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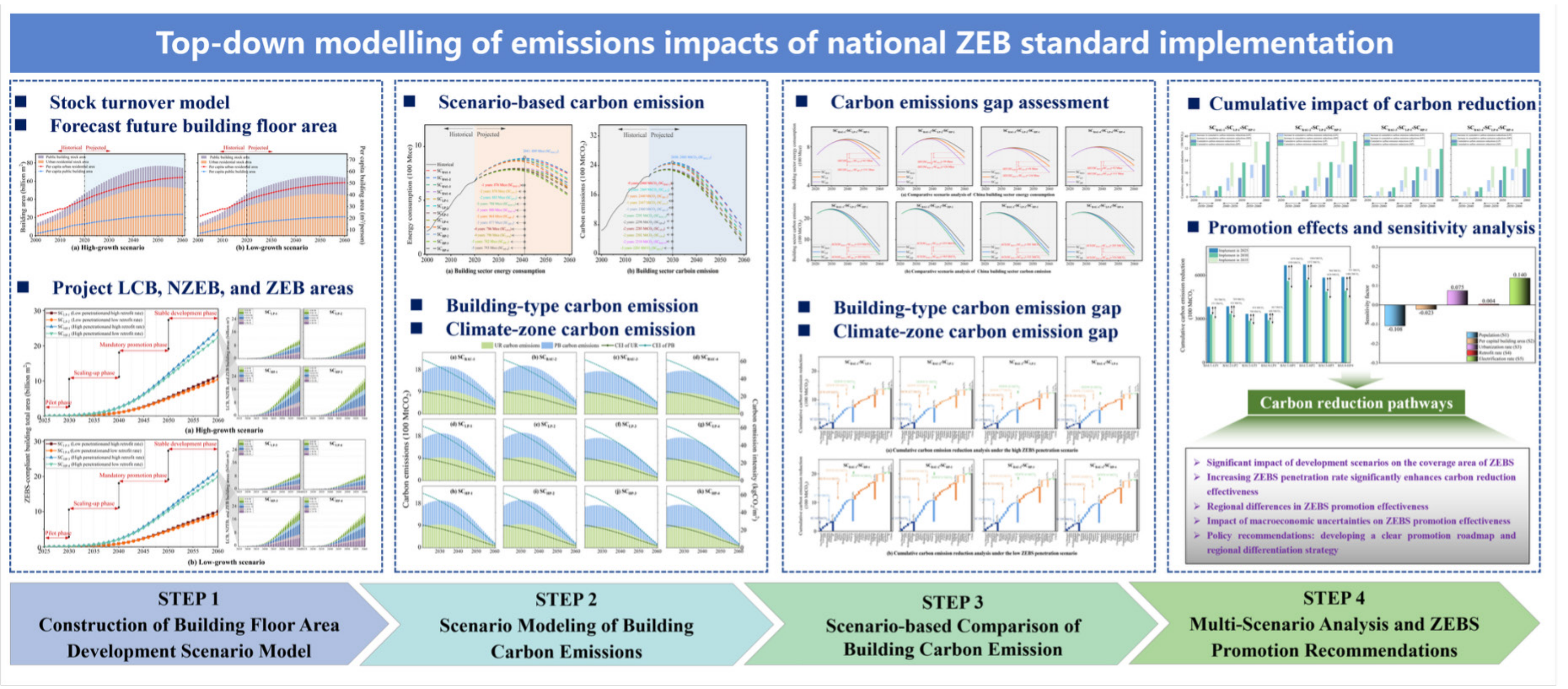
Sino-Swiss Cooperation on Zero Emissions Building

Technical Report

Top-down modelling of emissions impacts of national ZEB standard implementation

ENGLISH VERSION



OCTOBER 2025

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Building a climate-neutral future together

This report has been produced within the framework of the Sino-Swiss Zero Emissions Building Project; an international collaboration funded by the Swiss Agency for Development and Cooperation in partnership with the Chinese Ministry of Housing and Urban-Rural Development.

