REVIEW

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# Overview of research and development of nearly zero energy buildings in China

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**Abstract:** In recent years, the promotion of nearly zero-energy buildings (NZEBs) in China has emerged as a crucial step for the building industry in shifting towards a green and low-carbon future. Starting from scratch, the development of NZEBs in China has included the application and fundamental research, the compilation of national and local standards, and the rapid emergence of projects encompassing 23.89 million square meters nationwide. These efforts have yielded preliminary results in national standards, technology systems, technical roadmaps, and large-scale project demonstrations. However, challenges, including further reducing incremental costs, developing industries for retrofitting existing buildings into NZEBs, and expanding the range of policy incentives, remain to be addressed. This article provides an overview of the last decade's progress in NZEBs in China, covering key technological research, policy development, engineering demonstrations, and the current industrial development status. Finally, the prospects of the NZEB industry are discussed.

**Keywords:** nearly zero-energy buildings (NZEB), overview, cost, incentive policy, demonstration

## INTRODUCTION

The role of the construction sector in global energy consumption and carbon emissions is significant. As per a report from the United Nations Environment Programme (UNEP), the energy demand of the construction sector reached 127 EJ in 2020, contributing to 36% of the global end-usage. The sector's carbon emissions from building operations, construction, and material production were about 11.9 Gt, accounting for 37% of energy-related carbon emissions, with an ongoing upward trend [1]. Data from the International Energy Agency (IEA) revealed that in 2019, the operational phase of buildings in China produced approximately 2.1 billion tons of $CO_2$, representing about 20% of the nation's total carbon emissions. As urbanization and development continue in China, both the volume and share of building-related carbon emissions are likely to increase.

The significance of nearly zero-energy buildings (NZEBs) as a key technological concept for advancing building energy efficiency in China is becoming increasingly apparent, especially in light of China's ambition to achieve "carbon peaking and carbon neutrality" goals. Since the initiation of China's first building energy efficiency standard in 1986, a "three-step" strategy for building energy efficiency has reached its objectives by 2015, marking 30 years of progress, and energy efficiency in buildings has improved by 65% compared with the levels of the 1980s. This improvement has been instrumental in mitigating the rapid growth of energy consumption driven by China's swift urbanization. However, the need for new development goals and pathways remains critical for further advancements.

Over the past two decades, there has been a global surge in research on passive houses, ultra-low energy buildings, and zero-energy buildings [2,3]. Introduced to China in 2010, the German concept of passive houses significantly influenced China's engineering practices. In 2013, as part of the US-China Clean Energy Research Center (CERC) Building Energy Efficiency (BEE) Program, the China Academy of Building Research (CABR) undertook systematic research into the concept of NZEBs, by incorporating international experiences and adapting them to China's unique climate conditions, social patterns, and economic attributes. This led to a milestone in 2014, with the completion of China's first "nearly zero energy" pilot commercial building in Beijing.

The research conducted by the CABR has been pivotal in defining the concept of ultra-low energy buildings in China. This included establishing an indicator system and identifying key technologies. In 2015, the "Technical Guideline for Ultra-Low Energy Residential Buildings" (referred to as the Guideline) was compiled. This Guideline sets forth specific building energy targets, such as heating and cooling demands in various climate zones, and outlines performance-oriented design methods with detailed instructions. This framework has been instrumental in supporting a series of pilot projects for ultra-low energy buildings across China, propelling the enhancement of building energy efficiency standards towards the goal of nearly zero energy.

Further advancements were made under the National Key Research and Development Program of the Ministry of Science and Technology, led by CABR and participated by 29 other institutions. This comprehensive research covered fundamental theories, definitions, indicator systems, design methods, construction techniques, high-performance building components and equipment, renewable energy integration, demand-based precise control, and testing and evaluation. A significant outcome of this research was the creation of the "Technical Standard for NZEBs". This standard categorizes three types of NZEBs—ultra-low energy buildings, NZEBs, and zero-energy buildings—in a standardized manner. The definitions and mandatory indicators not only align with China's "three-step" strategy for building energy conservation but also effectively support China's medium and long-term goals for enhancing building energy efficiency by 2025, 2035, and 2050.

Quantitative studies on the contribution of NZEBs to China's carbon peaking and carbon neutrality goals suggested that accelerating NZEB development can significantly reduce peak energy consumption and carbon emissions in the building sector. This approach could advance the timing of the carbon peak by approximately 5 years. By implementing comprehensive measures such as ensuring new buildings meet NZEB standards by 2025 and achieving zero energy/carbon by 2050, retrofitting existing buildings, promoting building electrification, and applying renewable energy, it is feasible for China to reach its carbon emission peak and achieve carbon neutrality in the building industry as planned [4,5].

The evolution of NZEBs in China is rapid and dynamic. In recent years, Chinese researchers have been active in summarizing and comparing NZEB definitions between China and developed countries, outlining supportive policies, compiling national and local standards, and offering development recommendations [6–8]. However, there is still a shortage of comprehensive overviews and analyses of the current development status of industries related to NZEBs. The aim of this paper is to provide an updated review of the research and development status of NZEBs in China, including key technological research progress, policy development, engineering demonstrations, and the current industrial status, as well as to explore future development recommendations.

## DEFINITIONS OF NZEB

"Nearly Zero-Energy Building" (NZEB) is internationally recognized as a building with significantly higher energy efficiency than standard buildings. However, the specific interpretation of "nearly zero" varies considerably among countries.

In China, the concept of NZEBs has evolved from over 30 years of effort in building energy efficiency and is aligned with the nation's goals of achieving carbon peaking and carbon neutrality. After more than a decade of research and practical engineering experience with NZEBs in China, substantial progress and valuable insights have been gained, though not without controversies and challenges. Against this backdrop, and informed by an overview of international developments on the subject, this article reviews the key technological research advancements, government policies, engineering practices, and industrial development of NZEBs in China. It also provides a perspective on the future trajectory of NZEB development in the country.

