

Advancing zero-carbon community in China

Policy analysis, implementation challenges, and strategic recommendations

Zhou, Lin; Li, Shun; Liu, Zhengxuan; Zhou, Yuekuan; He, Bao Jie; Zhang, Zhenya; Wang, Hanbing; Zhang, Guoqiang

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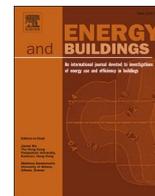
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Advancing zero-carbon community in China: policy analysis, implementation challenges, and strategic recommendations

Lin Zhou^{a,1}, Shun Li^a, Zhengxuan Liu^{a,b,1,*}, Yuekuan Zhou^c, Bao-Jie He^{d,f}, Zhenya Zhang^e, Hanbing Wang^b, Guoqiang Zhang^{a,*}

^a College of Civil Engineering, National Center for International Research Collaboration in Building Safety and Environment, Hunan University, Changsha 410082, PR China

^b Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628 BL Delft, Netherlands

^c Sustainable Energy and Environment Thrust, Function Hub, The Hong Kong University of Science and Technology (Guangzhou), Nansha, Guangzhou, 511400 Guangdong, PR China

^d Centre for Climate-Resilient and Low-Carbon Cities, School of Architecture and Urban Planning, Chongqing University, Chongqing 400045, PR China

^e School of Energy and Power Engineering, Zhengzhou University of Light Industry, Zhengzhou 450001, PR China

^f School of Architecture, Design and Planning, The University of Queensland, Brisbane 4072, Australia

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ABSTRACT

Zero-carbon community (ZCC) is essential in addressing critical social and environmental challenges, particularly in reducing energy consumption, lowering carbon emissions, and decreasing reliance on fossil fuels. However, several issues are still unclear, including inconsistent definitions of ZCC, the lack of detailed policy analyses, and limited exploration of implementation challenges and solutions persist. This study addresses these gaps by conducting a comprehensive analysis of the drivers and barriers to ZCC development in China. It begins with a detailed review of the definitions of ZCC, comparing and contrasting them from both domestic and international perspectives. Then, it evaluates existing incentives, categorizes them into policy documents, laws, and standards while assessing their evolution and real-world applications. This study also presents case studies of exemplary ZCC, including the Beddington Community in the UK and the Zero Carbon Pavilion at the Shanghai World Expo Park in China. These cases offer insights into practical approaches, societal impacts, and advanced practices, proposing a ZCC construction model tailored to China's unique economic and policy environment. Furthermore, the study identifies key barriers to adopting ZCC in China and proposes targeted recommendations across five domains: administrative, economic, technological, socio-cultural, and environmental. A "macro-meso-micro" implementation pathway is developed, emphasizing stakeholder collaboration as a core element for successful execution. This study systematically reviews and critically analyzes current policies and practices related to ZCC, and offering valuable theoretical guidance for developing regulations and standards, along with practical solutions to address current implementation challenges.

1. Introduction

1.1. Background

With the rapid development of the global economy, environmental and ecological problems like climate warming, energy shortages, and increased pollution have become increasingly prominent [1], and climate warming is a serious global risk [2,3]. At major conferences such

as the United Nations Conference on Environment and Development and the Paris Climate Conference, countries have actively formulated progressive carbon reduction plans and decarbonization targets tailored to their national conditions [4]. The Paris Agreement, a climate change pact signed by 178 parties worldwide, entered into force in November 2016. It calls for global action to build climate resilience and achieve low greenhouse gas (GHG) emission development [5]. Among the signatories, China stands out as a key member. In the Government Work

* Corresponding authors at: College of Civil Engineering, National Center for International Research Collaboration in Building Safety and Environment, Hunan University, Changsha 410082, PR China (Z. Liu).

E-mail addresses: zhengxuanliu@hnu.edu.cn, Z.liu-12@tudelft.nl (Z. Liu), gqzhang@hnu.edu.cn (G. Zhang).

¹ Zhengxuan Liu and Lin Zhou contributed equally to the work.

Report at the National People's Congress in March 2021, China set ambitious goals: to reach a carbon peak by 2030 and achieve carbon neutrality by 2060 [6,7]. China's rapid urbanization is evident in the increase of its urbanization rate from 45 % in 2010 to a projected 75 % by 2050. This urbanization generates significant GHG emissions, with large-scale infrastructure, buildings, transportation systems, and daily urban household activities being major drivers [8]. In 2021, energy consumption in China's construction industry accounted for 1.8 % of the country's total energy consumption, while residential energy use accounted for 12.8 %. Additionally, per capita energy consumption in residential life increased by 262 % between 2000 and 2021 [9]. The United Nations Environment Programme's 2020 Emissions Gap Report highlighted that current GHG emissions from household consumption account for about two-thirds of total global emissions. The report emphasized that accelerating the transformation of public lifestyles has

become an inevitable choice for mitigating climate change.

As the fundamental unit of the city, the community is where people work, live, and reside. It serves as a crucial spatial carrier for implementing the concept of carbon neutrality, playing a significant role in advancing the goal [10]. To construct green buildings (GB) and net-zero carbon buildings (NZCB) within the community that embody sustainable environmental principles, integrating them with transportation systems, waste management systems, and other components to form a cohesive whole. ZCC was established to address the challenge of climate change by employing technologies and systems designed to achieve zero carbon emissions within the community [11,12]. ZCC is a crucial measure in mitigating the climate change crisis by reducing greenhouse gas emissions through the use of renewable energy and improved energy efficiency, promoting sustainable development by encouraging low-carbon lifestyles, and enhancing adaptive capacity through the

Table 1
Current research status on ZCC in various countries.

Author/Citation	Countries or regions	Research theme	Research methods	Key findings
Osmani and O'Reilly [15]	UK	Zero-carbon homes delivery	Semi-structured interviews with developers	Housebuilders currently face legislative, cultural, financial, and technical barriers to delivering zero-carbon homes. The most important drivers and barriers are in the area of legislation.
Heffernan et al. [16]	UK	Zero-carbon community construction	Semi-structured interviews with professionals in design, construction, and management.	Barriers to constructing zero-carbon homes fall into five categories: economic, skills and knowledge, industrial, legislative, and cultural. There is a need to develop a clear policy framework for the forthcoming standard and to raise public awareness of zero-carbon homes.
Jenkins et al. [17]	UK	Zero-Carbon Community	Empirical analysis	Local stakeholders are passionate about their community and strongly support opportunities to shape it in ways that reduce its carbon footprint and enhance the quality of life.
Wu et al. [18]	China	Low-Carbon Community	/	There are four main barriers to action in building a low-carbon community: structural/operational, regulatory/legal, cultural/behavioral, and contextual.
Zhang et al. [19]	China	Low-Carbon Community	Literature review	Low-carbon community building is mainly confronted with constraints such as policy regimes, public behavior, developers' costs, revenues, etc.
Wang and Zhu [20]	China	Zero-Carbon Community	Comparative analyses	Low-carbon community represent a significant shift in community planning and construction, embodying a sustainable development model aimed at reducing carbon emissions. In contrast, zero-carbon community represent the ultimate goal of this development trajectory, achieving a state where net carbon emissions within a defined boundary are reduced to zero.
Chen and Zhun [21]	China	Low-Carbon Community	Empirical analysis	The development strategies of the low-carbon lifestyle concept, the concept of material recycling, and the concept of intensive urban space utilization.
Der Schoor and Scholtens [22]	the Netherlands	Sustainable community	Case studies	Local stakeholders are passionate about where they live and strongly support shaping the living environment while reducing their carbon footprint and improving quality of life.
Bauwens et al. [23]	the Netherlands	Community in Energy Systems	Literature review, Case studies	The concept of community and its goals vary significantly over time and in different contexts. Initially, the community emphasized participatory processes, but over time, it has evolved to primarily denote a physical place.
D'Agostino and Mazzarella [24]	European	Near-zero-energy buildings	Literature review	Proposal to clarify the meaning of near-zero, zero, and positive energy buildings.
Lilliestam et al. [25]	German	Carbon pricing policy tools	Literature review	The effectiveness of carbon pricing in stimulating innovation and zero-carbon investment is a theory, and there is no empirical evidence of its effectiveness in facilitating the technological change required for complete decarbonization.
Gao et al. [26]	China	Zero-Carbon Community	Game simulation analysis	Establish a ZCC framework including a ZCC operator and multiple building prosumers. Introduce reward and punishment mechanisms from both short-term and long-term perspectives to improve the energy conservation and emission reduction effects of ZCC.
Salvalai et al. [27]	European Union	Zero-Carbon Community	Literature review	Applying Urban Building Energy Modeling (UBEM) to reduce energy demand in the built environment.
Persson and Grönkvist [28]	Sweden	Zero-energy building	/	There is no specific factor for achieving low-energy buildings, but a range of issues need to be considered, with the individual being the strongest driver.
Rissman et al. [29]	Worldwide	Industrial decarbonization technologies and policies	Literature review	Achieving net-zero industrial emissions requires measures on both the supply and demand sides, along with the careful design of strategic, high-value policies. These policies must be implemented in a manner that ensures justice for displaced workers and affected community.

adoption of green and climate-resilient technologies [13]. Compared to GB and NZCB, ZCC not only focuses on the technology of individual buildings but also promotes changes in residents' lifestyles. It requires the joint efforts of multiple stakeholders, including the government, research institutions, developers, and the public, throughout the entire lifecycle of the community to ultimately achieve zero energy consumption and zero emissions. During the rapid development of China's urbanization, constructing an effective ZCC model is crucial for sustainable development and achieving carbon neutrality goals.

1.2. State-of-the-art

Extensive studies on ZCC have focused on developing practical models to support sustainable growth. The UK has been a global leader in advancing ZCC, with significant progress since 2006 when the UK government, in collaboration with local authorities, introduced the Zero Carbon Homes Policy to mandate zero-carbon standards for all new homes by 2016 [14]. Table 1 summarizes the current state of both domestic and international ZCC research.

Extensive studies on ZCC have explored various strategies to reduce carbon emissions and energy consumption. For instance, Nematchoua et al. [30] examined key parameters influencing these factors globally, while Fouad et al. [31] introduced a sustainable model of multi-building zero-energy communities aimed at achieving zero-energy urban areas. Moreover, Kayo et al. [32] analyzed energy-sharing potentials across different building types, finding that building combinations and equipment strategies significantly affect energy-sharing benefits. The prediction of building energy consumption and environmental evaluation, especially at large scales, are considered to be a major challenge confronting the research community. An outstanding strategy for mitigating energy consumption and carbon emissions resides in the field of energy modeling. Yang et al. [33] proposed a resistor-capacitance (RC) network model for rapid prediction of building energy consumption. Salvalai et al. [27] summarized the development trends and potential research directions in the field of Urban Building Energy Modeling (UBEM), underscoring its foundational role in reducing the built environment's energy demands. Despite these advances, there is limited research on a comprehensive ZCC development framework.

Most studies in the UK highlight the barriers that developers face in implementing zero-carbon standards, emphasizing challenges such as legislative, economic, cultural, and technical factors. Similarly, studies from China focus on regulatory and operational constraints to low-carbon community development. Research methods range from semi-structured interviews to empirical analyses, literature reviews, and case studies, combining qualitative and quantitative insights. Across these studies, common obstacles include insufficient policy support and limited stakeholder engagement, with local involvement frequently cited as critical to ZCC success. For instance, Osmani and O'Reilly [15], as well as Heffernan et al. [16], identify legislative hurdles as significant obstacles in the UK. Wu et al. [18] and Zhang et al. [19] highlight regulatory and operational constraints as primary barriers to low-carbon community initiatives. Additionally, several studies seek to clarify key concepts, such as the distinctions between near-zero energy, zero-carbon, and low-carbon communities, to ensure consistency in sustainable development discourse. The recommendations provided in the studies often call for improved policy frameworks, increased public awareness, and enhanced collaboration among sectors to effectively address the identified barriers.

1.3. Research gaps

Through the summary and analysis of existing studies, it is evident that current studies on ZCC primarily focus on the definitions of community, the development of zero-carbon technologies, and the obstacles to achieving zero-carbon processes. However, several critical research gaps remain, particularly in the context of China:

(1) Despite growing interest from both academia and industry in ZCC as a strategy for reducing emissions and enhancing energy efficiency, there is a notable absence of systematic summaries and comprehensive analyses of ZCC development. Existing literature lacks an integrated framework for understanding the construction and operationalization of ZCCs.

(2) Current definitions of ZCC focus mainly on the principle of maintaining emissions below consumption levels. However, fundamental elements such as setting clear community boundaries and accurately calculating energy consumption are underexplored. This limited conceptual scope impedes the development of targeted policies and standards, which are essential for effective ZCC implementation.

(3) Existing research is deficient in providing a thorough summary and classification of policies issued by the Chinese government related to ZCC, as well as an analysis of their evolution. Additionally, there is a relative scarcity of comparative studies examining the practices of ZCC in China versus those in Western countries, where zero-carbon development has progressed rapidly under the current policy context.

(4) ZCC in China is a recently introduced but highly prioritized national strategy. Due to its short development timeline, the implementation of ZCC faces numerous obstacles and constraints. The urgency of achieving China's dual carbon targets necessitates the rapid development of ZCC and the establishment of scalable templates for broader implementation. However, there is currently insufficient depth in the research on the challenges and constraints associated with promoting ZCC, as well as a lack of comprehensive and systematic pathways for development and implementation.

