circles and a significant increase in the number of papers published started to occur. In 2000–2011, zero-carbon-building-related studies were in low numbers, mainly because of the limitation of related technologies; in this phase, the zero-carbon building could not ensure that energy was wisely or effectively used, and if the integration of complementary green buildings, such as energy and energy conservation methods of the material used, was not maximized, the zero-carbon building could consume vast amounts of energy. Since 2011, research on zero-carbon buildings has witnessed explosive growth. Thanks to the continuous growth of and breakthroughs in degradable materials, photovoltaic technology, geothermal technology and constant humidity and temperature technology, researchers could also constantly summarize experiences in practice, from a single technology to multiple technology collocation and coordination, and finally, achieve success in producing overall zero-carbon buildings.

The following is a concise summary of the realistic background behind this rapid growth. On the one hand, there is a tremendous drive by governments and non-governmental groups to adopt zero-energy buildings; on the other hand, global carbon emissions continue to grow quickly. In order to combat climate change, the Copenhagen World Climate Conference was convened in 2009. A low-carbon economy was considered to set the pace for global economic growth and usher in a new phase of the global economy game. Because of this, it was not unexpected that research on zero-energy buildings would increase dramatically over the past ten years (308.96% from 2011 to 2021). This research provides a strong theoretical foundation and technical support for constructing a global zero-energy building development.

From this phenomenon, we can see that governments play an important role in the progress and development of zero-carbon buildings. International conferences will play a guiding role, conduct experiments around the world, improve the coverage rate and ensure the balance of regional development. At the same time, developed countries or more developed cities will play a leading role in improving public awareness of zero-carbon buildings with improved policy support and economic incentive systems.

4.2. Co-Cited Journal Discussions of Zero-Energy Buildings

The findings in Table 1 reveal that the ten nations with the highest levels of research activity in the field of zero-energy buildings are China, the USA, Italy, England, Spain, Germany, Australia, Canada, South Korea and Finland. The top three journals, including *Atmospheric Environment*, *Nature* and *Energy Policy*, are British journals, according to the results of journal co-citation (Table 9), which has a significant impact on the study of zero-energy buildings. From the ranking of the cited journals, we can see that the important factors affecting zero-carbon buildings are policy support and energy technology. Scholars no longer solely focus on the result of building carbon emissions, but pay more attention to the process and consider about how to improve energy efficiency. This article notes that, in recent years, the development of computer science and strict requirements for "green" building design have put forward an optimization method based on simulation research and application in the field of construction, considering the highest cited literature from the angle of the highly cited articles (Table 8) and using a database of the most frequently cited literature from Anh Tuan [12]. We explained the most recent developments and offered a general overview of the potential difficulties and barriers in architectural design optimization. The main discussion was centered on the handling of the discontinuous multimodal architecture optimization, the optimization algorithm and selection performance, the use of multi-objective optimization, the agent model, optimization, and optimization under uncertainty spread to the challenges of real-world design.

4.3. Research Discipline Discussions of Zero-Energy Building

Energy fuels, construction building technology, civil engineering and green sustainable science technology are the four fields with the most published articles, according to a disciplinary study of research objectives for zero-energy buildings. In recent years, more focused study areas such as stratum ventilation, wind turbines, and performance gap have also received more and more attention, and many significant research findings have been published, in addition to the standard energy, environment and building research. Liu [47] studied energy-saving practices and renewable energy technologies for zero-energy buildings and discussed the use and applicability of key technologies, namely, reducing the energy demand of zero-energy buildings through EEMs and using renewable energy technologies to meet the remaining energy demands. High-performance window systems [48], effective air tightness and fresh air–heat recovery systems are a few examples of EEMs. The solar photovoltaic/thermal system (PV/T), ground source heat pump system (GSHP), air source heat pump system and wind power generation make up the RETs system. They also emphasized life-cycle energy analysis (LCEA), modifications to climatic parameters, intelligent building operations management (IBOM) systems, energy storage systems and social policy challenges.