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Cite as:

Cai, W., Wu, Z., Zhang, S., Yang, X. (2025). Top-down modelling of emissions impacts of national ZEB standard implementation. Sino-Swiss Zero Emissions Building Project Research Report. Intep-Skat: Zurich

The Sino-Swiss Zero Emissions Building Project is an international collaboration funded by the Swiss Agency for Development Cooperation in partnership with the Chinese Ministry of Housing and Urban-Rural Development. The project aims to reduce greenhouse gas emissions and enable carbon neural development of the building sector in China by sharing Swiss know-how on sustainable and zero emission building.

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Summary

Under China's dual-carbon strategy, the building sector, as a major carbon emitter, urgently needs a clear pathway for deep decarbonization. Zero-Emission Building Standards (ZEBS) are regarded as a key solution, but their large-scale nationwide implementation's carbon reduction effects and impact on the carbon neutrality path for the building sector are unclear. To address this gap, this study develops a top-down model integrating the dynamic evolution of building stock with multi-scenario analysis. The model systematically simulates the carbon emission trends and reduction potential under different development paths across three spatiotemporal dimensions: climate zone, building type, and time.

The study's findings are as follows: 1) **Increasing ZEBS penetration significantly enhances emission reduction effectiveness**: Carbon emissions in the national building sector show a "rise-then-fall" trend under different scenarios, with emissions peaking between 2281-2483 $MtCO_2$ from 2027 to 2030, occurring 8-10 years earlier than the peak of energy consumption. By 2060, total carbon emissions in the high penetration (HP) scenario will drop to 273-689 $MtCO_2$, achieving a reduction of 79%-87%. By 2060, the carbon reduction potential of the "high penetration" scenario is about 63% higher compared to the BAU scenario, and about 25% higher compared to the "low penetration" scenario. This indicates a clear positive relationship between the level of promotion and the reduction in emissions. 2) **Regional differences in ZEBS promotion effectiveness**: At the climate zone level, high-energy-consuming northern heating areas show particularly significant emission reduction potential through ZEBS promotion. In the severe cold (SC) and cold (C) zones, carbon emissions are reduced by 67.6%-90.7% and 86.5%, respectively, while the reduction in the warm(warm) and hot summer and warm winter (HSWW) zones is relatively lower, at 85.5% and 81.7%, respectively. 3) **Significant impact of different promotion speeds and intensities on cumulative carbon reduction**: Over time, the emission reduction advantage of the high penetration scenario (HP) becomes increasingly evident. By 2060, the cumulative reduction in the LP scenario will be 2.1 $GtCO_2$, while the HP scenario will reach 3.7 $GtCO_2$, a difference of approximately 1.7 times. Regarding the promotion speed, early implementation brings significant benefits. In the high promotion scenario, advancing the timeline by 10 years could achieve an additional cumulative reduction of 141-160 $MtCO_2$. 4) **Impact of macro-level uncertainties**: Future uncertainties such as population size and electrification rates will significantly affect the final promotion outcomes and carbon reduction. Therefore, these uncertainties must be fully considered in policy formulation and promotion planning.

Based on the findings, future policies should prioritize creating a clear national promotion roadmap and region-specific strategies. This will offer scientific evidence and decision-making support for achieving systematic carbon reductions and high-quality development in the building sector. The research provides a thorough analysis of ZEBS promotion effects and key quantitative data to assist national and local governments in formulating carbon-neutral pathways for the building sector. These results enable decision-makers to assess the potential and risks of different emission reduction paths and develop targeted action plans.

Main findings («Take-Home Messages»)

- Impact of ZEBS Penetration on Emission Reduction: Increasing the penetration of Zero-Emission Building Standards (ZEBS) significantly enhances the effectiveness of emission reductions in the building sector. The study shows that higher ZEBS penetration accelerates the decline in carbon emissions, with a clear positive relationship between the level of ZEBS adoption and the reduction in emissions.
- Regional Variations in Promotion Effectiveness: The effectiveness of ZEBS promotion varies across different climate zones. High-energy-consuming regions, particularly northern heating areas, show the greatest potential for carbon reduction. In contrast, warmer regions experience a more modest reduction, indicating the importance of regional adaptation in ZEBS implementation.
- Influence of Promotion Speed and Intensity: The timing and intensity of ZEBS promotion significantly affect the cumulative carbon reduction over time. Early and aggressive implementation leads to more substantial emission reductions, with advancing the promotion timeline further enhancing the impact.
- Uncertainty Factors: Macro-level uncertainties, such as population growth and electrification rates, will play a critical role in shaping the final outcomes of ZEBS implementation. These factors need to be carefully considered in policy formulation and planning to ensure accurate and effective carbon reduction strategies.