Table 1 [9–14] summarizes the diverse definitions assigned to NZEBs across different countries. In Europe, the US, and Korea, NZEBs were defined using absolute energy values, while Denmark, Canada, and Japan used relative energy reduction proportions. The Chinese standard for NZEB stipulated that residential buildings are to be determined by absolute energy consumption, whereas commercial buildings are assessed based on relative energy-saving rates. Furthermore, the scope of energy items included in the NZEB assessment varies internationally. For instance, Germany's Passive House and the NEZBs in the US and Canada considered all building energy consumption, including heating, ventilation, air conditioning, lighting, domestic hot water, elevators, and plug loads, with the US additionally accounting for outdoor lighting. In contrast, most European countries, Japan, Korea, and China, focused on energy consumption related to building services like heating, cooling, ventilation, lighting, and domestic hot water, but excluded socket and cooking energy. Notably, China's NZEB energy use calculation includes elevators, heating and cooling systems, ventilation, lighting, and domestic hot water, which were different from European countries and Korean standards.

The primary energy requirements for NZEBs also vary significantly by country, especially for residential buildings, as shown in Figure 1 [9,15]. The variations are substantial even within European countries, owing to different energy boundaries and calculation methods, making direct comparisons challenging. Denmark, the first country to propose the ZEB concept, sets a stringent energy limit of 27 kW h/($m^2$ a), whereas other countries typically range between 50 and 120 kW h/($m^2$ a). Finland has the highest threshold at 158 kW h/($m^2$ a). Despite a later start in NZEBs development, China's energy consumption limits are relatively strict, which were set at 55 kW h/($m^2$ a).

The global push towards high-performance buildings as a means to reduce carbon emissions in the building sector is a widely accepted strategy. As depicted in Figure 2 [9,13], most European countries have mandated that new buildings meet NZEB standards by 2020, with Denmark leading the way by aiming to fully achieve

**Table 1** The definitions and energy boundaries of NZEBs and ZEBs in different countries and areas

| Nos. | Countries/Area | Definition | Energy boundary |
|---|---|---|---|
| 1 | Europe | NZEB: a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. Primary energy use 50–90 kW h/($m^2$ a) for single family house; 80–100 kW h/($m^2$ a) for office building [9]. | Heating, cooling, ventilation, domestic hot water, and lighting. |
| 2 | Denmark | NZEB: a building that reduces the energy consumption of the building by 75% in relation to the 2006 level [10]. | Heating, cooling, ventilation, domestic hot water, and lighting. |
| 3 | Germany | Passive House: a building that ensures comfort while achieving an energy saving of more than 90% compared with existing buildings, and an energy saving of more than 75% compared with new buildings [11]. | Total building energy consumption, or building cooling and heating load, alternatively meet the standard. |
| | | NZEB: a building that does not use more than 40% of the annual primary energy consumption of the corresponding reference building (for refurbishments: no more than 55%). | Heating, cooling, ventilation, domestic hot water, and lighting. |
| 4 | US | ZEB: an energy-efficient building, for which, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy [12]. | Total building energy consumption: at minimum, including heating, cooling, ventilation, domestic hot water, indoor and outdoor lighting, plug loads, process energy, elevators and conveying systems, and intra-building transportation. |
| 5 | Canada | Net-zero energy ready building: a building that saves more than 80% energy compared with current energy efficiency standards. Net-zero energy building means on-site (or near-site) renewable energy systems produce the remaining energy needed [13]. | Total building energy consumption: all energy sources used to keep buildings warm, cool, ventilated, lit, and powered. |
| 6 | Japan | NZEB: a building that reduces energy consumption by more than 75% compared with conventional buildings [14]. | Compliance is determined based on relative energy-saving rate, including heating, ventilation, air conditioning, lighting, domestic hot water, and elevators. |
| 7 | Korea | NZEB: a building that is rated class 1 or above according to the “Building Energy Efficiency Grading Certification Standard”. | Building service-related energy consumption, including heating, ventilation, air conditioning, lighting, and domestic hot water. |
| 8 | China | NZEB: a building that significantly reduces energy demand through passive technologies, improves energy efficiency through active technologies, and highly utilizes renewable energy. Primary energy use indicators: $\leqslant$55 kW h/($m^2$ a) for residential buildings; energy efficiency improvement rate $\geqslant$60%. | Energy consumption related to building services, including heating, ventilation, air conditioning, lighting, domestic hot water, and elevators. |

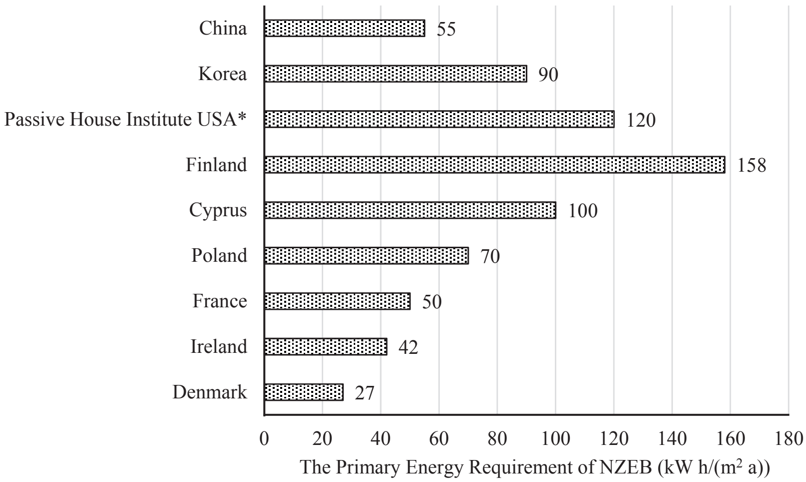


**Figure 1** Limits on primary energy consumption for NZEBs in various countries [9,15]. *: In the US, the Passive House Institute (PHI) standards for building energy consumption encompass all energy usage. In contrast, other countries typically focus only on energy consumption related to building services.