1.4. Innovation and contribution

ZCC is critical for China's efforts to achieve carbon neutrality. Therefore, it is essential to systematically summarize and analyze related policies and practices. This study aims to provide a comprehensive review of the current status of ZCC from the latest research perspectives, to promote sustainable community development in China.

The innovations of this paper are as follows: (1) This study summarizes and analyzes the concept of ZCC, comparing definitions adopted by various countries. It investigates differences between the development of ZCC in China and those in developed Western countries; (2) This study comprehensively summarizes existing policies related to ZCC from various perspectives using a classification approach. It conducts an in-depth analysis of the implementation status of these policies, synthesizing the characteristics of ZCC projects within the Chinese policy context. Furthermore, it includes a comparative and dialectical analysis with prominent international case studies; (3) The development of ZCC in China faces obstacles and limitations from five aspects based on the PESTEL analysis model: administrative, economic, technological, socio-cultural, and environmental. This study elaborates on these challenges and proposes targeted development recommendations and implementation roadmaps aligned with national policies.

The contribution of this study is to summarize and analyze the current development status of ZCC in China and the existing national policies related to them. It compares definitions of ZCC. This study also analyzes the current development barriers faced by ZCC in China through practical case studies. Based on this analysis and in conjunction with existing policies, it provides development recommendations. The research findings underscore the crucial role of ZCC in advancing sustainable development in China while also offering the government effective management strategies and incentives. Furthermore, the study offers a clear roadmap for the formulation of national laws, regulations, and standards to eliminate existing barriers.

2. Research methodology

This paper systematically analyzes research papers on ZCC published in journals from 2000 to the present, alongside government documents,

to provide an in-depth understanding of the current state and research trends of ZCC development in China. The research methodology consists of three steps: 1) data collection, 2) information filtering, and 3) content analysis, as shown in Fig. 1.

Firstly, the keyword 'zero-carbon community' was searched in the Web of Science Core Collection database. The data indicate that Brazil, the United States, and China lead in published research on ZCC, followed by the United Kingdom, Germany, Canada, Australia, France, India, and Italy. Fig. 2 illustrates the primary ZCC research areas, focusing on agriculture, environmental sciences, ecology, and plant sciences, with additional studies in engineering, fuels, and technology. This study aims to analyze significant policy and practice changes and establish a foundational database for the proposed framework. Notably, few ZCC-related papers were published before 2000, and the concept was absent in China at that time. To streamline our analysis, we set 2000 as the reference year, with data spanning from 2000 to 2024 and a search cutoff of 25 October. ZCC research has evolved through three phases: slow growth (2000–2007), moderate growth (2007–2017), and rapid growth (2017–2023). Despite fluctuations, as shown in Fig. 3, the third phase reflects an overall trend of accelerated growth.

Secondly, a search using the keyword 'Zero Carbon Community' yielded several publications. To narrow the initial results, specific criteria such as literature type and publication date were applied, reducing the dataset to 2,606 documents. Key journals identified on Scopus included the 'Journal of Cleaner Production', 'Energy and Buildings', and 'Renewable and Sustainable Energy Reviews'. Focusing on review articles and research papers aligned closely with the theme resulted in 1,058 documents. Additional screening of articles from other relevant subject areas added 532 more documents.

Finally, the body of papers was screened for detailed examination, and papers not directly related to ZCC were excluded from the study [34]. To further enhance the research content, supplementary materials

were selected, including research results from Chinese scholars in the CNKI database and various documents provided by official government websites. This additional selection yielded 170 documents.

After the above steps to get the research information and subsequently analyze it to get the various studies, the line of this study is shown in Fig. 4.

3. The concept of zero-carbon community

Currently, there is no standardized unique concept of ZCC, either domestically or internationally. However, it generally emphasizes reducing dependence on fossil fuels, improving energy efficiency, lowering carbon dioxide emissions within the community, and achieving harmonious coexistence with nature. Western countries began research on the definition of ZCC relatively early, with a focus on achieving zero-carbon emission goals. In particular, the development of ZCC practices in the UK is relatively mature. Domestic and international documents dealing with the concept of ZCC are shown in Table 2.

The zero-carbon concept builds on the groundwork laid by low-carbon initiatives [20]. Introduced by British scholars, the low-carbon concept gained traction internationally with the release of the second phase of the Eco-Community Guidance Program in 2008 [43,44]. By 2012, the U.S. military had committed to achieving zero carbon emissions across its bases by 2058, targeting zero emissions in water, waste, and energy within military communities [45]. In 2021, the U.S. government announced a zero-carbon goal for its electricity system by 2035 and for society at large by 2050 [46]. Responding to these ambitions, the American National Standards Institute approved ASHRAE's first standard for evaluating the performance of net-zero energy and net-zero carbon buildings (ANSI/ASHRAE Standard 228–2023) on March 8, 2023. This standard aims to determine whether the design solutions or operational status of new or existing buildings, communities, and

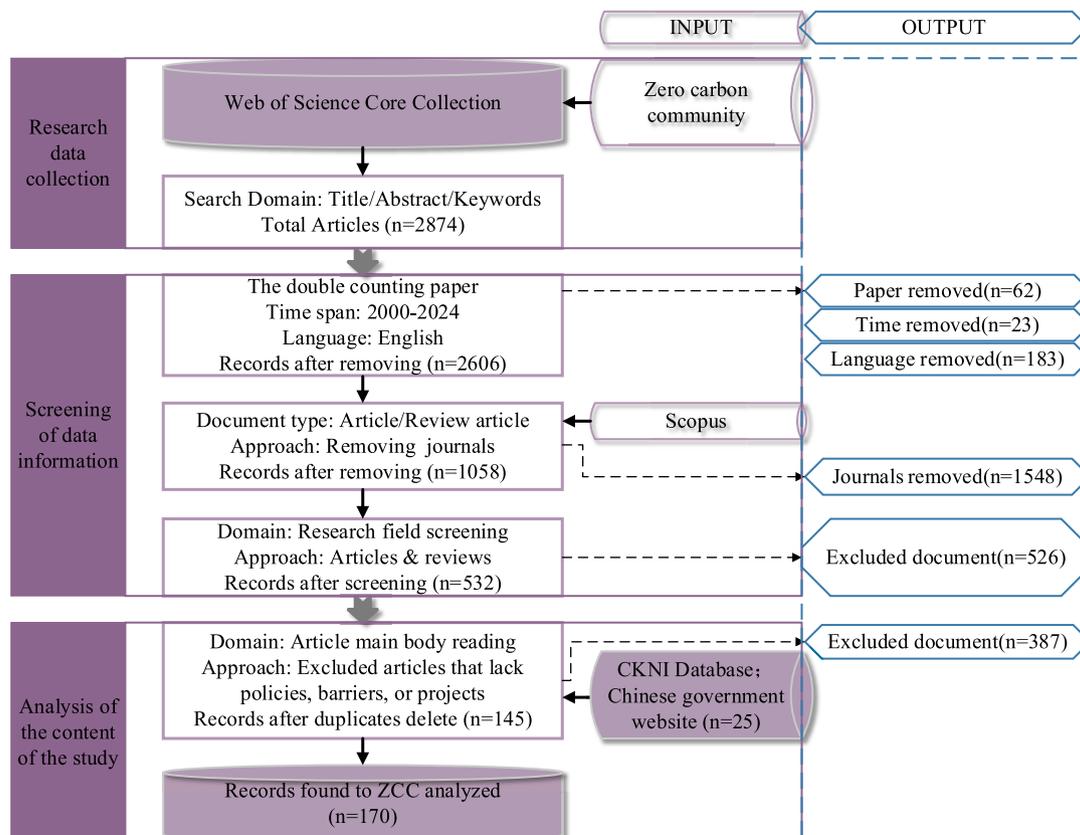


Fig. 1. Flowchart of the research methodology.

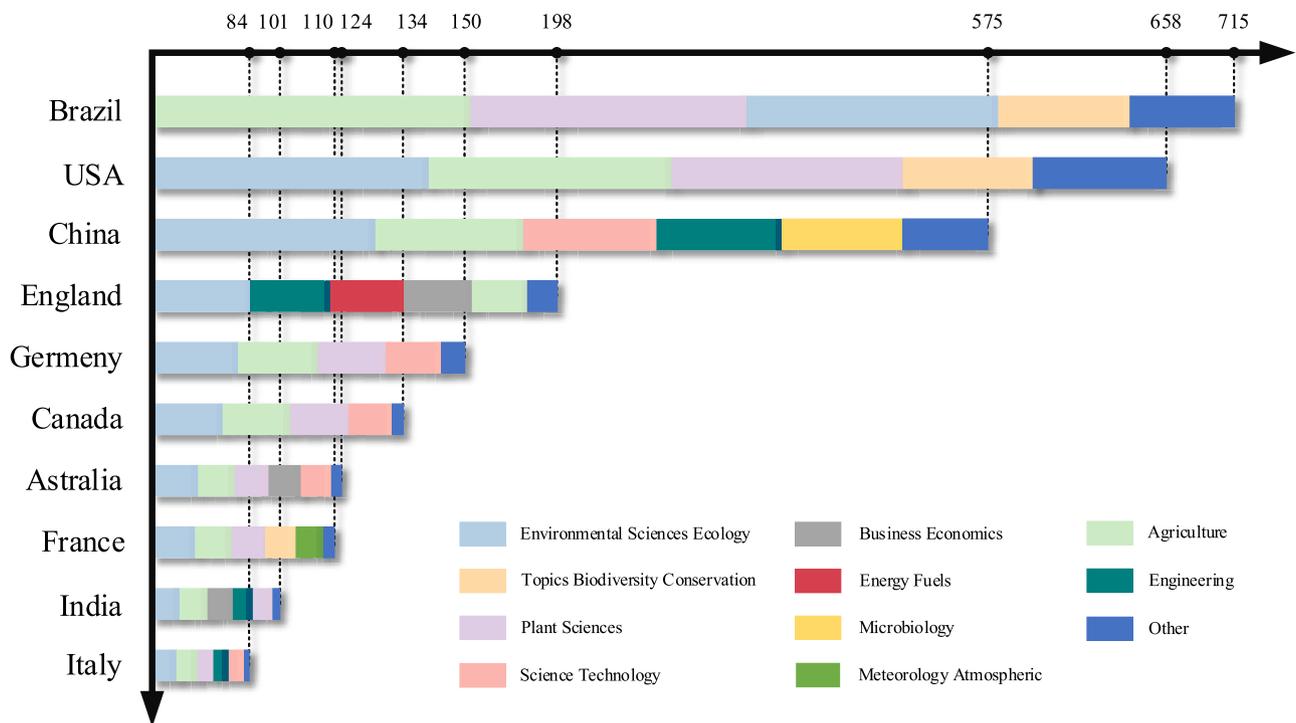


Fig. 2. National distribution of ZCC research areas.

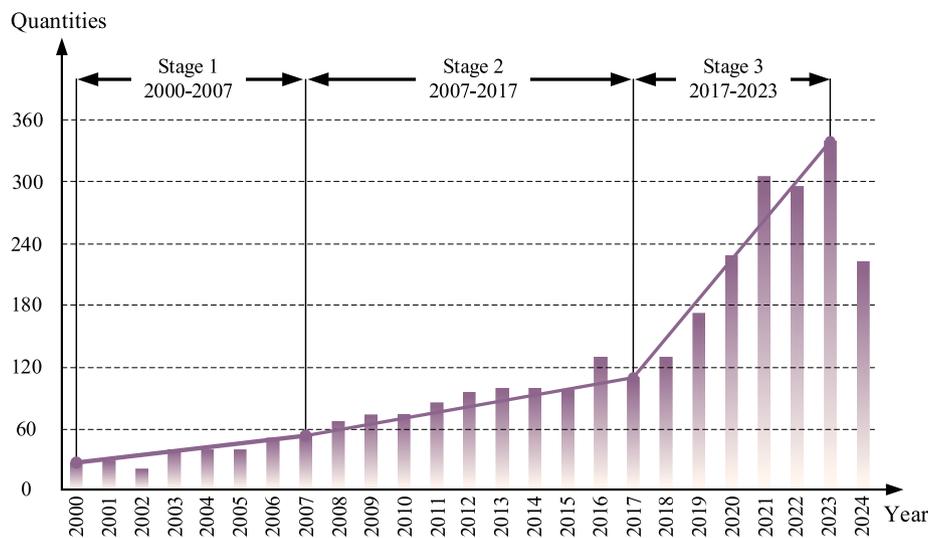


Fig. 3. Distribution of the number of papers on ZCC from 2000 to 2024.

freestanding building spaces meet net-zero energy or net-zero carbon emissions [37]. The Australian ZCC Guidelines 2020 set the benchmark for ZCCs, requiring that annual carbon reductions from renewable sources surpass the community’s carbon output. These guidelines prioritize energy efficiency, renewable integration, and the elimination of fossil fuels [35]. Similarly, Canada is advancing towards a healthier economy and environment with the enactment of a new law in 2020 requiring net-zero emissions by 2050. Many communities in Canada are already striving to achieve 100 % renewable energy use [47] and zero-emissions targets [48]. Western countries primarily define ZCC with a focus on achieving zero-carbon targets, adopting a results-oriented approach. For instance, in 2016, the U.S. Green Building Council (USGBC) defined the community carbon emission calculation boundary to encompass buildings, transportation, municipal lighting, water systems, waste management, and renewable energy sources, requiring all

buildings within the community to be included. These renewable sources encompass solar, wind, geothermal, small hydropower, and biomass. Similarly, the “Australian ZCC Guidelines 2020” categorizes community carbon emissions into four areas: building energy, waste disposal, transportation, and industry. Switzerland has also made significant strides in low-carbon community development. In 1998, the Swiss Federal Institute of Technology introduced the concept of a 2,000 W community, which includes carbon emissions from the building construction phase, the operational phase, and community transportation [49].