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List of abbreviations

- ZEBS: Zero-emission Building Standards
- LCB: Low Carbon Building
- ZEB: Zero-emission Building
- NZEB: Near-zero Emission Building
- IPCC: Intergovernmental Panel on Climate Change
- EU: European Union
- EPBD: Energy Performance of Buildings Directive
- CABEE: China Association of Building Energy Efficiency
- MoHURD: Ministry of Housing and Urban-Rural Development
- CBEED: China Building Energy Consumption and Emission Database
- CABEE: China Building Energy Efficiency Association
- BAU: Business-As-Usual
- LP: Low Penetration
- HP: High Penetration
- SC_{BAU-1}: High New Construction and Renovation Scenario under BAU
- SC_{BAU-2}: High New Construction and Low Renovation Scenario under BAU
- SC_{BAU-3}: Low New Construction and Renovation Scenario under BAU
- SC_{BAU-4}: Low New Construction and Low Renovation Scenario under BAU
- SC_{LP-1}: High New Construction and Renovation Scenario under LP
- SC_{LP-2}: High New Construction and Low Renovation Scenario under LP
- SC_{LP-3}: Low New Construction and Renovation Scenario under LP
- SC_{LP-4}: Low New Construction and Low Renovation Scenario under LP
- SC_{HP-1}: High New Construction and Renovation Scenario under HP
- SC_{HP-2}: High New Construction and Low Renovation Scenario under HP
- SC_{HP-3}: Low New Construction and Renovation Scenario under HP
- SC_{HP-4}: Low New Construction and Low Renovation Scenario underHP
- EUI: Energy Use Intensity
- CEI: Carbon Emission Intensity
- ESR: Energy Saving Ratio
- CERP: Carbon Emission Reduction Potential

1 Introduction

1.1. Background

Climate change has become a severe challenge facing the global community [1]. The Paris Agreement has positioned low-carbon development as a core strategy to address this issue [2]. In this context, the environmental impact of the building sector, as the largest energy consumer, is particularly prominent, affecting the entire lifecycle, including energy consumption, greenhouse gas emissions, material extraction, and waste generation [3]. Data show that carbon emissions from the global building sector account for nearly 40% of total emissions and 36% of final energy consumption. If current energy use and emission intensity remain unchanged, the share of carbon emissions from the building sector is expected to increase to 50% by 2050 [4]. This issue is particularly prominent in countries like China, which is undergoing rapid urbanization [5]. Latest data show that in 2022, China's building sector emitted a total of 513 million tons of CO_2, accounting for 48.3% of the country's energy-related carbon emissions. Of this, carbon emissions from building operations increased by 6 million tons compared to 2021, an increase of 2.7%, with an average annual growth rate of 3.0% over the past five years [6]. China has established the "dual carbon" strategic goals and pledged to reduce greenhouse gas emissions by 7%-10% below the peak level by 2035 [7]. These ambitious targets face tremendous pressure from the building sector. With the continuous expansion of new building construction and rising living standards, if energy consumption and carbon emissions in the building sector are not effectively controlled, they will become a significant obstacle to achieving the country's climate commitments [8].