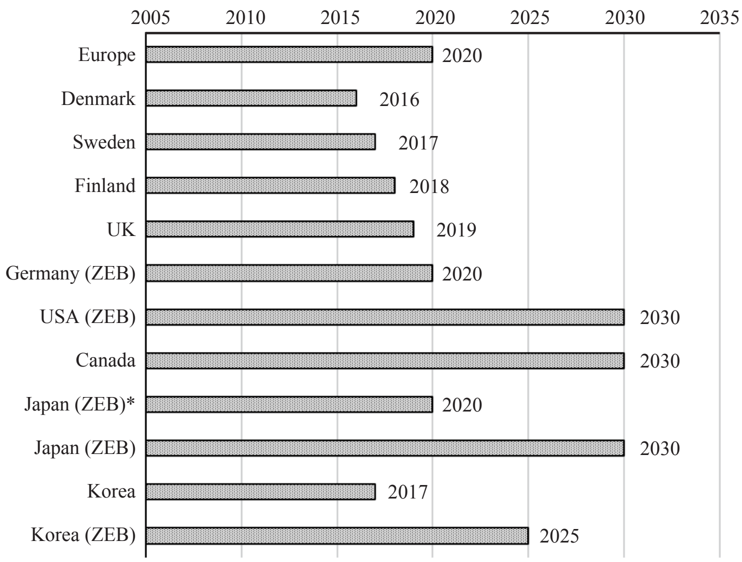


**Figure 2** Target year for newly built buildings to achieve NZEBs [9,13]. *: Japan has set an ambitious target to achieve zero-energy buildings for all new constructions by 2020. However, this goal is specifically tailored to commercial buildings.

NZEB status in 2016. Similarly, the US, Canada, and Japan have set goals to achieve nearly zero or zero energy use in buildings by 2030. Korea reached its NZEB target in 2017 and is on track to achieve zero energy building targets by 2025.

While the specific definitions of NZEBs vary worldwide, the core principle of high energy efficiency remains consistent. NZEBs significantly reduce energy consumption and carbon emissions in the building sector, making them a crucial component in helping countries achieve their carbon neutrality goals. This approach has gained widespread recognition and has been actively implemented internationally.

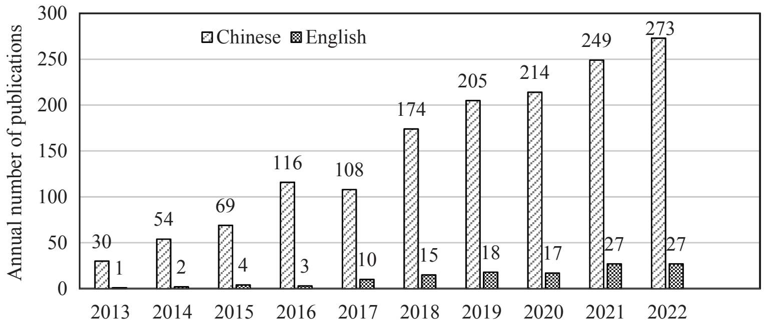


**Figure 3** Annual number of publications on NZEBs in Chinese and English.

## TECHNICAL FACTORS FOR NZEBS

The research on NZEBs in China can be categorized into three distinct phases.

**2010–2015**: The start-up period, which focused on defining ultra-low energy buildings, key technologies, and technology integration. **2016–2019**: The rapid development period, emphasizing R&D in key technologies, products, tools, and project demonstrations. In 2019, the Ministry of Housing and Urban-Rural Development published *The Technical Guidelines for Passive Ultra Low Energy Green Buildings (Residential)*. **2020–Present**: The refinement period, concentrating on engineering design tools, product upgrades, detailed optimization for different climate zones, and the promotion of large-scale projects. The national standard GB/T 51350 "Technical Standard for NZEBs" was released in 2019, defining NZEBs' indicators, technical measures, and evaluation methods.

Research on NZEBs has been one of the most important areas in the construction discipline over the past decade. Figure 3 illustrates the growth in research publications in Chinese and English. The volume of publications in 2022 was about ten times that of 2013, indicating a significant increase in interest and research in this field.

An analysis of around 600 categorizable publications revealed the dominant focus areas: technology development and research (87% of total publications), followed by technology economics (6%), management and policy (3%), applied fundamental research (2%), and industry development reviews (2%), as shown in Figure 4. This distribution suggested substantial advancements in theoretical and technological research and innovations in NZEBs over the past decade, laying a solid foundation for subsequent engineering practice design theories. However, there is a need to strengthen research in practical aspects such as construction, operational management, and performance evaluation. Accurately assessing the real-world impacts and challenges of new technologies is essential for promoting large-scale NZEB adoption.