In China, the ZCC concept evolves directly from low-carbon community efforts [38]. For example, the Guidelines for the Pilot Construction of Low-carbon Community, issued by the National Development and Reform Commission in 2014, define low-carbon community as urban and rural areas that reduce energy and resource

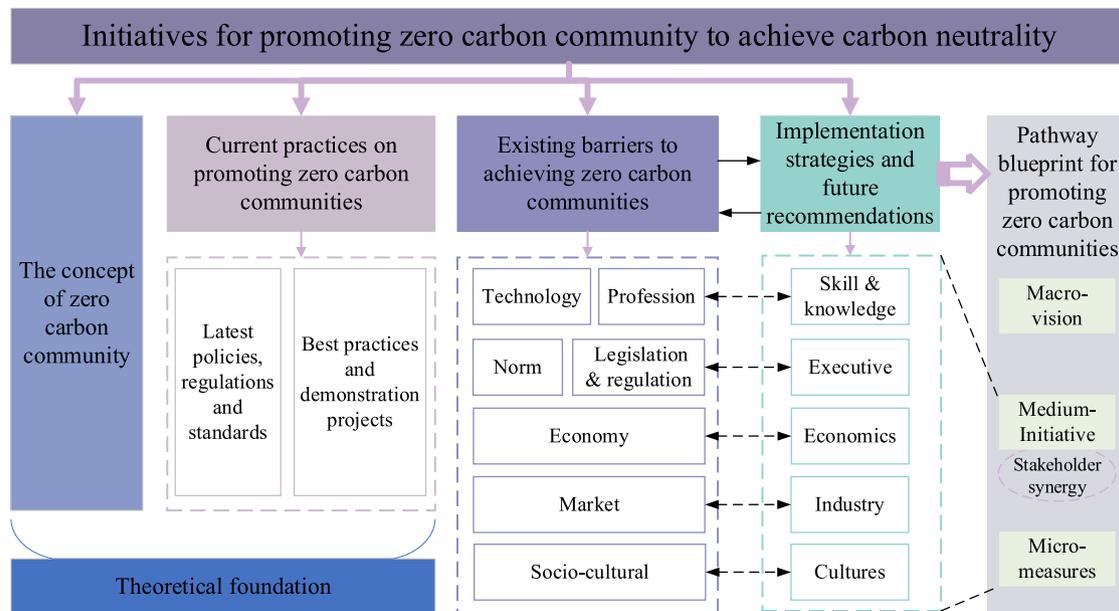


Fig. 4. Schematic diagram of the research contents and relevant relationships of each section.

consumption to achieve low-carbon emissions. This is accomplished through the development of climate-friendly natural environments, housing, infrastructure, lifestyles, and management practices [40]. Such communities reduce carbon by 25 % compared to standard communities. In 2021, Shenzhen City government released the “Implementation Plan for the Pilot Construction of Near-Zero Carbon Emission Zone in Shenzhen”, exploring pathways tailored to Shenzhen’s specific needs [41]. The 2022 “Zero Carbon Community Construction and Evaluation Guidelines” from the Guangdong Low Carbon Industry Technology Association outline ZCCs as communities that reach net-zero or negative carbon dioxide emissions through rigorous carbon reduction and neutrality practices during construction, renovation, and operation phases. Currently, however, China lacks a unified calculation boundary for community carbon emissions, with varying standards across waste, water, lighting, and carbon offsets. Establishing consistent boundaries and technical benchmarks is essential for ZCC development [50]. Building a ZCC is a process of continuous practice and iterative revision, involving the iterative determination of various indicators and the exploration of zero-carbon technologies [51]. Beyond zero emissions, an internationally recognized climate change think tank, recommends transitioning from low to zero-carbon emissions within a decade [52]. Worldwide, governments are committing to significant emissions reductions aligned with scientific recommendations and global agreements [53]. The progression from low- to zero-carbon communities is outlined in Fig. 5.

National Renewable Energy Laboratory (NREL) defines a ZCC as one that meets its energy needs through renewable sources by significantly reducing energy demand via efficiency measures. According to a technical report by NREL, ZCC can integrate transportation, homes, and the grid, thereby facilitating the incorporation of substantial amounts of renewable electricity into the grid [57]. In addition, applying the concept of layered renewable qualities of zero-carbon buildings proposed by Pless and Torcellini [58] to the concept of communities, four characteristics of ZCC are proposed: 1) improving the energy efficiency of the building stock; 2) minimizing occupant energy demand for buildings and transportation; 3) maximizing on-site renewable energy production; 4) using off-site renewable energy production [59]. In 2020, the seven largest carbon emitters (China, the US, India, the EU, Indonesia, the Russian Federation, and Brazil) accounted for about half of global greenhouse gas emissions [60]. Most developed countries in Europe and the US have enacted numerous climate plans to legislate

zero-carbon initiatives, while China has been slow to develop in comparison.

ZCC protects the environment by reducing carbon emissions and increasing economic efficiency. These communities feature zero-energy buildings, which significantly reduce energy consumption and carbon emissions through efficiency gains, such as balancing energy demand with renewable energy sources [32]. Reduced energy consumption in buildings leads to lower construction and operating costs, with cost optimization achieved by improving energy efficiency and using low-consumption material [61]. An estimated \$6 in avoided climate costs is realized for every \$1 invested in developing ZCC [62]. Early action on ZCC is critical, enabling communities to upgrade infrastructure and improve environmental accessibility [63].

4. Current practices on promoting zero-carbon community

4.1. Existing policies, regulations, and standards

Various measures have been formulated to accelerate the construction and development of these communities. Drawing on the theoretical foundations of Geels [64] and Coenen et al. [65], ZCC can be viewed as complex socio-technical systems. These systems encompass the production, diffusion, and use of technologies that contribute to achieving the zero-carbon goal and involve a wide range of stakeholders [64,65]. ZCC measures consist of formal rules, standards, and procedures that are mandatory for stakeholders and co-evolve within relevant sectoral regulatory, social, and geographic contexts, as shown in Fig. 6.

Many countries and regions have proposed policy goals to achieve zero carbon, related to zero carbon, and near-zero carbon, etc. The timing of policy introduction varies, mainly between 2015 and 2020, during this period, the urgency of global climate change accelerated the development of zero-carbon initiatives, leading to the introduction of numerous policies aimed at advancing zero-carbon technologies and achieving zero-carbon goals, as shown in Table 3.

In 2011, China issued the “Twelfth Five-Year Plan for Controlling Greenhouse Gas Emissions”, which included the development of specifications and evaluation standards for pilot low-carbon community. Subsequently, the “National Plan for Responding to Climate Change (2014–2020)” in 2014 aimed to enhance policies and evaluation systems supporting experimental low-carbon development. That same year, the National Development and Reform Commission issued the “Notice on

Table 2
Domestic and international definitions of ZCC.

Country	Year	Filename	Element	Key Points	Carbon Emissions Calculation	Ref.
Australia	2020	Australian Zero Carbon Community Guidelines 2020	Community with annual renewable energy carbon reductions greater than or equal to carbon production.	Carbon production is less than carbon reduction	Measurement method: Total carbon emissions	[35]
UK	2009	Eco-towns Planning Policy Statement (Eco-towns PPS)	Zero-carbon eco-town means an eco-town development in which the overall annual net carbon emissions from all energy use in buildings are zero or below zero.	Net carbon emissions do not exceed zero	/	[36]
USA	2023	ANSI/ASHRAE Standard 228–2023	During the community's operation, the energy input is equal to or less than the energy output. The community's carbon emissions are also equal to or less than the allowable offsets and compensations, ensuring net-zero carbon impact.	Carbon neutrality does not exceed zero	Measurement method: carbon emissions per capita; Calculation boundaries: buildings, transportation, water supply and drainage, waste, community lighting, renewable energy, carbon trading and green electricity mechanism	[37]
Canada	2014	Social Sciences and Humanities Research Council of Canada, through Insight Grant 435–2014-0465.	Natural ecosystems between people, community, and carbon reduction are zero-carbon community, also known as single-earth community, eco-cities, eco-districts, or eco-cities.	Natural ecological environment	/	[38]
	2022	2030 Emissions Reduction Plan	Near-zero energy communities consist of centralized, continuous near-zero energy buildings.	/	/	[39]
China	2014	Guidelines for the Pilot Construction of Low-Carbon Community	Urban and rural communities with low carbon emissions through the construction of climate-friendly natural environments, buildings, infrastructures, lifestyles, and management patterns that reduce the consumption of energy resources.	Integration of environment, buildings, facilities, lifestyles, and management models	Measurement method: carbon emissions per capita; Calculation period: year; Calculation boundary: buildings, transportation, water supply and drainage, waste, community lighting, renewable energy, carbon sink	[40]
	2021	Implementation Programme for the Pilot Construction of Near-Zero Carbon Emission Zones in Shenzhen City	Building on the existing low-carbon initiatives, within specific districts and cities, innovative management practices are implemented through the integrated application of low-carbon technologies across energy, industry, construction, transport, waste treatment, and other fields. This approach aims to achieve a sustained reduction in total carbon emissions, gradually converging to zero.	Integration of multi-disciplinary carbon reduction technologies	Measurement method: carbon emissions per capita; Calculation period: year; Calculation boundary: buildings, transportation, water supply and drainage, waste, community lighting, renewable energy, carbon trading and green electricity mechanism, carbon sink	[41]
	2022	Guide to Building and Evaluating Zero-Carbon Community	Developing green buildings in the community, innovating low-carbon technologies, advocating green living, constructing efficient, energy-saving, and recycling systems, and achieving net carbon dioxide emissions of zero or less at all stages of construction, renovation, and operation through carbon emission reduction and neutrality measures.	System Creation	Measurement method: carbon emissions per capita; Calculation period: year	[42]

Pilot Work in Low-Carbon Community” along with the “Guidelines for Pilot Construction of Low-Carbon Community,” initiating pilot projects across the country. By 2021, the Central Committee of the Communist Party of China (CPC) and the State Council emphasized the acceleration of green community construction in their “Opinions on Fully Implementing the New Development Concept, Achieving Carbon Peak, and Carbon Neutrality”. The Ministry of Housing and Urban-Rural Development’s “14th Five-Year Plan” for Building Energy Efficiency and Green Building Development aims to pilot the construction of zero-carbon buildings and communities [81]. In response to the global call for carbon reduction, China has developed strategic policies tailored to its national circumstances to promote the development of both newly constructed and existing communities. According to available data, 12 provinces and cities including Guangdong, Shenzhen, Beijing, and Shanghai have implemented pilot policies for low-carbon communities. State-issued policy guidelines for ZCC are detailed in Table 4.

Beyond policy documents as guiding principles and laws and regulations as foundational requirements, the establishment of ZCC necessitates a range of normative guidelines, including those for greening and beautification. These guidelines are outlined in the “Basic Standards for National Community Building Demonstration Cities” as mandatory

criteria. The standard specifications aim to standardize the construction of ZCC, enhancing safety and regulatory ease, and thereby promoting residents’ quality of life. Table 5 details the current standards.

A summary analysis of the above documents reveals that, while there are no direct policy documents specifically addressing ZCC, there are numerous related orientation documents. However, there is a notable lack of specific normative standards and other guiding documents. Additionally, the Chinese government has developed other important measures to achieve its carbon reduction targets, as illustrated in Fig. 7.

Based on the above issues, the government needs to introduce clear guidelines for the construction of ZCC. Once such policies are issued, the industry should respond vigorously to standardizing the construction of these communities. This will encourage widespread participation in community maintenance and green living, thereby accelerating progress toward achieving carbon neutrality and carbon peaking.