The Intergovernmental Panel on Climate Change (IPCC) has pointed out that building energy efficiency standards are one of the most effective policies for addressing energy and environmental challenges [9]. In line with this consensus, higher building standards are being developed and updated globally, ranging from passive houses [10], near-zero energy buildings [11] to zero-energy buildings [12]. China's newly issued "Near-Zero Energy Building Technical Standards" (GB/T 51350-2019) and "Building Carbon Emission Calculation Standards" (GB/T 51366-2019) also provide the technical basis for achieving the "dual carbon" goals [13][14]. These standards elevate modern building energy efficiency to a new level. The future evolution of building energy efficiency standards will focus on three core directions: 1) improving energy efficiency through technological innovation and optimization of user behavior; 2) reducing reliance on fossil fuels by promoting building electrification; and 3) accelerating the decarbonization of energy supply systems and promoting the widespread application of renewable energy [15]. The concept of Zero-Emission Buildings (ZEB) provides a systematic solution to achieve these goals [16]. The core advantage of ZEB is that the renewable energy it generates can offset the greenhouse gas emissions produced throughout the building's lifecycle, including in materials, construction, operation, and demolition recovery. This is considered the most effective way for the building sector to achieve decarbonization [17]. The implementation of ZEB not only involves innovations in building technology and electrification but also requires the comprehensive decarbonization of the energy supply system, particularly large-scale applications of renewable energy [18][19]. Developing low-carbon or zero-carbon buildings (ZEB) has become an inevitable trend in the global response to climate change and is recognized as the core pathway for driving the transformation of the global energy system [20]. Many countries have already incorporated ZEB into their long-term development plans [21]. The European Union (EU), in its latest revision of the "Energy Performance of Buildings Directive" (EPBD, EU/2024/1275), has raised the standard for new buildings from "near-zero energy" to the more stringent "zero-emission" standard [22]. The United States has proposed achieving net-zero emissions for federal buildings by 2045 in its "Federal Sustainability Plan" [23]. China has also vigorously promoted zero-carbon technologies and strategies, with the "13th Five-Year Plan for Controlling Greenhouse Gas Emissions" proposing the development of net-zero carbon emission projects, aiming to build 50 demonstration projects by 2020. In the future, as related policies are further implemented and technologies continue to advance, ZEB will see broader application worldwide.

1.1. Purpose of the study

In recent years, research on ZEB has expanded from an initial focus on technical pathways (such as ultra-low energy envelope systems [24], efficient energy use systems [25], and renewable energy integration [26]) to a more comprehensive framework. This expanded perspective also emphasizes various dimensions, including the environmental impact throughout the entire lifecycle [27], economic feasibility and cost optimization [28], as well as policy, regulation, and market promotion [29]. This shift in research focus, from isolated technical issues to complex system issues involving policy, economics, and the entire lifecycle, has revealed the inherent limitations of traditional analysis methods focused on "individual buildings." The long-term effectiveness of Zero-Emission Building Standards (ZEBS) is not a simple addition of isolated technologies, but rather is determined by the dynamic evolution of the entire building stock during its metabolic process (i.e., construction, renovation, and demolition) [30]. Therefore, building energy models capable of simulating the long-term dynamic evolution of building stock are considered the key methodological prerequisite for evaluating the effectiveness of future energy policies [31]. However, despite the recognition of this methodology's importance in academia, most actual research still confines its analysis scale to individual buildings or small-scale cases, using relatively static evaluation methods. While this micro perspective allows for detailed assessment of specific technologies and projects, it cannot reveal the macro, dynamic, and systemic effects of large-scale ZEBS promotion over a long period, whether on a national or regional scale. Therefore, how to use a refined building stock energy model to systematically quantify the overall emission reduction potential and comprehensive effects of future ZEBS policies under various development scenarios remains an important research area that requires further exploration.

To fill this research gap, this study aims to systematically assess the long-term impact of ZEBS on building stock operational carbon emissions in various development scenarios at the macro level. The core methodology involves constructing a comprehensive building stock dynamic evolution and carbon emission scenario analysis model. This model will couple three modules: building area development modeling, carbon emission scenario modeling, and emission reduction potential and variance assessment, to achieve the following goals:

- Simulate the dynamic evolution of future building stock (including both new and existing buildings) under different zero-carbon development paths, taking into account variations in building types, regional climate, and time series.
- Quantify and evaluate the emission reduction potential of ZEBS under different policy intensities and implementation rhythms, while identifying key influencing factors.
- Reveal the phased emission reduction benefits of ZEBS implementation. By comparing the carbon emission trajectories under different scenarios, provide scientific, quantifiable decision support for formulating ambitious yet feasible medium- and long-term policy roadmaps.