### Key indicators

The development of NZEBs in China has been significantly influenced by European technical frameworks. For instance, the Germany Passive House (Passivhaus) system [11] emphasizes aspects like high-performance wall insulation, high-performance external windows, efficient ventilation with heat recovery, thermal bridge-free design, and high air tightness. It sets key technical indicators such as cooling and heating demand,

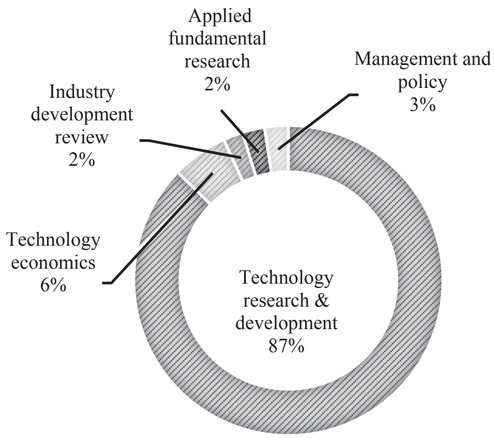


**Figure 4** Research content and proportion of 600 classified publications on NZEBs.

primary energy consumption, and an air tightness indicator of N50 ⩽ 0.6 (N50 is a parameter indicating the volume of air being exchanged through the building envelope during one hour at a pressure difference of 50 Pa between indoor and outdoor environments). Passive House certification allows for flexibility between the cooling and heating load indicator or the primary energy consumption indicator; meeting either of them would be sufficient.

The NZEB definition framework proposed by the EU's EPBD2010 (Energy Performance of Buildings Directive) [16] urges member countries to consider factors such as envelope insulation improvement, reduction of cooling and heating demand through passive measures, natural ventilation, building air tightness and thermal bridge control, lighting optimization, indoor environment control, and the efficiency of heating/cooling sources along with solar energy usage.

France's energy efficiency standard, RT2012 [17] implemented in 2012, aligned with NZEB standards with an energy consumption limit of 50 kW h/(m² a). It introduced the bioclimatic demand (Bbio) indicator, reflecting the extent of passive optimization in buildings. A lower Bbio value indicates a reduction in energy demand through passive measures like building orientation, envelope structure, window-to-wall ratio control, and daylighting, showcasing France's focus on passive optimization strategies.

In 2017, China's Ministry of Science and Technology initiated the key national research project "Development of Technical System and Key Technologies for NZEBs," laying the groundwork for NZEB indicator systems in China. This led to the establishment of the national standard "Technical Standard for NZEBs", defining both mandatory and recommended indicators for NZEBs, as detailed in Table 2.

The key indicators for NZEBs in China are characterized by the following aspects:

(1) Dual indicator types: The standards specify mandatory and recommended indicators. Mandatory indicators encompass indoor environmental parameters and building energy efficiency, while recommended indicators focus on building envelope and energy system performance.

(2) Climate-specific limits: Distinct cooling and heating load limit values are proposed, tailored to different climate zones. This approach acknowledges the diverse climatic conditions across China.

(3) Building type-based evaluation: The evaluation criteria vary based on the type of building. Residential buildings are assessed by their energy consumption, while commercial buildings are evaluated based on their

**Table 2** The national standard "Technical Standard for NZEBs" GB/T 51350 indicators system for NZEB

| Mandatory indicators | Recommended indicators |
|---|---|
| **Indoor environment**<br>(1) Temperature 20°C–26°C;<br>(2) Relative Humidity 30%–60%. | **Envelope**<br>(1) Thermal transmittance;<br>(2) Door and window air tightness grade;<br>(3) Solar heat gain coefficient (SHGC) of transparent parts. |
| **Energy efficiency**<br>(1) Residential buildings: The standard stipulates a building energy consumption of ⩽55 kW h/(m² a), with specific annual cooling and heating demand requirements. Additionally, the air tightness of buildings is set to vary according to different climate zones.<br>(2) Commercial Buildings: These buildings are required to have an energy saving rate of ⩾60%. Similar to residential buildings, the air tightness of the building envelope is determined based on the climate zone.<br>(3) Renewable energy utilization: Both residential and commercial buildings must achieve a renewable energy utilization rate of ⩾10%. | **Energy source and electric equipment**<br>(1) Cooling/heating equipment efficiency;<br>(2) Performance of ventilator with heat recovery;<br>(3) Lighting power density;<br>(4) Energy consumption sub-metering and indoor environment monitoring.<br>**Thermal bridges**<br>Comprehensive thermal bridge management. |

energy saving rate.

Key technical factors for NZEBs include high-performance thermal insulation, high-performance doors and windows, comprehensive handling of thermal bridges, appropriate air tightness design, high-efficiency energy recovery ventilators, efficient cooling and heating systems, and the utilization of renewable energy. These factors align with the international technical system for NZEBs. However, the specific implementation of each technical measure varies according to different climate zones in China.

## Building performance optimization and calculation tools

Building performance optimization (BPO) plays a crucial role in the design of NZEBs. The concept of building performance simulation (BPS) was introduced to the architecture, engineering, and construction (AEC) industry in the late 1980s [18]. In performance-based design, indoor environmental parameters are considered constraints, with energy consumption as the target for optimization. Simulation tools are used to iteratively calculate and optimize design schemes to achieve predetermined performance indices. In NZEB design, multiple factors like building orientation, window-to-wall ratio, thermal insulation, and solar radiation influence energy consumption. Performance-based optimization methods help identify the most energy-efficient design.

Multi-objective optimization (MOO) methods, which consider factors such as energy consumption, investment, and carbon emissions, are increasingly preferred in project design. The BPO process under these objectives requires numerous iterations. Heuristic optimization methods like genetic algorithms (GA) and particle swarm optimization (PSO) can significantly reduce optimization time and have shown success in BPO applications [19]. For example, Wang *et al*. [20] used the NSGA-II genetic algorithm for multi-objective optimization of passive buildings. Wu *et al*. [21] developed a multi-objective optimization method for NZEBs in different Chinese climates, integrating BIM-DB and PSO-RF-NSGA-III.

The computational time for BPO is often substantial. To address this, scholars have proposed improved methods based on pre-trained fast load prediction models, reducing optimization time [22–24]. Shen *et al*.

[25] introduced an explainable machine learning framework for automated training and optimization in NZEB design. These pre-trained models can rapidly identify optimal designs from millions of options, enhancing BPO's industry acceptance.