4.4. Co-Cited Network Discussions of Zero-Energy Buildings

The definition, concept, calculations and viability of zero-energy buildings were primarily addressed and examined in the co-citation literature before 2011, according to the network of types of literature that tracks co-citations. The phrase "zero-energy building" has been defined by academics in a variety of qualitative and quantitative ways. Cost-optimal performance has been mentioned by academics [25] as a calculation factor that greatly aids in the quantitative calculation of zero-energy structures. In recent years, new concepts, new technologies and new products, such as energy-saving buildings, green buildings, prefabricated buildings and zero-carbon buildings, have emerged one after another, and a hundred flowers have blossomed and gradually taken root. Around these architectural concepts, a series of corresponding systems have been established within the industry. However, the technical strategies and systems corresponding to the above architectural concepts overlap to a certain extent, which makes it difficult for practitioners to effectively distinguish the logical relationship among energy-saving, green, low-carbon

and zero-carbon, resulting in more confusion. In terms of viability, academics consider the equilibrium between economic and environmental advantages and look for the best answer.

The keywords after 2011 can also be broken down into three pieces, according to the literature's co-citation network. First, researchers have examined the state of development in various areas related to zero-energy buildings or problems. From a macro-perspective, they have considered the current state of zero-energy building development in order to identify bottlenecks and obstacles, such as incoherent policy and economic development, high technical requirements and unclear evaluation methods. Second, researchers have looked at this issue from various angles and considered it from the perspective of the entire building to a more specific level, concluding that the realization of zero-energy buildings necessitates the harmonious cooperation of many systems, including thermal systems, power systems and energy storage systems. The ultimate goal of academic study is to minimize the entire building's carbon emissions to achieve zero-energy buildings, which is why scholars are devoted to conducting in-depth research on a variety of specialized technologies, enhancing and realizing coordinated and integrated use. The majority of academics have discussed the benefits of photovoltaic power generation as well as the significant strain this process places on the power grid. The imbalance issue is quite clear and needs to be solved immediately for zero-energy buildings to be developed in the future.

These conclusions show a substantial change in the direction of zero-energy building research, with a greater emphasis on exploring numerous and more focused methods of creating zero-energy structures, such as wind turbines, formation ventilation and solar cells. In contrast, before 2011, socioeconomic research was in its early stages, and its primary focus was on the fundamental theoretical investigation of the zero-energy building itself, including the definition of the term and the idea of multi-objective optimization.

From the aforementioned analysis, it is evident that research on zero-energy buildings has recently progressed in the direction of being more concrete and detailed, moving from macroscopic overall architectural design considerations to the idea of multi-objective optimization design, and finally to the micro-level of practical operation and technical research. This analysis also demonstrates that zero-energy buildings are no longer just a theoretical concept.

4.5. Development Trends of Zero-Energy Buildings

Zero-energy structures have net socioeconomic benefits that far outweigh their expenses [49]. It is pessimistic, though, to think that significant barriers to the creation of zero-energy buildings still exist. Even though zero-energy structures are more cost- and energy-effective in the long run, their adoption is dependent on a variety of factors, including societal perception, the state of scientific research, construction costs, management systems and implementation strategies. At the moment, there is still much work to be conducted in the development and construction of zero-energy buildings. This calls for widespread promotion of the idea of "zero energy", increased public awareness of energy conservation education and a strengthened sense of civic duty among people to preserve the environment.

Sustainable development depends not only on technology but also on deep learning by individuals, groups, professional groups and other institutions [50]. Technological innovation is not just about technology but also people, their perceptions, their interactions with others and the physical world. This calls on us to study the developed experiences of other nations, develop appropriate low-carbon energy-saving technology and significantly lower the price of zero-energy structures.

There are three obstacles to the development of zero-carbon buildings.

First, the standards are not clear. Although the goal of a zero-energy building has been proposed for a long time, the definition of a zero-energy building has not been clarified. Various construction companies advocate zero-energy buildings, but the scope of the definition varies and is difficult to compare from a consumer's perspective. Internationally, definitions vary from country to country. If a narrow definition is adopted, it is difficult

to achieve the target due to physical constraints, such as use and scale. For example, the strict implementation of the definition of zero primary energy consumption requires the use of renewable energy. Due to the limited roof area, high-rise buildings cannot be equipped with a large number of photovoltaic power generation modules; even if full of photovoltaic modules, it is difficult to achieve energy self-sufficiency. It is therefore physically difficult to achieve a zero-energy building. This elusive goal can easily dampen the enthusiasm of the enterprise. If a broad definition is adopted, the objectives and policies promoted by the government will lose their meaning. Therefore, governments must find the appropriate definition and standard between the guiding role of policy and the possibility of realization. The government's proposed standard for new housing is poorly defined and lacks a benchmark for evaluation.