1.2. Objectives of the study

China has started to gradually improve zero-carbon standards and promote the implementation of demonstration projects, but large-scale promotion and the quantification of its impact on building carbon emissions reduction still require further research. The core objective of this study is to use a top-down approach to construct a building stock dynamic evolution model to systematically evaluate the macro emission reduction potential of China's

ZEBS and provide decision support for the development of a scientific implementation path. To achieve this overall objective, the study has set the following three progressively specific goals:

- Construct a Building Stock Dynamic Evolution Model: Develop a model that can finely reflect the dynamics of new construction, renovation, and demolition, in order to predict the scale and structure of future building stock in China under different socio-economic development scenarios.
- Simulate Multi-Scenario Carbon Emission Evolution Trends: Based on the above stock model, couple various ZEBS implementation paths and existing building renovation strategies to simulate and compare the carbon emission evolution trajectories in the building sector under multiple scenarios.
- Quantify and Evaluate Emission Reduction Potential and Benefits: Through in-depth comparative analysis of carbon emission trajectories across different scenarios, precisely quantify the overall emission reduction potential, phased benefits, and key driving factors of ZEBS.

2 Approach and data

To systematically evaluate the carbon reduction potential of China's Zero-Emission Building Standards (ZEBS), this study constructs a building stock dynamic evolution model that integrates a top-down logic. The core feature of this model lies in its multi-dimensional and refined setup: In terms of spatial dimension, the model is based on data covering 30 provincial-level administrative regions, aggregating the analysis scale to China's five major climate zones in order to accurately capture regional differences in building development and energy efficiency characteristics. In terms of building types, the model distinguishes between urban residential buildings and public buildings, using a dynamic stock turnover model to simulate their life cycles of new construction, renovation, and demolition. In terms of the time dimension, the model is calibrated with historical data from 2000 to 2020, with the forecast period set from 2021 to 2060, to precisely align with the medium- and long-term goals of China's dual-carbon strategy. **Fig. 1** presents the research framework of the model, which is centered around three core tasks:

- T1-Building Stock Scenario Prediction: Focuses on constructing a zero-carbon development scenario model that simulates both new construction and renovation of existing buildings, predicting the scale and structural evolution of future building stock.
- T2-Carbon Emission Scenario Simulation: Based on the building stock scenarios predicted in T1, this task combines various ZEBS implementation paths to forecast the carbon emission evolution of the building sector under multiple development scenarios.
- T3-Emission Reduction Potential and Differential Assessment: By comparing the carbon emission results from the multiple scenarios simulated in T2, this task systematically quantifies the emission reduction benefits and contributions achievable through large-scale ZEBS promotion.

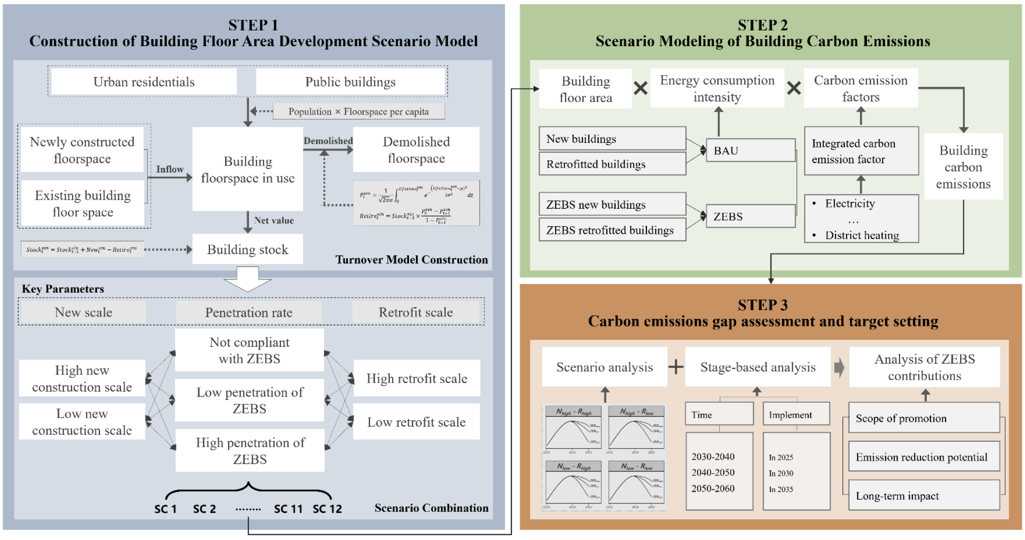

Fig. 1 Framework of the calculation model.