Popular BPO tools include DesignBuilder and TRNOPT [18], widely used in NZEB research. The China Academy of Building Research developed the IBE toolbox, which employed the quasi-steady-state calculation method of ISO13790 to simplify and expedite computations. This tool aids design teams in making quick, early-stage decisions in NZEB projects. Despite significant research, the widespread application of the BPO concept in NZEB design remains limited, indicating potential areas for further development and implementation.

## Enhancement of building envelope

Enhancing the thermal performance of building envelopes is a key strategy for achieving NZEB. The IEA suggested that envelope retrofit measures, as part of a "faster transition scenario", could reduce global energy intensity by more than 35% by 2050, while also enhancing indoor thermal comfort [26]. Research by D'Agostino *et al*. [27] on the impact of building envelope performance in the context of climate change highlighted significant changes in heating and cooling loads. Their analysis of climate evolution in eight representative European cities showed a decrease in heating loads by 38%–57% and an increase in cooling loads by 99%–380%. Recent studies have further explored the energy-saving contributions of building envelopes to NZEBs [28]. Key research topics include the energy-saving potential of improved envelopes [29,30], the influence of thermal bridges and air tightness on energy consumption [31,32], and the applicability of varying insulation requirements across different climate zones [29,31].

China's NZEB requirements incorporate climate-adaptive adjustments for different zones. Research using the life cycle cost (LCC) method has examined the optimal thermal performance of insulation. Enhanced insulation consistently reduces total annual heat transfer across various climate zones. Moreover, different thermal insulation materials are associated with varying optimal life cycle economic thicknesses [33,34].

The correlation between annual heat transfer and thermal insulation thickness in cities representing different climate zones is illustrated in Figure 5 [35]. Taking Beijing as an example, the economically optimal thickness for EPS (expanded polystyrene) insulation ranges from 100 to 160 mm. While increasing the insulation thickness beyond this range can further enhance the building's energy-saving rate, it results in diminishing economic returns.

In China, addressing thermal bridges and ensuring air tightness are highly emphasized. Studies showed that in severe cold, cold, and hot summer-cold winter climate zones, the heating load attributable to thermal bridges can account for 8.7% to 11.6% of the total, even with careful treatment of these thermal bridges. Therefore, the effect of thermal bridges should be factored into the energy simulation and assessment of NZEBs.

Regarding the impact of exterior windows on energy performance, research indicated that window heat loss represented about 35% of the energy consumption of building envelopes in NZEBs. This is more than double the energy loss through external walls, highlighting the significant role windows play in the overall energy efficiency of NZEBs.

The cost-saving benefits associated with window design in NZEBs are explored, with results presented in

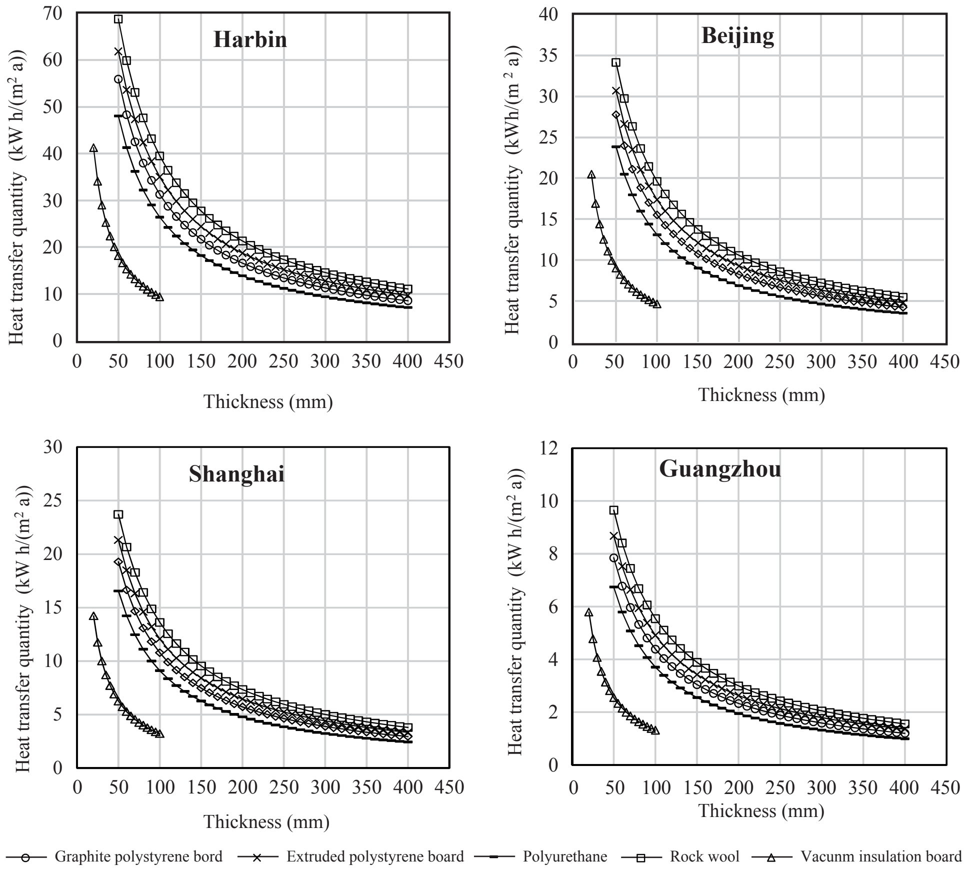


**Figure 5** Annual heat transfer of different materials with different thicknesses in typical cities of China [35].

Figure 6. These findings showed how the life cycle costs in different climate zones varied with the heat transfer coefficient (U-value) of the window. For instance, in Beijing, the optimal economic U-value for the life cycle of windows was between 1.4 and 2.1 W/(m² K). These results were sensitive to the market pricing of windows with differing thermal performance levels. Notably, the cost of high-quality windows with superior thermal performance has dropped significantly in recent years.