4.2. Praiseworthy practices and demonstration projects

With the development of policies and state directives, many ZCCs have been constructed and are now operational. Aligning with the “One Planet Living” concept, the WWF and the UK Eco-Regional Development

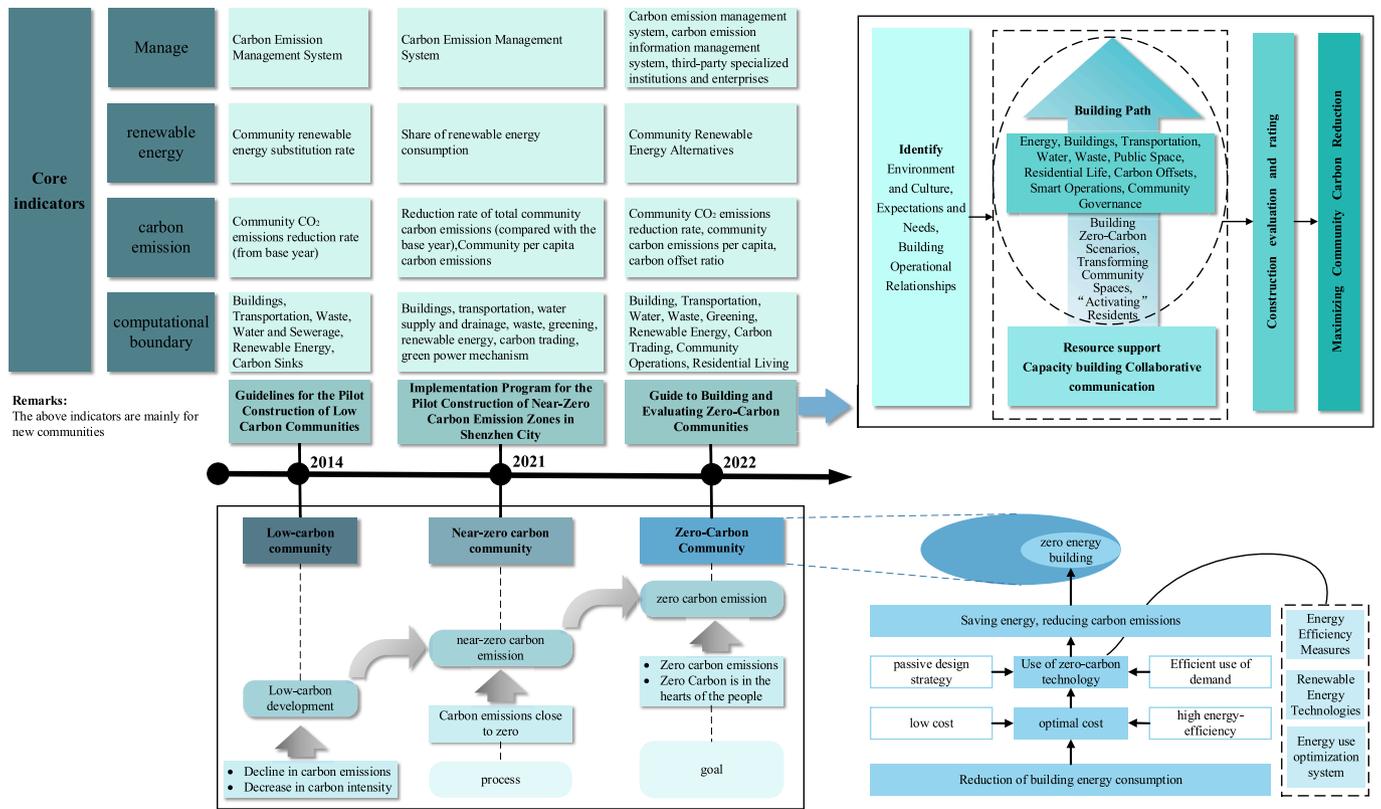


Fig. 5. Different stages of development from low carbon to zero carbon (the figure was created by the authors, with information sourced from references [41,54–56]).

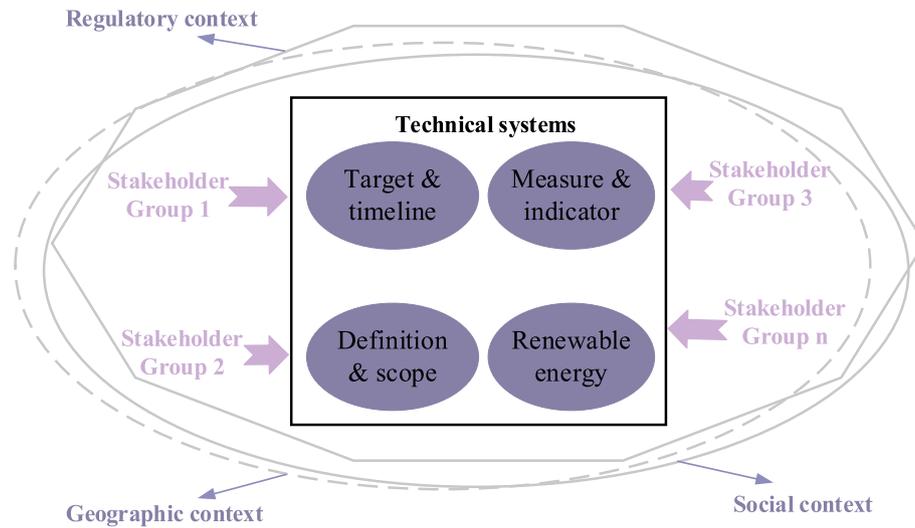


Fig. 6. Evolution of ZCC Measures [66,67].

Group advocated the creation of the world’s first zero-energy community, BedZED (Beddington Zero Energy Development). BedZED’s construction began in 2000 and was largely completed by 2002 [82]. According to available data, more than 10 countries, including the United Kingdom, the United States, Germany, Denmark, Singapore, and the United Arab Emirates, have implemented practices for ZCC. Some notable examples include BedZED in the UK, Vauban District and Bahnstadt Heidelberg in Germany, and Halifax Southside Park Eco-village in Australia, each of which has significantly influenced ZCC development [83–86]. China began its ZCC journey in 2010 with the construction of the Zero Carbon Pavilion at the Shanghai World Expo. By

2012, China had completed additional ZCC projects such as Zero Carbon World in Hong Kong and the Public Housing Exhibition Center in the Sino-Singapore Tianjin Eco-city. Table 6 provides a comparison of early ZCC practices in China and abroad.

The UK has been at the forefront of developing ZCC, implementing several key policies such as the Code for Sustainable Homes, which mandates that new homes in the UK achieve zero-carbon status from 2016 [91,92]. In Beddington, key stakeholders in community development, including government bodies, foundations, technical advisors, and investment firms, play pivotal roles, as illustrated in Fig. 8. BedZED’s community planning emphasizes five primary goals: sustainable

Table 3
Global zero carbon policy targets document [66].

Region/Country	Target	Reference
EU	All new buildings are nearly zero energy buildings after 31 December 2020 New buildings occupied and owned by public authorities are nearly zero-energy buildings after 31 December 2018.	[68]
Finland	Passive House standards by 2015.	[69]
France	By 2020, all new buildings are to be net-positive energy, i.e. to produce more renewable energy than the building's needs.	[70]
Germany	By 2020, new buildings should be operating without fossil fuels.	[69]
Hungary	By 2020, zero emissions for all new buildings.	[69]
Netherlands	By 2020, all new buildings to be energy-neutral.	[71]
Belgium/Brussels Region	From January 2015, all new public and residential buildings have to fulfill a primary energy need at the level of Passive House standard.	[72]
UK	Zero carbon for new-build homes from 2016 and non-domestic buildings from 2019.	[73]
USA	All new commercial buildings must be net-zero energy by 2025; All US commercial buildings must be net-zero energy by 2050, including retrofits of pre-2025 buildings.	[74]
USA	All planning in 2020 and thereafter for new federal buildings requires design specifications that achieve net-zero energy use; From 2015, large government buildings have to start showing progress; From 2015, at least 15 % of any federal agency/s existing buildings and building leases above 500 m ² must conform to net-zero energy, and ongoing improvements are required.	[75]
California, USA	All new residential construction in California will be net-zero energy by 2020; All new commercial construction in California will be net-zero energy by 2030.	[76]
Massachusetts, USA	Recommended that all new buildings should achieve zero net energy by 2030.	[77]
Australia	Proposed the definition of and roadmaps to ZCBs.	[78]
Japan	Discussed plans to adopt a goal for zero-energy buildings by 2030.	[79]
German	The first is to achieve a 65 percent reduction in total greenhouse gas emissions by 2030 compared to 1990 levels, up from the 55 percent target set for 2019. The second is to achieve “carbon neutrality”, i.e. net zero GHG emissions, by 2045, five years ahead of the 2019 plan.	[80]

construction practices, utilization of green energy sources, efficient recycling of resources, promotion of low-carbon transportation, and construction of energy-efficient homes. Additionally, BedZED prioritizes community maintenance and management to ensure sustainable long-term development.

A unique feature of the BedZED development was that it brought together so many technologies and techniques in one development [93]. The BedZED energy strategy comprised the use of passive design principles described above to minimize energy demand and energy supplied by biomass-fuelled CHP units and photovoltaic cells (PV). The technical solutions include combined heat and power (CHP) design [94], lighting design, ventilation design [95] and heating design [96], BedZED aimed to harness the comprehensive benefits of all these technologies. Residents of BedZED have embraced zero-carbon principles, fostering awareness and community cohesion. Residents' behaviors and attitudes toward zero carbon have driven the community's overall development. Community cohesion is fostered through initiatives like community blogs and newsletters, enhancing communication and cooperation among residents. People in BedZED have reduced their eco-footprints

Table 4
Policy documents related to ZCC in China.

Time	Launch office	Document name	Thrust
2011	State Council (PRC)	Work Programme for the Control of Greenhouse Gas Emissions in the Twelfth Five-Year Plan	Following the principles of green, convenient, energy-efficient, and low-carbon development, low-carbon community construction is being implemented.
2014	NDRC (China National Development and Reform Commission)	Notice on Pilot Low-carbon community	By the end of the Twelfth Five-Year Plan, the number of pilot low-carbon Communities nationwide should reach about 1,000.
2014	NDRC	Circular on the issuance of the national plan for addressing climate change (2014–2020)	To achieve green and low-carbonization in community planning and design, choice of building materials, heating, cooling, power and hot water supply systems, community lighting, community transport, and building construction.
2014	NDRC	Work program the control of Greenhouses emissions in the Thirteenth Five-Year Plan	The construction of demonstration projects for near-zero carbon Communities and even ZCC are important demonstration pilot objects.
2015	NDRC	Guidelines for Pilot Construction of Low-Carbon Community	Promoting the low-carbon development of towns and cities and controlling the carbon emissions of residents' lives.
2016	NDRC/Ministry of Housing and Construction	Programme of Action on Urban Adaptation to Climate Change	Community, as the basic building blocks of cities, will be one of the vehicles and beneficiaries of urban adaptation to climate change.
2021	Ministry of Housing and Construction and other departments jointly	Action Programme for the Creation of a Green Community	Promoting green and low-carbon community infrastructure, improving the level of community information technology and intelligence, and fostering a green culture in the community.
2021	State Council (PRC)	Notification of the Action Programme on Peak Carbon by 2030	Focusing on the implementation of the “Ten Peak Carbon Actions”.
2021	Ministry of Housing and Construction	Guide to Building Complete Living Community	Guidance is given on the concept of residential neighborhoods, their size, etc.
2021	State Council (PRC)	Comprehensive Work Programme on Energy Conservation and Emission Reduction in the 14th Five-Year Plan	Promoting energy conservation and emission reduction, accelerating the establishment of a robust economic system focused on green, low-carbon, and recycling

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Table 4 (continued)

Time	Launch office	Document name	Thrust
			development. This initiative aims to foster a comprehensive green transformation of economic and social development, contributing to the attainment of carbon peak and carbon neutrality goals. Implementing the construction of green and low-carbon community involves integrating the concept of green development throughout the entire process of community planning, construction, and management. The goal is for 60 percent of urban communities to initially meet the creation requirements, with exploration into the development of ZCC.
2022	NDRC/Ministry of Housing and Construction	Peak Carbon Implementation Programme for the Urban and Rural Construction Sector	

greatly by using the ZED’s tech-dependent facilities, recycling their waste and having local food, as shown in Fig. 9.

Enacting an alternative lifestyle is extremely important to implement sustainability in China. To this populous country, which is developing at a high speed but with relative less-developed technologies and less-trained local labour. At the Shanghai World Expo, the London Zero Carbon Pavilion stands as one of China’s pioneering ZCCs, featuring two interconnected buildings designed to emit zero carbon dioxide. Created by the Zero Carbon Centre, the same team behind BedZED, this pavilion incorporates advanced zero-carbon concepts from London, tailored to the climatic conditions of Shanghai. Fig. 10 depicts the structure and functionality of the Zero Carbon Pavilion, illustrating its role as a model for ZCC in China. The pavilion aims to establish a sustainable urban environment by integrating zero-carbon principles such as green energy, recycling initiatives, and promoting low-carbon transportation. These efforts are intended to foster a green economy [97].

During the construction of the Shanghai World Expo Zero Carbon Pavilion, there was a strong emphasis on public engagement. The following measures were implemented to support this initiative: (1) Policy Implementation and Public Awareness: This initiative was supported by the implementation of relevant policies and extensive public awareness campaigns focused on educating the public about zero-carbon initiatives and the importance of environmental and ecosystem protection; (2) Resource and Energy Recycling System: A comprehensive system for recycling and utilizing resources and energy was put in place. The pavilion generated sufficient electrical energy using solar photovoltaic panels and thermal power converters. Rainwater harvesting systems and solar thermal panels provided the necessary water resources; (3) Energy from Organic Sources: The kitchen was powered by biogas energy derived from the fermentation of food and organic fertilizer; (4) Green Roofing and Vertical Greening: The pavilion’s green roof, equipped with wind caps, facilitated the conversion of indoor carbon dioxide into oxygen through photosynthesis. Additionally, vertical greening systems were integrated to effectively absorb carbon emissions; (5) Sponge City Concept: The pavilion incorporated the “sponge city” concept, featuring a living water park designed to use natural infiltration processes to recharge groundwater, enhance regional water quality, and reduce pressure on municipal drainage systems [98]. Utilizing the Internet of Things (IoT) technology, integrate and

Table 5

China’s ZCC-related standards and norms.