2.1. Analysis framework and model method

2.1.1.Building area estimation model construction

To predict the dynamic evolution of building area from 2021 to 2060, this study improves and applies the existing building stock model developed by the team [32]. The core of the model lies in coupling the dynamic processes of new construction, demolition, and renovation to forecast the structural changes in building stock under different scenarios, providing foundational data for subsequent carbon emission calculations. The calibration data for the model is sourced from the China Statistical Yearbook for the Building Industry and the China Urban and Rural Construction Statistical Yearbook. The dynamic turnover process of the stock over time is defined by Eq. (1) and Eq. (2).

$$Stock_{t,i}^{vin} = Stock_{t-1,i}^{vin} + New_{t,i}^{vin} - Retire_{t,i}^{vin} \tag{1}$$

$$Stock_{t,i}^{vin} = A_{t,i}^{vin} \times P_{t,i}^{vin} \tag{2}$$

where, *Stock*$_t^{vin}$represents the building stock area of the i-th building type constructed in year vinat year t; *New*$_t^{vin}$represents the new construction area of the i-th building type in year $t$constructed in year vin; *Retire*$_t^{vin}$represents the demolished building area of the i-th building type in year $t$constructed in year vin; $A_{(t,i)}^{vin}$represents the per capita building area of the i-th building type in year $t$constructed in year vin; and $P_{(t,i)}^{vin}$represents the population size of the i-th building type in year $t$constructed in year vin.

In this study, buildings are considered to be demolished once they reach their service life. Therefore, the "demolished area" of a building actually refers to the area that exits the building stock system. Following the methods of Müller [33] and Huo et al. [34], the building lifespan is treated as a random variable following a normal distribution. Given year t and construction year vin, the demolition probability P_t^{vin} is calculated according to Eq. (3) and Eq. (4).

$$P_{t,i}^{vin} = \frac{1}{\sqrt{2\pi}\sigma} \int_0^{lifetime_{t,i}^{vin}} e^{-\frac{(lifetime_{t,i}^{vin} - \mu)^2}{2\sigma^2}} dt \tag{3}$$

$$Retire_{t,i}^{vin} = Stock_{t-1,i}^{vin} \times \frac{P_{t,i}^{vin} - P_{t-1,i}^{vin}}{1 - P_{t-1,i}^{vin}} \tag{4}$$

where, μ represents the average lifespan of a building; σ is the standard deviation, set as $\mu/3$; $P_{(t,i)}^{vin}$and $P_{(t-1,i)}^{vin}$represent the cumulative demolition probability of the i-th building type in years $t$and $t-1$, respectively, indicating the natural retirement process of buildings during their lifecycle; and *Retire*$_{(t,i)}^{vin}$represents the demolished building area of the i-th building type in year t. Considering that different building types may have varying design lifespans and actual service lives, this study assumes that the average lifespans of non-energy-efficient buildings, energy-efficient buildings (those meeting building energy efficiency standards at the design stage), and high-performance buildings (e.g., ultra-low energy, low-carbon, and zero-carbon buildings) are 30 years, 40 years, and 50 years, respectively.