Shading plays a crucial role in reducing heat gains from solar radiation during summer, thereby decreasing the cooling energy consumption of NZEBs. However, shading can also lead to increased lighting energy consumption, which in turn may indirectly increase the cooling load. Therefore, the interplay between shading and daylighting in NZEBs warrants further investigation [36,37].

In terms of materials and envelope components, traditional options can generally satisfy the requirements of NZEBs in China. However, there is an ongoing need for lightweight materials with low heat conduction coefficients and fire prevention capabilities. Furthermore, materials that effectively address the thermal moisture challenges in southern China remain a priority for future development.

## Energy systems with higher efficiency

The IEA has identified that after building envelope improvements, the adoption of low-carbon, energy-

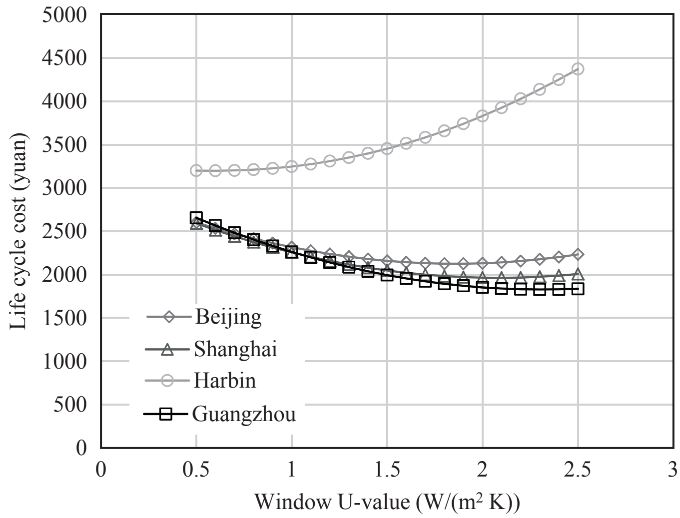


**Figure 6** Full life cycle cost of different performance plastic windows in typical cities.

efficient systems, such as efficient lighting and heat pumps, is the second most effective method for decarbonizing buildings [23]. Heat pump technology, in particular, is vital for NZEBs in colder regions. Several countries have set ambitious targets to promote heat pumps. For instance, the UK and Netherlands aimed to achieve decarbonized heating by 2050, with the Netherlands planning to cease natural gas production entirely by 2030 [26,38]. Compared with traditional boilers or central heating systems, heat pumps can offer over 40% operational cost savings in cold climates throughout the year.

For cooling and ventilation in NZEBs, technologies like heat recovery ventilation (HRV) systems and radiant heating and cooling systems are gaining widespread attention due to their significant energy-saving potential. Displacement ventilation and independent temperature and humidity control systems are more common in China and the US. In contrast, evaporative cooling and chilled beams are widely used in the European Union [39]. Integrated ventilation-heat pump systems are frequently employed in residential NZEBs. Some demonstration projects have utilized capillary ceiling radiation and displacement ventilation schemes for higher efficiency and improved comfort.

Research by Liu *et al*. [40] explored the quantitative relationship between air tightness and energy consumption in fresh air systems of nearly zero energy residential buildings. The study concluded that with high building airtightness and high heat recovery efficiency, the equivalent efficiency of HRV systems can reach 4.0 or above during the heating season and 5.0 or above during the cooling season, surpassing the energy efficiency of heat pumps in the same climate zone.

In recent years, innovative HVAC systems have been implemented in NZEBs, such as household variable refrigerant volume (VRV) with chilling fan coil and floor heating modules, and household air-source heat pumps with radiant cooling systems. However, the limited availability of small-capacity equipment suitable for NZEBs has increased initial investment costs and hindered the scalability of these projects.

## Renewable energy technologies

Research on renewable energy technologies in China has predominantly focused on photovoltaic (PV) power generation. Liu *et al*. [41] conducted an analysis of the load matching capabilities of PV systems in zero energy buildings (ZEBs) across various Chinese climate zones. They found that rooftop PV systems on low-rise buildings could meet at least 70% of the energy demands in most zones. Yao and Zhou [42] examined the status and applications of roof-mounted PV systems, providing a comprehensive economic analysis over the full life cycle of PV components. Their findings indicated that cadmium-telluride solar cells have the shortest payback period.

According to the IEA's faster transition scenario, it was projected that over 45% of heating and hot water in the European Union will be electrically powered by 2050, a significant increase from 25% in 2017 [26]. This shift poses substantial challenges for electricity load regulation in future cities. While PV systems were traditionally used to meet a building's power requirements, the decreasing costs and increasing efficiency of PV technology mean that buildings will increasingly utilize solar-generated power. This has led to the concept of energy flexible buildings (EFB), which are designed to adapt to flexible energy demands using a combination of PV, energy storage, DC distribution, and smart control systems.

The Ministry of Housing and Urban-Rural Development of China, in Building Energy Conservation and Green Buildings Development Plan, set a target to install 5 GW of building-integrated photovoltaics (BIPV) during the 14th Five-Year Plan period. The EFB concept was highlighted in this plan, with an emphasis on NZEBs integrating PV, energy storage, and electric vehicles to transition into electricity "prosumers" in the future [43]. Given China's global leadership in installed PV capacity and market share [44], the adoption of PV systems in NZEBs within the country is expected to increase significantly.