Time	Launch office	Document name	Thrust
2000	Ministry of Civil Affairs (MCA) of the PRC	Basic standards for national model cities for community building	To make “purifying, greening, beautifying and maintaining a good ecological environment in the community” a mandatory criterion for community building.
2012	China Academy of Building Research (CABR)	Technical Guidelines for the Application of Low-Carbon Homes and Community	Technical recommendations to guide the development of low-carbon communities are presented in terms of low-carbon community planning, low-carbon construction, and waste recycling.
2014	NDRC	Measures for evaluating and assessing the responsibility for the goal of reducing carbon dioxide emissions per unit of gross domestic product	Pilot low-carbon communities within the jurisdiction will receive an additional 2 points in the provincial assessment.
2019	China Construction Industry Press	Technical Standard for Near-Zero Energy Buildings GB/T 51350–2019	The design of building programs should consider building functions and environmental resource conditions, adhering to the principle of climate adaptability. This approach aims to reduce annual heating and cooling energy consumption by maximizing natural lighting and ventilation. Passive building design strategies, such as heat preservation and insulation of the enclosure structure, should be employed to minimize the building’s overall energy demand.
2021	Tianjin Society of Environmental Science	Guidelines for the Identification and Evaluation of Zero-Carbon Buildings T/ CASE 00–2021	Take the overall energy-saving effect of the building body as the control index, and set the limits of control indexes for residential buildings and public buildings, respectively.
2022	Guangdong Low Carbon Industry Technology Association	Guidelines for Building and Evaluating Zero-Carbon Community T/ GDDTJS 06–2022	It sets out the basic principles of ZCC building, the path of building, the areas to be built, and the support and improvement required in the process.
2022	Shenzhen Institute of Standards and Technology	Norms for the Evaluation of Sustainable Development Neighbourhoods T/ SZS4049-2022	It covers key indicators such as neighborhood infrastructure, ecology, energy and resource use, and neighborhood governance, to raise the level of sustainable development of neighborhoods and residents’ awareness of sustainable development.

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Table 5 (continued)

Time	Launch office	Document name	Thrust
2023	Ministry of Housing and Urban Development, Municipal Council	Technical Standards for Zero-Carbon Buildings (Exposure Draft)	Design, construction, operation, and judgment standards for new and existing retrofitted low-carbon, near-zero-carbon, and zero-carbon buildings and zones to reduce building energy demand, improve energy efficiency, create a healthy and comfortable indoor environment in buildings, and develop the application of renewable energy and zero-carbon energy buildings.

synchronize new energy sources, power grids, natural gas, heat systems, electrified transportation, and other traditionally isolated subsystems to establish an Energy Internet service platform. This platform facilitates energy data mining and optimization of energy efficiency within the operational area, significantly enhancing urban energy system efficiency [99]. By effectively aligning human activities, ecosystems, and advanced technology, this initiative aims to serve as a model and reference for developing ZCC across other regions of China.

Currently, regions in China that have initiated low-carbon pilot projects are experiencing a greater decline in carbon dioxide emissions per unit of GDP compared to non-pilot regions. Drawing from international practices and tailored to China’s context, measures such as promoting voluntary community engagement, optimizing existing ecological systems, innovating and deploying zero-carbon technologies, and establishing an Energy Internet platform are pivotal for advancing ZCC. ZCC aims to be both environmentally sustainable and economically prosperous. Achieving zero-carbon emission goals requires a balanced approach that prioritizes community well-being and economic vitality [100].

5. Existing barriers to achieving zero carbon community

While zero-carbon buildings have emerged as innovative models for sustainability in the built environment, their widespread adoption faces significant challenges. These challenges, in turn, present barriers to the construction of ZCC [101]. In the long term, the strategic vision for carbon dioxide reduction is driven by inherent uncertainties and unforeseen fluctuations. As various challenges arise, both exogenous and endogenous factors have exerted considerable influence on the development trends of ZCC. The use of the PESTEL analysis model, which evaluates six key factors—Political, Economic, Socio-cultural, Technological, Environmental, and Legal—facilitates informed decision-making [102]. Since the political and legal aspects of ZCC

construction are determined by governmental actions, they are consolidated under “Administrative” factors. The barriers influencing the development of ZCC across various contexts are synthesized in Table 7.

Table 7 provides an overview of existing research and outlines the challenges in implementing ZCC in China. The main existing obstacles and their manifestations can be analyzed using the PESTEL model to construct an obstacle framework, which can then guide the formulation of targeted improvement strategies.

5.1. Administrative barriers

A significant legislative barrier to ZCC is the lack of government support. This deficiency is evident in several key areas: weak and ambiguous policies that hinder progress towards zero carbon, minimal concessions on gross floor area, inadequate collection of energy performance data, insufficient incentives for private sector involvement, and the absence of a certification system [6].

China currently lacks government legislation and tax regulations mandating the adoption of low-carbon energy and materials. As a result, numerous organizations have yet to embark on ZCC projects. Furthermore, the adoption of these technologies is intertwined with broader support systems such as knowledge structures, supply chains, business interests, and practices. The absence of these supportive frameworks poses a significant constraint on the development of ZCC in China [109]. Legislative clarity plays a pivotal role in driving the realization of ZCC [110]. The incorporation of the Code for Sustainable Homes (CSH) into legislation stands out as a particularly influential factor motivating housebuilders to pursue ZCC projects [111]. Research by Vorsatz et al. [112] underscores the potential success of mandating CSH legislation in significantly reducing carbon emissions and improving cost-effectiveness, thereby serving as a major catalyst for the development of ZCC.

China’s building codes and regulations may not be as stringent as those in developed countries [113]. While existing codes and standards provide clear definitions and criteria for green buildings, concepts such as green community, low-carbon community, and green eco-urban areas lack uniform definitions, consistent community boundaries, standardized evaluation methodologies, and construction index systems [114,115]. The Paris Agreement underscores the need for solutions to achieve peak carbon emissions and carbon neutrality, yet there is a noticeable absence of reasonable normative standards for ZCC. Regarding the calculation scope of carbon emissions, it should encompass conventional energy consumption and carbon emissions related to buildings, transportation, waste management, water supply, and drainage within the region. However, current standards do not comprehensively cover all these indicators and lack corresponding evaluation methods, highlighting the need for improvement and refinement [116].

5.2. Economic barriers

Economically, green building practices in some developing countries

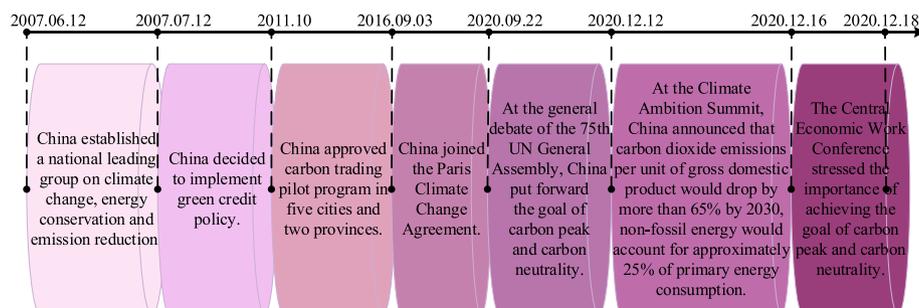


Fig. 7. Important Measures for Carbon Emission Reduction in China from 2007 to 2020.

Table 6
Comparison of ZCC practices in China and abroad.

Item	China	Foreign
Practice	Zero Carbon Pavilion at the Shanghai World Expo	Beddington Zero Energy Development
Time	2010	2000
Scale	Total construction area of 2,675 m ² , two four-story buildings.	Total construction area of 1,560 m ² , 82 households, 18 work/living units.
Features	Reduced fossil fuel usage (coal, oil, natural gas) for lower carbon emissions; maximized use of solar, wind, biomass, and geothermal energy to achieve building energy self-sufficiency [87].	Excellent passive building envelope to minimize heating/cooling demands; exports electricity to grid in summer and imports during winter [88].
Measures	<ul style="list-style-type: none"> – Key technologies [89] Wind-driven energy storage, heat preservation and dehumidification bidirectional ventilation cap; Liquid dehumidification system; Solar water heating system; Solar photovoltaic power generation system; Concrete structure; Insulated wall and hollow glass; Roof greening; Sunshade; Sun room; LED lighting; Rainwater recycling system; Capillary radiation; River water source heat pump system; Energy consumption monitoring and environmental parameter measurement system 	<ul style="list-style-type: none"> – Social aspect [90] Mixed-use & mixed-development for tenure; Living and working from home; Outdoor private space for all properties; Green transport plan: pedestrian first; bicycle storage; Proximity to community facilities for local activity; Local car pool; Choice for an alternative carbon-free lifestyle. – Economical aspect Affordable accommodation with high design quality; Commands margin over market value; High density plan to add development value; Low energy running bills; Low risk based on existing prototype: Hope House. – Environmental aspect Zero fossil fuel and carbon neutral 2.100 % renewable energy use: PV & Bio-fuelled CHP; Zero heating by passive solar gain & high insulation; Heat recovery ventilation systems powered by wind; Low embodied energy materials: sourced locally; Recycled materials – timber and steel; Water recycling and water efficient appliances; Waste recycling.
Connection	China's first zero-carbon building, the London Zero Carbon Pavilion at the Shanghai World Expo, was designed based on BedZED's technical framework, tailored to Shanghai's climate.	

often face financial constraints and a lack of incentives [117]. Higher initial costs and uncertain long-term financial returns are significant barriers to the development of ZCC. From a homebuilder's perspective, zero carbon is a relatively new concept, and there is currently limited understanding among builders regarding the net financial costs and overall profitability of constructing ZCC [15]. The enforcement costs of code standards vary for each homebuilder, making it challenging for companies to rely on government or industry estimates. The exact construction costs of zero-carbon buildings remain uncertain, and developers are primarily focused on profitability, making the promotion of ZCC exceptionally difficult. From the consumer's perspective, housing prices in ZCC can be high, along with higher unit costs of electricity sourced from renewable energy [6]. In addition, due to its relatively low level of economic development, China's ability to withstand economic risks is weaker compared to developed regions such as the European Union and the United States, so the pace of China's promotion of the ZCC development process will be slower [118].

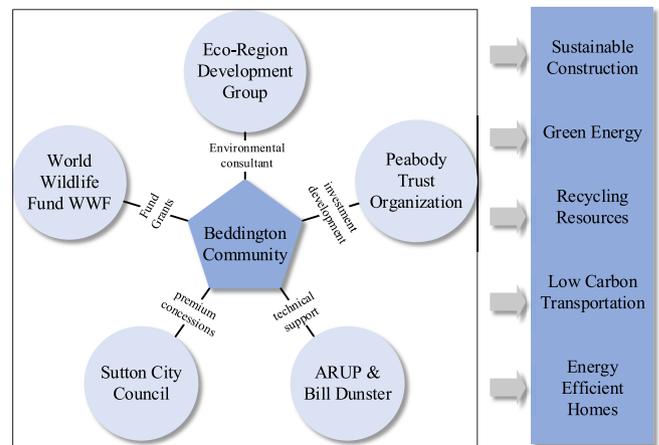


Fig. 8. Bed ZED construction body (the figure was modified from [18,82]).

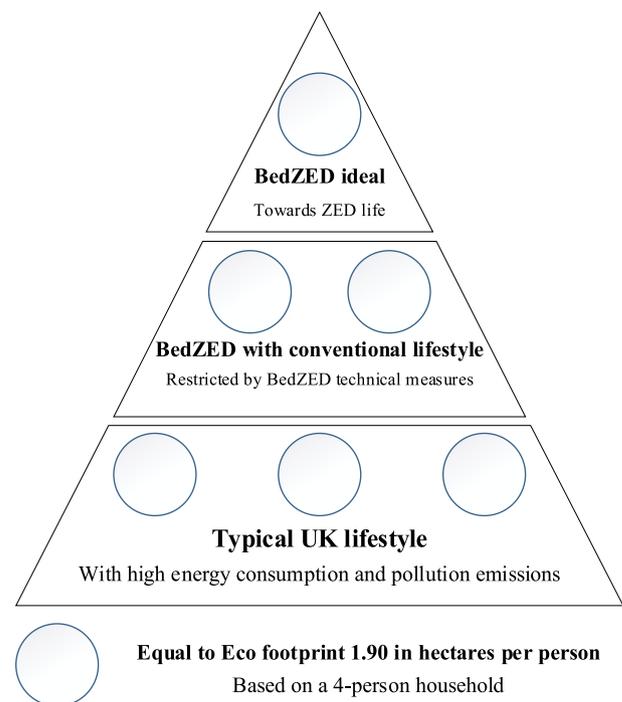


Fig. 9. Ecological footprints for UK lifestyle in hectares per person [90].