Second, the technology is not mature. The 2009 ZEB Research Institute Report on Achieving and Promoting Zero-energy Buildings argues that it is possible to achieve zero-energy buildings through technological innovation and identifies a list of technologies that can be developed to significantly improve the energy efficiency of buildings. However, in reality, it is difficult to design a zero-energy building simply by adding up these technologies. Since buildings are not mass-produced products, each building has different scales, design methods and technologies, and different costs, so it is difficult to share relevant information and technologies. This is an important reason why zero-energy buildings are difficult to popularize. In particular, small- and medium-sized construction enterprises and design firms cannot design and construct zero-energy buildings. Without accounting for the cost of zero-energy building, how to ensure the economy is also a vast problem.

Third, the driving force is insufficient. To promote and popularize zero-energy buildings, it is very important to capture the enthusiasm of developers. For developers, poor economics is the most considerable obstacle. The advantage of a zero-energy building is that it can reduce utility bills. Energy self-sufficiency leads to improvements in energy efficiency, benefits that may not necessarily be appreciated by the vast majority of owners. The rental building will increase the burden on the owners, and water and electricity expenses are not proportional to the reduction. The comfort and health brought by the high-efficiency thermal insulation of zero-energy buildings are not well understood. There are many subsidising and marking systems for energy-saving and green buildings, which are difficult for ordinary consumers to recognize, and it is more difficult to supervise existing buildings. Additionally, these new technologies, new materials and new products also bring the difficulty of construction technology.

The quick development and use of ZEB can be hampered by the lack of an incentive mechanism [51]. Building energy savings are greatly aided by voluntary home certification criteria in addition to building codes [52]. As a result, the government needs to improve the management of energy conservation and emission reduction, develop zero-energy building standards, and more actively support and encourage the adoption of zero-energy energy-saving technologies by construction companies by offering corresponding preferential policies. The government should also support zero-energy building facilities so that these buildings can operate at a maximum efficiency and reap the greatest possible economic and social benefits.

NZEB technology has many commercial and residential applications, there is little support for the viability and effectiveness of sustainable animal husbandry [53], which necessitates state personnel training. Architectural design personnel and the related specialized student should strengthen the awareness of low-carbon energy saving measures and actively conduct zero-energy building and zero-energy city scientific research to achieve a low-carbon building. The goal of minimal carbon emissions and good health is within reach as long as these barriers are removed. More details are shown in Figure 9.