## INCENTIVE POLICIES

Incentive policies are crucial for overcoming resistance to new technologies and subsidizing incremental costs. Since 2015, a series of policies supporting NZEBs have been introduced to foster pilot projects. In January 2017, China's State Council released the 13th Five-Year Plan for Energy Efficiency and Carbon Emission Reduction Comprehensive Work Plan, which proposed to "carry out pilots of NZEBs" [45]. Following this, in March 2017, the Ministry of Housing and Urban-Rural Development of China announced the 13th Five-Year Plan for Building Energy Conservation and Green Building Development, setting a target of over 10 million square meters of NZEB demonstration projects by 2020 [46]. The 14th Five-Year Plan for Building Energy Conservation and Green Building Development, issued in March 2022, further stated that constructed NZEBs would exceed 50 million square meters by 2025 [43].

In June 2022, the Ministry of Housing and Urban-Rural Development and the National Development and Reform Commission issued the "Implementation Plan for Carbon Peaking in the Field of Urban and Rural Construction". This plan sets ambitious energy-saving targets for new buildings: by 2030, residential buildings in severe cold and cold zones are expected to achieve an energy saving ratio of 83%, while those in summer hot-winter cold, summer hot-winter warm, and temperate climate zones should reach 75%. For new commercial buildings, the target is set at 78% [47].

Prompted by these central government policies, local governments have also been proactive in offering incentives for NZEBs. Since 2016, provincial and municipal governments across China have introduced a range of economic incentives, providing financial support and floor area regulation benefits for NZEBs.

Direct subsidy rewards, accounting for 36.6% of these incentive policies, vary significantly across provinces, with the highest subsidies reaching up to 1000 RMB/m², and most ranging between 200–500 RMB/m².

Floor area regulation incentives represent the second largest proportion of these policies, at 21.95%. Several cities have implemented floor area bonus policies, with some offering up to a 9% increase in floor area ratio. Notably, in Shanghai, the additional building area resulting from external wall insulation in NZEBs was excluded from the floor area ratio calculations. For real estate developers, this can translate into an additional maximum 3% salable area. Given that the average new house price in Shanghai was around 50,947 RMB/m² in 2020, this incentive effectively equates to an additional value of about 1500 RMB/m², making it highly attractive to developers.

Currently, government incentive policies for NZEBs in China are primarily directed at developers. In contrast, France has implemented a variety of energy-saving incentives targeting individuals. These measures include tax rebates for energy transition for owners and tenants undertaking energy-saving renovations, zero-interest green loans for energy-saving and low-carbon projects, and a reduction in VAT for energy-saving renovation contractors from 10% to 5.5% [48]. These diverse incentives have successfully fostered a culture of building energy efficiency among the French populace.

Similarly, other European countries have developed a range of incentive policies, such as promoting building energy audits and energy labeling. The transformation of buildings towards NZEBs does not require an "settle a matter at one go", instead, a step-by-step optimization process is beneficial for initial promotion, a notable example is France's "1 Euro Insulation" campaign, which subsidized roof insulation upgrades for existing buildings, significantly boosting the building efficiency market [48].

Looking ahead, China could draw on European experiences in policy-making for NZEBs and building efficiency to enhance its own initiatives. Potential measures might include implementing graded incentive systems, lowering application thresholds for incentives, and increasing application flexibility. Additionally, promoting public awareness about green and low-carbon building practices could further support the development of NZEBs in China.

## PRACTICE OF NZEB IN CHINA

### NZEB projects

The global market for NZEBs is expanding rapidly. Europe, a pioneer in NZEB development, saw a significant increase in the number of NZEBs from 2012 to 2016. During this period, 1,238,184 buildings were constructed or renovated to meet NZEB standards. Residential NZEBs dominated the market, accounting for 95.6% of these buildings. The commercial NZEB sector also shows notable growth, with increases of 63% and 52% for new and retrofitted buildings, respectively. As Europe enters a period of slower urbanization, the NZEB market for new constructions and renovations has reached a state of equilibrium [49].

In China, driven by national advocacy, local policy incentives, and market recognition, the NZEB projects have expanded significantly over the past decade. By 2023, several provinces announced their NZEB targets and progress, as illustrated in Figure 7. By the end of 2022, the total area of NZEBs nationwide reached 23.89 million square meters, approximately 48% of the 2025 target.

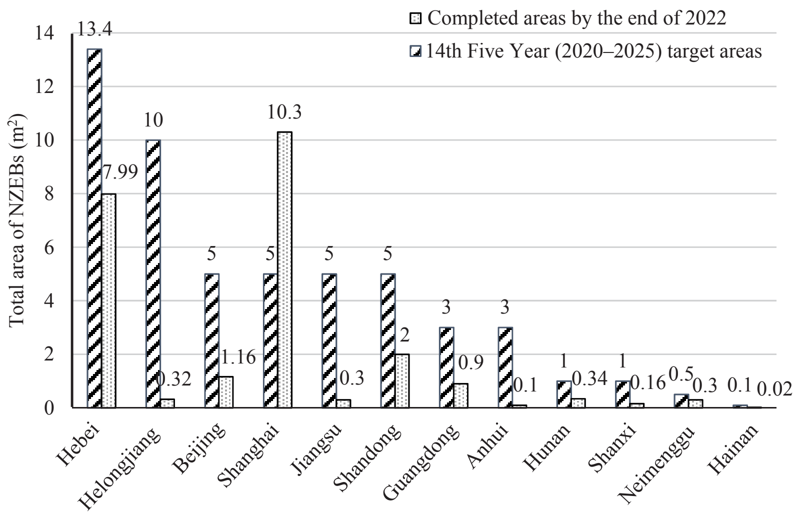


**Figure 7** Areas of NZEBs completed compared with 14th Five Year target for main cities/provinces in China.

When ranked by completion rate, Shanghai leads, followed by Hebei, Shandong, and Beijing, with rates of 206%, 60%, 40%, and 23%, respectively. Shanghai's rapid NZEB development was partly attributed to the local government's 3% floor area bonus incentive. NZEB projects are gradually expanding from north to south, although acceptance in southern China remains limited. Challenges in this region include the lack of mature high-efficiency dehumidification equipment and difficulties in reducing cooling energy demand. Severe cold climate zones also present significant challenges for NZEB development, such as the stability of air source heat pumps in extreme cold conditions and the need for more high-performance, affordable insulation materials and window products.