The substantial cost associated with meeting stringent standards for ZCC presents a significant barrier, constraining housebuilders' ability to address technical and planning challenges [119]. Developers are often hesitant to embrace innovation and sustainability standards due to the anticipated high costs of complying with ZCC requirements. Many real estate developers prioritize maximizing short-term economic gains, viewing the longer development cycle and higher upfront costs of ZCC as deterrents [120,121]. While there may be some tenants who support ZCC, and to cater to these buyers who value the quality of their living environment, some developers have labeled them as "eco-green/zero-carbon communities," in essence, these communities often remain in the realm of green landscaping or green technology, which is ineffective in reducing carbon emissions.

5.3. Environmental barriers

As the construction industry increasingly becomes a cornerstone of the national economy, corporate social responsibility (CSR) has gained

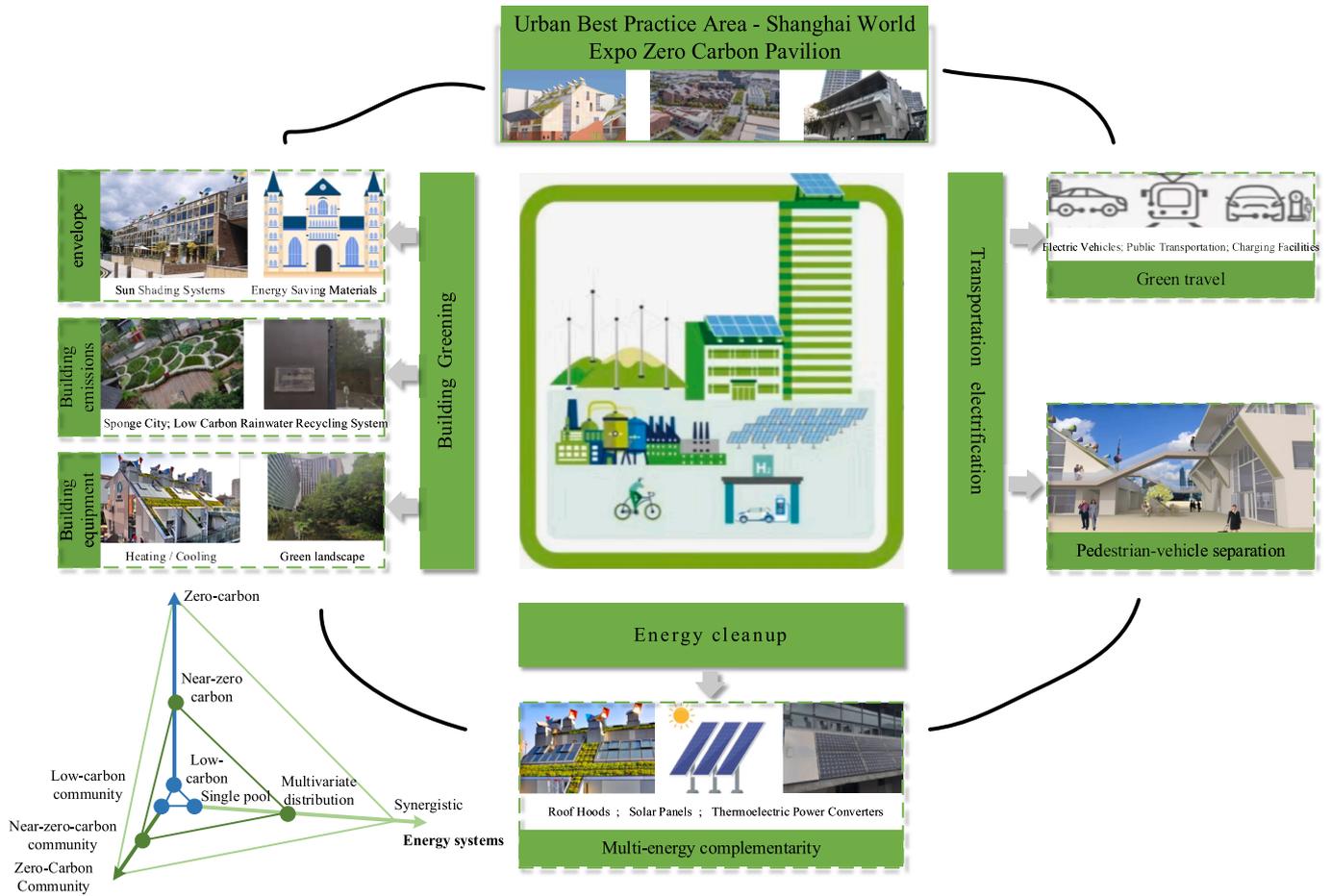


Fig. 10. Composition of the Expo Zero Carbon Pavilion (the figure was created by the authors based on internet information).

prominence. The importance of CSR is underscored in the WWF report “Building a Sustainable Future” from 2007, advocating for socially responsible practices within companies [122]. Carte highlights that exceeding minimum sustainability standards can enhance brand recognition and reputation for homebuilders, providing valuable market insights for companies involved in constructing ZCC [111]. Similarly, WWF’s 2005 report “Investing in Sustainability” emphasizes that developers can leverage high standards of environmental and social performance to attract both customers and top-tier employees [123]. Furthermore, the impact of construction supply chains on the zero-carbon process is significant. Keeping and Shires [124] indicate that supply chains are increasingly motivated to develop green products and practices to align with marketing objectives and achieve market differentiation. However, the current Chinese market may not heavily invest in these marketing strategies.

China, as one of the largest developing countries, has a nascent carbon market characterized by incomplete market mechanisms and higher risks, which discourages developers from investing in new projects. Moreover, the concept of ZCC started relatively late in China, and its full market potential has yet to be realized [125]. Additionally, the development of ZCC introduces disruptive and radical innovations that can create business and market instability, further hindering their acceptance in the market [92].

5.4. Technological barriers

Zero-carbon technologies in China are still in a nascent stage of development [6]. The Chinese industry currently lacks a comprehensive understanding of the technologies and methods. Challenges in this

process include the effective deployment of research and development towards integrating technologies, systems, and knowledge.

Technical and technological barriers present a common challenge in the global South, exacerbated by restricted access to green technologies and materials, along with a shortage of skilled contractors and professionals [126]. The adoption of new building materials, such as lightweight EPS concrete and alternative cement, and advanced building technologies like additive manufacturing and digital fabrication, may entail higher initial costs. These factors contribute to high development expenses [117,127], while limited familiarity with new products, materials, and technologies [128] has resulted in relatively low demand for sustainable environmental technologies and green products in the Chinese market [129]. Transforming an existing community into a 100 % net-zero carbon environment poses considerable challenges, particularly in addressing ongoing heat supply deficits. Insufficient technology can result in nesting, interruptions, and other setbacks during the housing construction process [130]. At the heart of constructing ZCC is the incorporation of renewable technologies into small-scale developments. However, these technologies are currently viewed as unreliable [131], and their implementation is often perceived as detrimental to profitability, external space, and aesthetics [132].

Experienced professionals serve as strong motivators in steering communities towards sustainability goals. While vendor training for staff members is essential, managing training internally through recruiting professionals with adequate research, innovation, and competency skills can be more effective in the long term and potentially less costly [133]. Implementing ZCC policies poses greater challenges than simply setting targets, for at least two main reasons. Firstly, the lack of clarity and appropriateness in ZCC policies remains a significant issue,

Table 7
Barriers to the process of promoting ZCC.

Barrier	Manifestation	Ref.
Economic	Higher initial cost	[6]
	Uncertainty of long-term economic returns	
	High-end product prices/tariffs	
	Insufficient incentives for end-users	
	Insufficient financial support	[15,104]
	Costs are too high	[104]
	Economic viability	[105]
Administrative (Political and legal)	Lack of cost data, lack of financial incentives, lack of sales data	[16]
	Lack of policy support	[6]
	Insufficient incentives for private developers	
	Renewable energy legislation issues	
	Lack of policy clarity	[106]
	Legislation (unclear definition of zero carbon, too many government policies, lack of understanding of requirements)	[16]
	Lack of understanding of zero carbon principles, insufficient practice, unclear policies, conflicting priority management	[101]
Socio-cultural	Lack of public awareness	[6,103]
	Lack of industry awareness	[6,15]
	Lack of customer recognition	[6,104]
	Risk aversion culture	[6,105]
	Insufficient public and stakeholder participation	[106]
	A culture built around current regulations, lack of confidence in emerging technologies, insufficient customer demand, and management not proactive	[16]
	Lack of clear definitions	[6,106,107]
Technological/Skill and knowledge	Lack of skilled labor	[6]
	Lack of zero-carbon technologies	[6,103]
	Inadequate design	[15]
	Skills shortages and knowledge gaps related to planning, designing, building, and maintaining homes	[107]
	Reluctance to change traditional designs, reduced amount of design data, and not enough aesthetics in renewable technologies	[16]
	Industry immaturity	[104]
	The nature of the house-building industry and resistance to change	[16]
Environmental	Practitioner resistance to fossil fuel policies	[108]

primarily attributed to policymakers [134]. Secondly, there is low awareness and acceptance of ZCC among market participants, influenced by inadequate guidance from professionals and limited manufacturing capacity [135].

5.5. Socio-cultural barriers

In many developing countries, there is limited awareness of the importance of sustainable building practices and a lack of understanding regarding the benefits of high-performance, sustainable buildings, which results in insufficient public and industry involvement in the development of ZCC [136]. The scope of “zero carbon” is not yet uniformly defined and remains more conceptual than practical, with related terms such as “zero carbon,” “net-zero carbon,” “zero emissions,” and “near-zero energy” often used interchangeably. Conceptual inconsistencies reveal the fragmentation and complexity of zero-carbon building knowledge [137]. A precise definition of zero carbon is essential and a measurement and benchmarking system should be developed, and there is also a need to clarify the scope of zero carbon [6].

The high investment costs associated with developing ZCC and the elevated prices of zero-carbon products contribute to limited public

demand and low enthusiasm for participating in these communities [111]. The Sponge Sustainability Network identifies a growing public interest in adopting sustainable lifestyles, but awareness gaps about the sustainability benefits of ZCC hinder widespread adoption [138]. Increasing public demand can incentivize housebuilders to voluntarily integrate sustainable features into developments, highlighting the need to enhance cultural awareness among the public. Establishing a sustainable culture around ZCC requires robust government initiatives, such as strong planning policies and financial incentives [139]. Policies like Planning Policy Statement 1 (PPS 1), along with existing government sustainability initiatives in the built environment, can foster a zero-carbon culture [140]. However, cultural resistance not only discourages community support for zero-carbon initiatives but also limits developers’ ability to innovate and implement sustainable practices [131,141]. Changing the attitudes and behaviors of developers and users remains a significant challenge.

5.6. Summary and discussions

The construction of ZCC faces barriers across five main aspects: administrative, economic, skills and knowledge, cultural, and industrial. These barriers can be further categorized into technological, legislative, standards and norms, economic, market, professional, and cultural barriers, among others. Fig. 11 illustrates the interrelation between these barriers, which often reinforce each other, posing significant resistance to sustainable urban development models [142].

In the context of China, various economic drivers and barriers significantly influence the development of ZCC. Key economic drivers, such as commercial viability, underscore the importance of ensuring that ZCC initiatives are financially sustainable and appealing to investors and other stakeholders. Conversely, barriers, particularly the high initial costs associated with implementing advanced technologies and sustainable practices, present considerable challenges that can hinder progress in this field. Furthermore, legislative factors, including robust policy support from the government, are critical to fostering an environment conducive to the growth of ZCC. Effective legislation can incentivize green technology investments, simplify regulatory processes, and provide a framework for sustainable construction practices. To successfully advance the development of ZCC, it is imperative to address a synergistic combination of both economic and legislative factors. This multifaceted approach will enable the formulation of strategies that not only enhance economic efficiency but also ensure adequate legislative backing. Skill and knowledge barriers are relatively easier to address compared to other barriers due to fewer conflicts of interest. However, the industry faces significant technical uncertainties, necessitating industry practitioners to acquire sufficient skills and knowledge to enhance building energy efficiency and gain public trust. To support the development of ZCC, it is crucial to raise awareness of socio-cultural among governments, developers, and the public. Overcoming public perception barriers is essential for ZCC success, as user behavior is a significant factor in building energy efficiency, potentially contributing to substantial energy savings ranging from 62 % to 86 % [143,144].

Achieving ZCC requires comprehensive institutional and policy support across multiple levels of governance, alongside user behavior-centered and innovation-driven approaches [145]. These communities are complex socio-technical systems that encompass not only green or zero-carbon products but also innovative and integrated processes involving stakeholders throughout the building life cycle [52]. Therefore, cities must consider multiple institutions, actors, and governance levels when devising strategies to reduce greenhouse gases, particularly in the context of scaling up community-wide efforts towards zero carbon [146]. These strategies involve: 1) clarifying the roles of different governance levels and policies; 2) providing financial and institutional support for city-level initiatives; 3) coordinating the diverse array of public and private actors engaged in decarbonization to facilitate cultural diffusion [147,148].