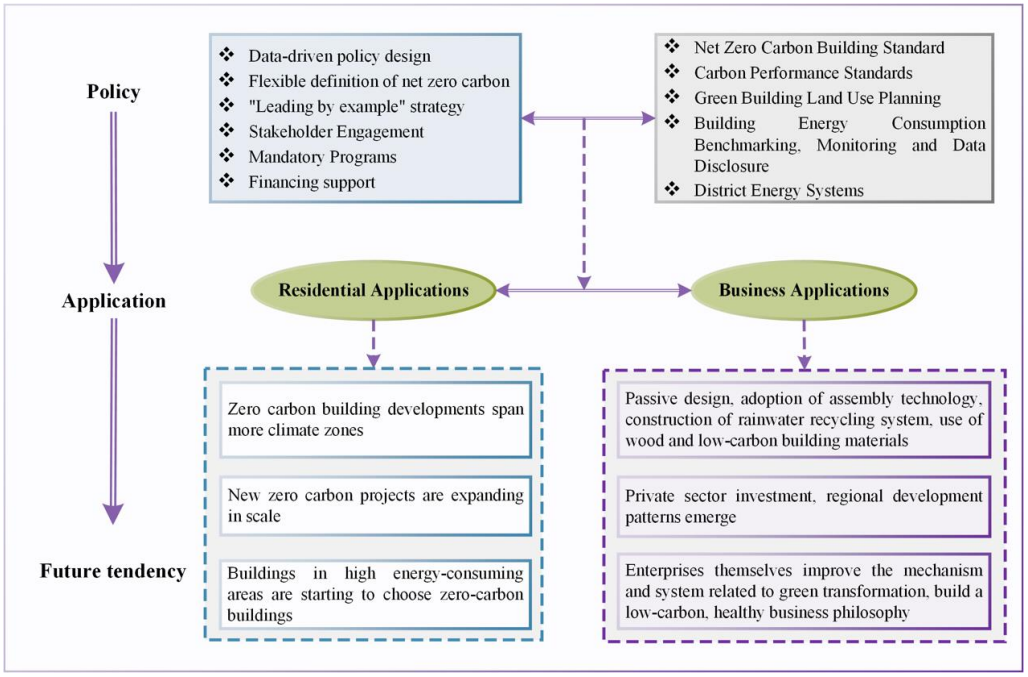


Figure 9. Development focus and trends in zero-carbon building research.

5. Conclusions

Based on the original data of 2869 articles in the zero-energy building discipline from 2000 to 2021, this paper used CiteSpace to describe the overall characteristics, hot topics and development trends of zero-energy building research. Since 2000, the research on zero-carbon buildings has made remarkable progress, especially entering a rapid development stage after 2011. Not only construction technology scholars, but also energy and fuel researchers, have begun to pay attention to this field. From the initial discussion on the definition and case analysis of zero-energy buildings, scholars have gradually started to study the internal multi-systems of zero-carbon buildings. At present, they have studied and analyzed how to improve the efficiency of energy use in relation to the technology itself. Each step has laid a solid foundation for the achievement of zero-carbon buildings. The main findings are as follows. (1) The development trends and research focus were determined by using the method of discipline analysis. Specifically, energy fuels, construction building technology, civil engineering and green sustainable science technology are the four research fields with the most published papers. China, the United States and Italy are the countries with the most active zero-energy building research. (2) The top three journals with a cumulative number of published papers are *Energy and Buildings*, *Applied Energy* and *Renewable and Sustainable Energy Reviews*. (3) In terms of research topics, performance, system, design, optimization, zero-energy building, building, residential building and energy efficiency are the eight most popular keywords. (4) The most cited papers in the field of zero-energy buildings include four basic aspects: the design of zero-energy buildings, carbon emission calculation of zero-energy buildings, technical barriers of zero-energy buildings and subsequent energy-saving measures of zero-energy buildings. Through co-citation network clustering analysis, 14 research hotspots were identified, including case study, multi-objective optimization, net-zero-energy building, wind turbine, zero carbon, performance gap, energy flexibility, LCA, compliance, heat insulation, stratum ventilation, parameter variation, solar pond and building operation.

The following is a summary of the research and development directions for zero-energy buildings based on the findings of this paper. The benefits of zero-energy buildings for the environment and how to construct a widely accepted zero-energy building standard should be prioritized. Secondly, efforts should be made to create a platform for cooperation and a security system that coordinates the actions of all nations and the involvement of

all parties. Technical advancements are required to assist the realization of zero-energy buildings with the long-term support of reliable assurance mechanisms. Last, but not least, the research scale can be flexibly adjusted at the local, national, and international levels to examine how effective incentives can be built over time to encourage a wider range of contributors, such as the general public, businesses or NGOs, to participate and join in the realization of zero-energy buildings. In order to emphasize the synergistic effects of economic development, improved socioeconomic welfare and environmental protection, this once again calls for policymakers to increase the environmental awareness of the general public, businesses and social organizations. They should also offer them more alluring zero-energy building projects.

This study has some limitations. First, the data were collected only from literature in English. Thus, language settings can be extended beyond this, and incorporating sources across language boundaries in a broader context may provide more comprehensive results on the salient features of zero-energy building research at the global level. This proposal requires the establishment of links between different academic databases with different institutional and cultural contexts. Secondly, researchers choose to cite literature from high-quality journals, which makes it difficult to eliminate the influence of literature self-citation in the co-citation analysis. Therefore, there is still room for improvement in the specification of analytical methods. Third, this paper only analyzed the highly cited works without studying the authors and their follow-up studies, which is of great significance for revealing the current situation and characteristics of zero-energy-buildings-related fields. Finally, this paper lacked data from papers in this field in 2022. After the research, it was confirmed that the number of published papers in this field in 2022 is 328, but the number of highly cited papers is no more than 5 and the research topics are in the direction of our discussion, so this does not affect our research results. These limitations point out feasible directions for further research.

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