Since 2019, over 70 demonstration projects have been documented in an online database developed by the China Academy of Building Research [50]. This database captures essential data such as energy consumption, indoor temperature and humidity, and air tightness, among others. Analysis of operation data from 10 commercial buildings in the database revealed annual energy consumption ranged from 24.67 to 46.56 kW h/(m² a), as shown in Figure 8, with energy saving rate between 51.5% and 77.3%. Excluding the contribution from photovoltaics (PV), the average energy savings rate of these 10 projects was 62.5%. Both heating and non-heating energy consumption were found to be less than half of the values suggested by the Chinese national energy consumption code, affirming the effectiveness of NZEB technologies.

## NZEB related industry development

NZEBs necessitate higher performance in building insulation, windows, air tightness, and heating/cooling source efficiency. Under the guidance of national standards, industries related to high-performance building components, such as insulation materials, windows, air impermeability materials, waterproofing materials, and high-efficiency heating/cooling sources and ventilation systems, have experienced rapid growth. The NZEB-related industries encompass many sub-sectors, characterized by long value chains and high added value.

In China, it has been observed that industry responsiveness to new market needs can significantly support

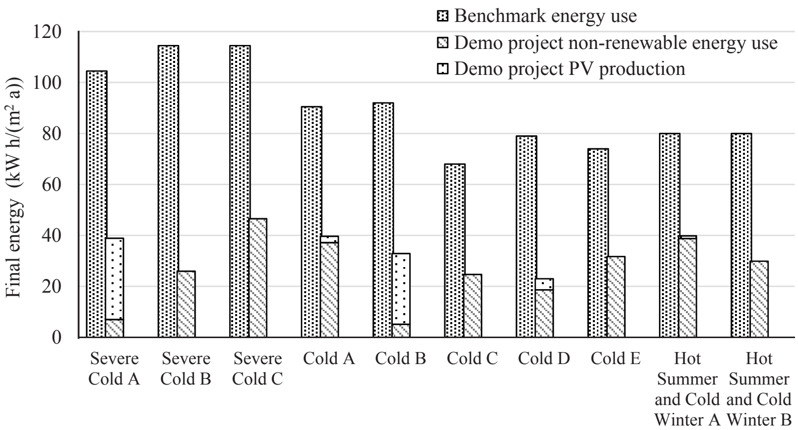


**Figure 8** Energy consumption of 10 nearly zero energy demonstration buildings in different climate zones.

NZEB demonstration projects, leading to a decline in incremental costs alongside industry development. For instance, the cost of passive windows with high thermal performance has dropped markedly, from 2950 RMB/m² in 2016 to 2250 RMB/m² in 2023. Similarly, the incremental costs for NZEB demonstration projects have shown a consistent downward trend. For residential NZEBs, the incremental cost decreased from 1300 RMB/m² in 2016 to between 400 and 600 RMB/m² in 2023, a reduction of 53.8%. In the case of office buildings, the incremental cost reduced from 1620 RMB/m² to between 600 and 800 RMB/m² in 2023, a reduction of 50.6%. It is anticipated that the incremental cost for residential NZEBs could further decrease to between 300 and 500 RMB/m² in the coming years.

## CONCLUSIONS AND PROSPECT

Over the past decade, China has achieved remarkable progress in research, policy support, demonstration projects, and industrial development for NZEBs. The main advancements include:

(1) Continuous improvement of the NZEB technology systems, with the development of technical roadmaps tailored to different climate zones.

(2) Rapid development of key NZEB technologies to meet market demands, supported by intensive research and development activities.

(3) Policy incentives have played a crucial role, although most have targeted development parties rather than individual users or value chain stakeholders. Additionally, public awareness and understanding of NZEBs need to be enhanced.

(4) Significant growth in the number of providers of NZEB components, such as manufacturers of high-performance thermal insulation and passive windows, as well as efficient small-capacity cooling and heating devices, leading to a reduction in incremental costs.

The large-scale promotion of NZEBs in China is crucial for the building industry to meet climate control targets. Collaborative effort in technology development, policy incentives, and industry technology upgrading, along with continuous innovation, is vital.

Looking forward to the future, the major challenges and opportunities include:

(1) Alongside energy reduction in buildings, the management of direct and indirect $CO_2$ emissions is increasingly important, requiring a shift from NZEBs to Nearly Zero Carbon Buildings (NZCBs) through further research and practice.

(2) The development of envelope materials or systems with excellent fire-resistant, moisture-proof, and heat-resistant properties is crucial, especially for NZEBs in southern China.

(3) A shortage of domestic small-capacity cooling and heating source equipment to meet the needs of nearly zero-energy residential buildings.

(4) With over 60 billion square meters of existing buildings in China, and more than 350 million square meters slated for retrofitting in the coming decades, transforming existing buildings into NZEBs presents a significant industry challenge.

(5) The incremental cost remains a major barrier to the widespread adoption of NZEBs. Reducing the incremental costs of high-performance windows, doors, insulation materials, etc., will be a long-term focus for both academia and industry.

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## Author contributions

Z.Y. leaded the team, proposed the article structure and content, revised and improved the manuscript. C.G. and J.Y. did the literature review and drafted major parts of the manuscript, J.W. provided some materials and polished some parts of the manuscript, and H.Z. drafted one part of the manuscript.

## Conflict of interest

The authors declare no conflict of interest.

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