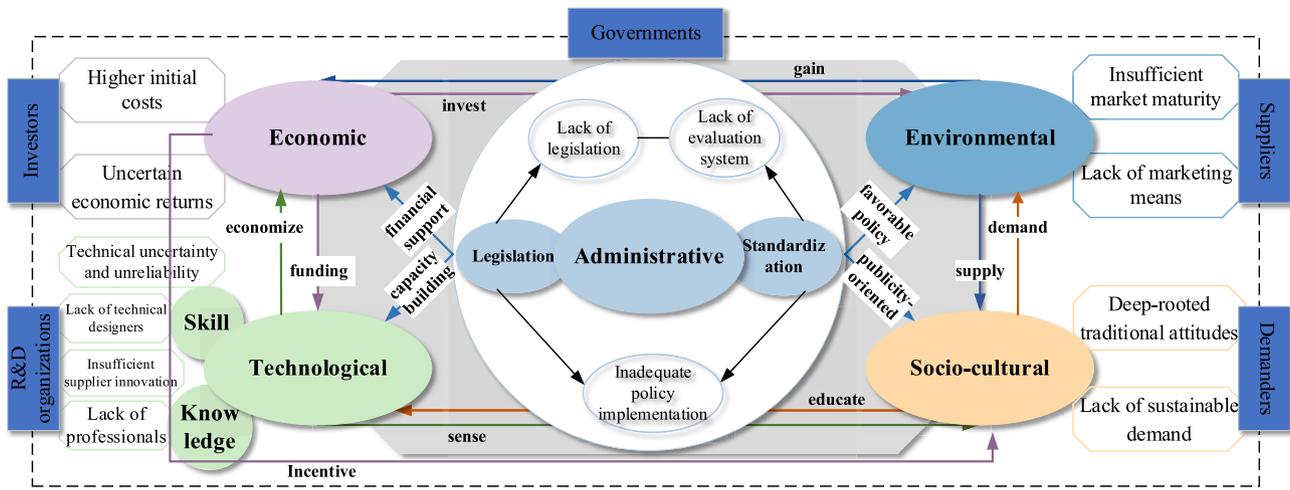


Fig. 11. Correlation between barriers to ZCC development.

To successfully implement these strategies, synergistic mechanisms must be established among stakeholders across various sectors: 1) Demand side: including the public, households, customers, investors, and government; 2) Supply side: encompassing developers, professional consultants, contractors, facility managers, and energy producers and suppliers; 3) Regulatory side: involving government departments and agencies responsible for regulations; 4) Institutional side: comprising financiers, bankers, universities, and professional groups. Only through the concerted efforts of society as a whole can we achieve long-term promotion of zero-carbon construction in alignment with sustainable development goals [101].

6. Implementation strategies and future recommendations

Previous research has examined barriers to achieving ZCC from various perspectives. Based on this research, a comprehensive strategic framework has been developed, addressing user behavior, building energy efficiency, technology adoption, and macro-level industry practices. This framework can guide future government policies and industry initiatives [6].

Zhang identified four key aspects in the system for constructing low-carbon community: technical, organizational, institutional, and cultural dimensions [149]. This study categorizes barriers to constructing ZCC into five aspects: administrative, knowledge and skills, cultural, economic, and industrial. Therefore, the framework for developing ZCC

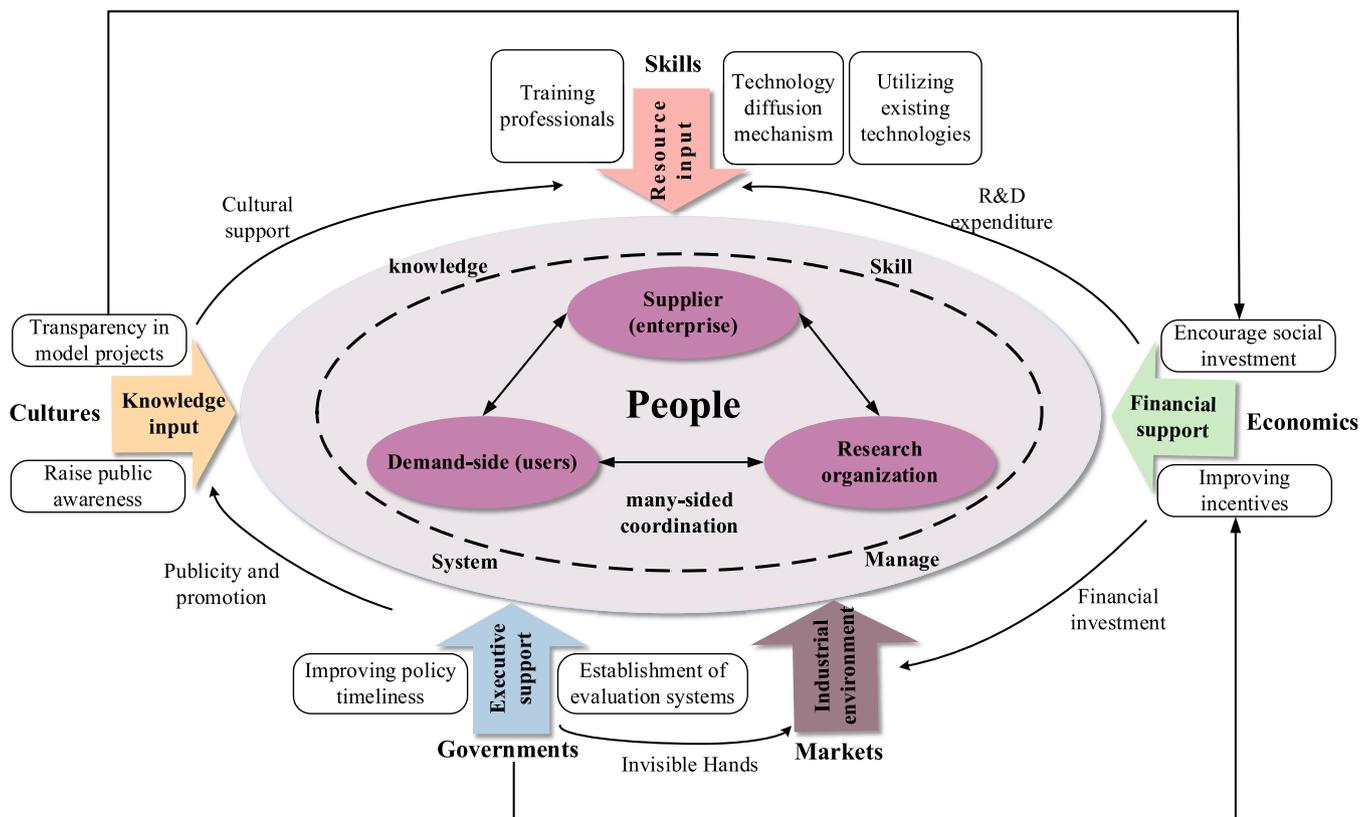


Fig. 12. Proposed framework for ZCC development.

includes economic considerations alongside these four aspects. To effectively build ZCC, targeted responses are needed within social, economic, and cultural contexts. Fig. 12 illustrates the development framework, with “people” at the center. The framework positions enterprises (supply side), users (demand side), and research institutions as central actors, fostering synergies among knowledge, technology, systems, and management. Surrounding this core, resource and financial inputs, knowledge exchange, administrative support, and an enabling industrial environment interact to influence technology, culture, economy, government, and market dynamics, facilitating community construction.

6.1. Increasing the reliability and stability of existing zero carbon technologies

To address skills and knowledge barriers in community building, it is essential to streamline the utilization of existing zero-carbon technologies, optimize integrated design and system compatibility, and establish mechanisms for technology diffusion.

China’s Research and Development (R&D) strategy prioritizes enhancing energy efficiency and reducing carbon intensity [150]. Drawing from global practices, many countries and regions have promoted green technologies, such as ground-source heat pump technology [151] and energy-efficient equipment and appliances utilizing natural ventilation [152]. These technologies are recognized for their effectiveness in lowering operational energy consumption and carbon emissions. Developing clean energy is crucial for balancing energy supply and reducing carbon emissions [153]. In recent years, China has made significant strides in advancing various zero-carbon technologies, including wind power, hydropower, nuclear power, and biomass, alongside efforts in carbon-neutral technologies and low-carbon treatment of coal combustion [118]. Simultaneously, China aims to enhance its energy structure while encouraging active participation in optimizing the existing ecological system. This involves innovation and promotion of zero-carbon technologies such as photovoltaics, research and development of energy internet platforms, and systematic improvements in zero-carbon energy technologies [154]. In technology development, the initial focus centered on the energy balance and consumption within individual buildings, gradually shifting towards a broader scope that includes regions, communities, and cities. Calibration of an urban-scale building energy model is crucial for advancing building energy efficiency codes and policies to reduce carbon dioxide emissions whereas the accuracy of the model is challenged by performance gaps resulting from sparse data and uncertainties in modeling [155]. Accurately calculating energy consumption and production at this scale requires advanced tools and models capable of multi-level operation and urban-scale analysis, with UBEM simulation tools now widely used for community design and analysis [156–158].

An information management platform system should be established to create a cross-sectoral digital information network for the community. This system would integrate data from buildings, energy networks, planning, environmental systems, transportation infrastructure, and socio-demographic indicators [159]. Additionally, using a collaborative optimization design approach for stand-alone and grid-connected zero/low energy buildings and their energy systems to reduce design costs and improve safety [160–162]. Use solar thermal electric cooling technology, which can be directly powered by photovoltaics (PV), is environmentally friendly, maximizes energy efficiency and reduces fossil energy consumption in buildings [163].

The government should collaborate with industry and universities to develop guidelines and standards that support technology research and development. This includes increased use of energy simulation tools and new materials, along with more investment and support for development. Additionally, the government should provide subsidies to encourage developers to use efficient equipment and incentivize the public to purchase energy-efficient appliances. Zero-carbon buildings

currently lack professionals to ensure energy efficiency from design to operation. Therefore, specialized training in the design and implementation of zero-carbon technologies needs to be strengthened to develop a skilled workforce capable of operating ZCC effectively [6].

6.2. Improving the consistency and timeliness of zero-carbon community policies

While community building becomes feasible once technical barriers are overcome, “soft” issues such as legislation, finance, and culture present more substantial challenges. Research has shown that once a comprehensive legal system is established, the construction industry can rapidly meet government goals, as developers are compelled to abandon their reluctance to change traditional designs during the policy phase [15]. Therefore, legislation is crucial to ensure timely and consistent policies, avoiding the adverse effects of outdated or inconsistent regulations on technological research and development, as well as public perceptions.

As the economic effects of different technologies can change over time based on government policy guidance, governments need to issue timely guidelines to facilitate the development and use of advanced technologies. Outdated policies can cause delays in the adoption of various standards, and lapses in policy documents during the construction of ZCC can reduce builders’ motivation and hinder monitoring efforts. In terms of legislation, climate legislation is an effective means to ensure the achievement of carbon-neutral targets as planned [164]. China should accelerate the process of enacting climate change laws and improving relevant market-based systems to effectively mitigate the greenhouse effect, address climate change, and achieve carbon neutrality. Incorporating climate change into social development work plans and enhancing relevant laws and regulations will help raise national awareness of carbon neutrality. Additionally, implementing market-based climate policies, such as carbon taxes, subsidies, and other economic instruments, will promote long-term emission reductions [118].

6.3. Developing the market-based financial support system for zero carbon community

Financial support from governments is a major source of funding for research and development of advanced technologies and construction projects. Economic incentives can significantly drive the rapid development of ZCC. However, ZCC projects, which emphasize local development effects, face greater economic constraints than traditional real estate projects, such as high costs and low returns. The substantial cost of research and development for zero-carbon technologies makes the return on investment in ZCC a high-risk endeavor for local investors and developers. Based on this, local governments need to play a dual role as implementers and facilitators in ZCC projects. They should formulate financial strategies and promote incentives to alleviate the financial pressure on residents, thereby supporting zero-carbon development and facilitating behavioral and lifestyle changes [19]. To encourage more developers to participate, the government should offer additional incentives, such as subsidies, tax reductions, and funding for the adoption of zero-carbon technologies. The EU’s coordination of Energy Performance Certificates (EPCs) plays a vital role in transforming buildings into carbon-neutral assets, which is essential for addressing climate change and improving energy efficiency [165]. Similarly, China can draw from international experiences to implement graded certification systems that encourage the development of ZCC.

In addition, the introduction of peak carbon and carbon-neutral targets has given new impetus to the development of green finance [166]. China’s promotion of ZCC necessitates improving the green financial system and balancing the relationship between the government and the market. Enhancing the planning and design of green financial policies can be achieved by integrating finance, fiscal policy, and

environmental protection, establishing appropriate incentive and constraint mechanisms, and ensuring the optimal allocation of resources. Additionally, the government should strengthen cooperation with private capital to address resource shortages for green and low-carbon development. This involves establishing a unified and standardized green financial market, promoting pilot projects in green finance, and leveraging the guiding and incentivizing role of government capital [118].

6.4. Establishing an assessment and certification framework for zero-carbon community

The development of ZCC in China is still in its infancy, and the lack of a reliable assessment and certification system, along with clear performance standards, is hindering the full implementation of these communities. Establishing a comprehensive assessment framework is crucial to addressing challenges such as program inefficiency, difficulties in securing financial support, and the lack of data.