2.1.2.Building carbon emission scenario modeling

To quantify the building carbon reduction potential under different scenarios, this study develops a bottom-up operational carbon emission accounting model. The basic framework of the model is "Building Area × Energy Consumption Intensity × Comprehensive Carbon Emission Factor." The model tracks the new construction, renovation, and stock evolution of urban residential and public buildings from 2021 to 2060 on an annual basis, and dynamically calculates the total carbon emissions during the operational phase, taking into account the ZEBS penetration levels under different scenarios. The total carbon emissions during the operational phase of a building are calculated according to Eq. (5):

$$CE_{i,t} = \left[FA_{i,t}^{ren} \times EUI_{i,t}^{ren} + FA_{i,t}^{unren} \times EUI_{i,t}^{unren} + FA_{i,t}^{new} \times EUI_{i,t}^{new} + FA_{i,t}^{zebs} \times EUI_{i,t}^{zebs}\right] \times \delta_{i,t} \quad (5)$$

where $FA_{(i{\cdot}t)}^{ren}$, $FA_{(i{\cdot}t)}^{unren}$, $FA_{(i{\cdot}t)}^{new}$, and $FA_{(i{\cdot}t)}^{zebs}$ represent the renovated, unrenovated, newly constructed, and ZEBS-compliant building areas, respectively, for the i-th building type (urban residential or public building) in year t; EUI denotes the corresponding unit building energy consumption intensity.

This study calculates building energy consumption intensity by considering building energy efficiency standards, the age effect, and regional climate differences. The calculation process first uses non-energy-efficient buildings as the baseline, and based on the relative energy savings rates of different energy-saving design standards (30%, 50%, 65%, etc.), it determines the unit energy consumption for buildings of different energy efficiency levels. On this basis, by coupling the "age spectrum" and "energy efficiency spectrum" of building stock, the model dynamically simulates the evolution trend of overall building average energy consumption intensity from the past to the future. To ensure the accuracy of the calculation, the model results are further calibrated with official data from the China Association of Building Energy Efficiency (CABEE) and adjusted for regional climate differences based on the latest research. For newly constructed buildings that comply with ZEBS, their energy consumption intensity is directly set according to the minimum equivalent energy consumption limits specified by the standards.

Considering the diversity of energy consumption structures during the building operation phase, the carbon emission factor is determined using a comprehensive weighted calculation method. The comprehensive carbon emission factor $\delta_{(i{\cdot}t)}$ is determined by the proportion of coal, oil, natural gas, and electricity, as well as their respective carbon emission coefficients. The calculations are performed according to Eq. (6) and Eq. (7):

$$\delta_{i,t} = Pro_{c,i,t} \times \delta_1 + Pro_{o,i,t} \times \delta_2 + Pro_{n,i,t} \times \delta_3 + Pro_{e,i,t} \times \delta_4 \quad (6)$$

$$\delta_4 = \left(1 - Pro_{ce,t}\right) \times \frac{\delta_1}{PGE_t} \quad (7)$$

where, $\delta_{(i,t)}$ represents the comprehensive carbon emission factor for building type i in year t; $Pro_{(c,i,t)}$, $Pro_{(o,i,t)}$, $Pro_{(n,i,t)}$, and $Pro_{(e,i,t)}$ represent the proportions of coal, oil, natural gas, and electricity, respectively, in the final energy consumption of that building; δ_1, δ_2, and δ_3 are the carbon emission factors for coal, oil, and natural gas, respectively; δ_4 is the carbon emission factor for electricity, which needs to be adjusted according to the share of clean energy generation and power generation efficiency; $Pro_{(ce,t)}$ represents the proportion of clean energy (including hydropower, wind, solar, nuclear, etc.) in total electricity generation; and PGE_t denotes the power generation efficiency (representing the efficiency of converting primary energy into electricity).

2.1.3.Carbon emission difference assessment

To systematically assess the carbon emission differences across different building types and ZEBS promotion scenarios, this study first establishes a baseline scenario (BAU) as a reference. This scenario simulates the carbon emission trajectory of buildings under the assumption of no additional ZEBS policy interventions, relying only on conventional energy efficiency improvements. Based on this, two additional scenarios are constructed: the "Low Penetration (LP)" scenario, representing gradual promotion, and the "High Penetration (HP)" scenario, representing an accelerated promotion. In modeling the carbon emission trends for these scenarios, key variables such as building types, energy efficiency levels, new construction and renovation status, and changes in energy structure are considered. The cumulative carbon emissions for each scenario and their differences are calculated using Eq. (8) and Eq. (9):