Developers should provide carbon ratings for buildings upon the delivery of ZCC, serving as an indicator of whether the community meets zero carbon emission standards. Therefore, establishing comprehensive construction specifications and evaluation indicators is necessary to ensure standardization throughout the entire process, from construction to delivery. Improving the energy efficiency of monitoring and evaluation systems, both for new building estimates and for audits of existing buildings by relevant authorities, facilitates government oversight and raises public awareness of the carbon emissions associated with ZCC [6]. Establishing an assessment framework for ZCC, encompassing standardization and zero-carbon building certification, can significantly enhance the motivation of developers. Through sustainable design, the impact of buildings on the natural environment can be mitigated, by regulating construction activities, improving building safety performance, and standardizing the industry system involving ZCC.

6.5. Fostering professionals and organizations related to zero-carbon community

The provision of zero-carbon services to homeowners by professionals and organizations is critical to the spread and development of ZCC. The key to developing the new and emerging phenomenon of ZCC in developing countries is the use of technological tools that are adapted to local conditions to maximize social, economic, and environmental benefits [19]. To effectively promote green technologies and strategies, it is crucial to establish a technical team comprising senior management, engineering and technical staff, and finance and facilities management personnel. This team should coordinate efforts and institutionalize frameworks to ensure comprehensive strategy implementation. The professionalism of this team is vital, as it determines the success of installing, operating, and maintaining technologies. Strengthening the training of experts in zero-carbon technologies is essential for achieving these goals. Enhanced communication between industries and communities can facilitate the sharing of experiences and help overcome cultural, skills, and knowledge barriers. Learning from the practices of other countries and regions, such as Singapore, which has effective measures to promote energy and carbon dioxide savings in buildings, can provide valuable insights and experiences in technology adoption [19].

Governments need to reform education and promote a strategic transformation of built environment education. Educators need to embrace new interdisciplinary education and work practices before teaching and training. In addition to this, students, non-governmental organizations, and practitioners need to work with educators to rapidly increase their skills in acquiring zero-carbon knowledge [167]. For the development of ZCC, it is essential to formulate a series of professional training policies to build up human resources, stock up innovative knowledge, expand knowledge, incorporate relevant knowledge

into the content of continuing education for professional and technical personnel, and encourage institutions of higher learning to add relevant courses.

6.6. Popularizing knowledge and information on zero-carbon community

Since the energy consumption has been concentrated on the operational phase of house occupation, an essential lifestyle change by the occupants (typically with no specialist knowledge) has to be made to achieve energy efficiency, carbon reduction and climate improvement [90]. Public participation should begin with community planning and continue throughout the process of community implementation. In promoting ZCC, public-private partnerships should be strengthened to improve the governance of community building, fully engage the energy, transportation, waste management, and water management sectors, and sustain the effective application of green technologies/services [19].

Insufficient public knowledge and information about ZCC often result in low participation rates. The presence of inconsistent concepts further complicates public understanding of these communities. Therefore, it is crucial to first clarify the definition of a ZCC and establish a comprehensive knowledge base for the industry. This will facilitate public education and guide user participation in the development of ZCC. Educational initiatives and demonstration projects play a pivotal role in raising public awareness and promoting energy-saving behaviors. Transparency in energy use data can also enhance awareness among building occupants, encouraging behavioral changes based on factual information. To stimulate market demand, both government and industry need to actively promote the benefits of ZCC to the public [16].

Occupant behavior is a significant source of uncertainty in building energy performance simulation. Therefore, it is essential to incorporate occupant behavior into building design practices through effective modeling techniques [168]. In 2021, the Hong Kong Government unveiled the Hong Kong Climate Action Blueprint 2050, highlighting the significant challenge of achieving carbon neutrality by 2050 and emphasizing the need for community-wide participation. The blueprint encourages the public to adopt low-carbon lifestyles by practicing energy conservation, waste reduction, and recycling in their daily routines. Public education is recognized as a critical strategy for promoting behavioral change, ensuring that individuals understand how to minimize carbon emissions and address key climate change issues, thereby fostering sustainable development [6]. In educating the public, the economic and health benefits of adopting a zero-carbon building or lifestyle can be emphasized, and the consequences of not adopting a zero-carbon building or lifestyle can also be clarified so that the public can have a more complete understanding of a ZCC and be better informed for public decision-making.

6.7. Pathway blueprint for promoting zero-carbon community

ZCC needs to manage a complex set of interdependencies, and the development of a zero-carbon vision will require new forms of cooperation between cities, utilities, and other energy sector players, as well as transportation providers, building owners, and technology companies [159].

Building a community needs to focus on the synergistic drive of social, environmental, ecological, and economic aspects [17], and at the same time, to reduce carbon emissions to zero as stipulated by the Chinese government, it is also necessary to look for powerful measures for zero-carbon development at the behavioral, institutional, and structural levels through the cooperation of the government, enterprises, and the public. According to China's management theory, three sets of mechanisms are established: the government-administration system, the enterprise-market mechanism, and the public-society mechanism under the ZCC management framework, which requires stakeholders to perform their respective functions in different areas and at different

levels, as shown in Table 8. It is necessary to organically combine these three mechanisms, with the government taking the lead and the participation of for-profit enterprises and the public to conserve and rationally utilize resources and energy.

The integrated efforts of multiple parties are crucial in the development of ZCC. Collaboration between government and industry is essential to support their construction, as no single entity can independently achieve this goal. ZCCs are established through strategies that address carbon emissions during the building construction process, reduce emissions from building operations, and enhance public awareness of sustainable practices [116].

To summarize, to overcome the obstacles encountered in the process of building a ZCC, a “macro-meso-micro” implementation pathway is proposed in light of China’s national conditions and existing policies, as shown in Fig. 13. To achieve global carbon emission reduction and protect the ecological environment, as well as to improve the people’s aspirations for a better life to create a humanistic environment, the macro vision is to build a ZCC. Given the complexity of building a ZCC, it is necessary to break down the goal into meso-initiatives and communicate them to the government, enterprises, and the public, who will then formulate the three mechanisms of “administration-market-society”, which will be realized by the four major stakeholders, namely, the supply side, the demand side, the government, and the scientific research institutes, each of which will play its role in the realization of the three mechanisms. To realize the three mechanisms, micro-measures need to be taken, such as land development, policy incentives, industry guidance, technology upgrading, awareness-raising, and other top-down efforts by the government, bottom-up efforts by the public, and horizontal efforts by profit-seeking enterprises.

The implementation pathway underscores synergies among stakeholders to maximize regulatory, implementation, and support functions across government, industry, and non-governmental organizations (NGOs). This approach operates within the context of natural and human environments, addressing challenges and optimizing measures in five dimensions: administration, economics, skills and knowledge, culture, and industry: 1) micro-level measures focus on achieving technical zero carbon emissions; 2) meso-level initiatives support the delivery of zero-carbon projects; 3) macro-level visions guide industry practices toward zero carbon transitions. Identified drivers and barriers, along with corresponding measures, initiatives, and visions, form a multi-level strategic framework to achieve zero carbon goals. This framework emphasizes policy guidance, business strategies, and stakeholder collaboration to explore pathways for ZCC. Key elements include structural transformations in energy supply, the establishment of comprehensive zero-carbon systems encompassing energy, buildings, transportation, finance, humanities, and research, and lifecycle management for zero-carbon achievement to foster synergistic development of environmental, social, and economic systems.

7. Conclusions and future studies

This paper provides an in-depth examination of ZCC, focusing on their connotation, policy frameworks, development barriers, and real-

Table 8
Management model with government, business, and public participation [21].

	Government	Enterprise	The public
Behavioral level	Incentive and subsidy	Improving service	Operate in coordination
Institutional level	Policies support Traffic management	Faultless management	Participation ensures
Structural level	Compact city Land exploitation Environment shaping	Improving technology	Material Compensate Changing ideas

world applications. By critically analyzing these dimensions, the study sheds light on the essential role of ZCCs as integral to China’s sustainable development agenda. The main findings are as follows.

(1) China has enacted and implemented several national-level policies, including guiding documents, laws and regulations, and standards, there remains a critical need to establish a unified definition of ZCCs and standardized metrics for assessment; (2) The Chinese government has carried out various initiatives to promote ZCCs, leveraging successful international examples to create a framework tailored to national conditions. Notable projects, such as the Zero Carbon Pavilion at the Shanghai World Expo, showcase innovative practices inspired by the Beddington community in the UK, exemplifying effective ZCC development; (3) In combination with China’s national conditions and policy characteristics, the PESTEL model is established to analyze the several barriers hindering ZCC implementation in China, including administrative (i.e., insufficient legislative strength), economic (i.e., a lack of financial support for ZCC initiatives), socio-cultural (i.e., limited public awareness and engagement), technological (i.e., inadequate innovation and a lag in technological development relative to industry needs), environmental (i.e., an immature market with insufficient industry participation); (4) A “micro-meso-macro” ZCC development pathway is proposed, and key recommendations include enhancing public awareness, establishing rigorous certification and assessment standards for ZCCs, investing in professional training, increasing funding mechanisms, and improving the timeliness and consistency of relevant policies.

Despite the insights gained, the study has some limitations: (1) The term “ZCC” has received attention only in recent years. Therefore, when summarizing the relevant policies of ZCC, the policies and research on low-carbon communities are referenced. While ZCC demand higher standards than low-carbon communities, the relationship between the two underscores the necessity of referencing LCC research to enhance the completeness of this study; (2) Although a literature review was conducted, the conclusions drawn are broad rather than scientifically rigorous due to variations in journal quality and scholarly perspectives. To improve the analysis of ZCC in China, this study incorporates Chinese papers, which provide more comprehensive insights into the development status; (3) The focus on the keyword “Zero Carbon Communities” revealed a predominance of literature centered on low-carbon and zero-carbon buildings rather than communities. Nonetheless, ZCCs are fundamentally rooted in buildings, and insights from zero-carbon building research can inform community-level strategies.

ZCC involves multiple stakeholders, advanced technologies, and stringent management requirements. Future research should focus on rationalizing the synergistic relationships among stakeholders—government, investors, and users—and identifying both barriers and drivers for their collaboration. Additionally, future studies should consider to develop methodologies to accurately measure carbon emissions from ZCC, with comparisons to international standards. Moreover, the use of UBEM in ZCC computing energy will be studied in the future, including its workflow and related simulation tools, to establish optimal carbon emission benchmarks specific to ZCC. By addressing these future research avenues, we can further advance the knowledge base surrounding ZCC and contribute to the successful implementation of sustainable development practices in China and beyond.

CRediT authorship contribution statement

Lin Zhou: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Shun Li:** Writing – original draft, Methodology, Investigation. **Zhengxuan Liu:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yuekuan Zhou:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Bao-Jie He:** Writing – review & editing, Supervision, Methodology, Investigation. **Zhenya Zhang:** Writing – original draft,

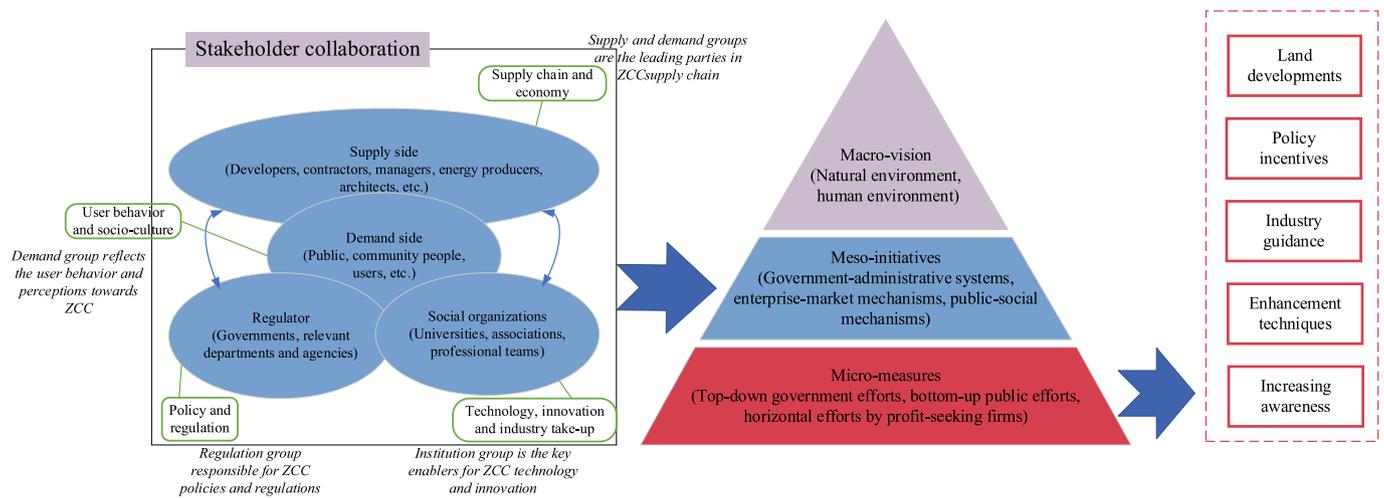


Fig. 13. The implementation pathway diagram of ZCC.

Methodology, Investigation. **Hanbing Wang:** Writing – original draft, Methodology, Investigation. **Guoqiang Zhang:** Writing – review & editing, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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