$$CE_{s,t} = \sum_{i} \sum_{k \in \{ren,unren,new,zeb\}} FA_{s,i,t}^{(k)} \times EUI_{s,i,t}^{(k)} \times \delta_{s,i,t} \tag{8}$$

$$\mathrm{Cum}\Delta CE_s(t_0, T) = \sum_{t=t_0}^{T} \Delta CE_{s,t} = \sum_{t=t_0}^{T} \left(CE_{\mathrm{BAU},t} - CE_{s,t} \right) \tag{9}$$

where, $FA_{(s,i,t)}^{(k)}$ represents the area of the k-th category (renovated/unrenovated/new/ZEBS) of the i-th building type in year t under scenario s. $Cum\Delta CE_s(t_0, T)$ represents the cumulative emission reduction from the baseline year t_0 to the target year T under scenario s. $\Delta CE_{(s,t)}$ represents the annual emission reduction in year t under scenario s. $CE_{(BAU,t)}$ represents the carbon emission under the BAU scenario in year t, while $CE_{(s,t)}$ represents the actual carbon emission under the LP/HP scenarios in year t.

2.2. Scenario design and parameter setting

Based on the calibration of historical data and dynamic modeling of building stock, this study focuses on two major aspects and five key policy variables for simulating future scenarios from 2021 to 2060. In terms of building area evolution, the focus is on the impact of new construction scale, intensity of existing building retrofits, and ZEBS penetration rates. Regarding carbon emission intensity, the key focus is on the evolution of energy consumption intensity per unit area and the carbon emission factors of the energy system. The final scenario differences assessment will integrate the heterogeneity of building types and climate zones, systematically analyzing the impact of different ZEBS promotion paths on the peak timing and scale of carbon emissions, cumulative emission reduction potential, and their contribution to achieving carbon neutrality targets. **Fig. 3** shows the set values for some parameters under different scenarios.

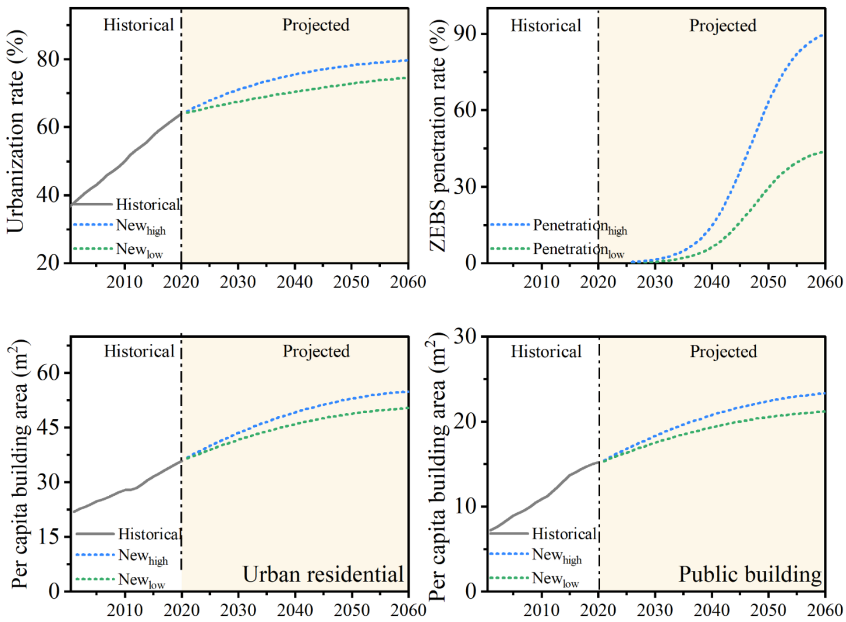

Fig. 2 Key parameter settings.

2.2.1.Building area development scenario design and parameter setting

(1) New Construction Scale

To capture the uncertainty in future building demand, this study constructs two scenarios: "high new construction scale" and "low new construction scale." **Table 1** presents the settings for urbanization rates and per capita building area under high and low growth scenarios. The parameters for these scenarios are based on a combination of official statistical data and authoritative academic forecasts. Regarding urbanization rates, considering the prediction by Yu et al. that the urbanization rate will reach 77% by 2065 [35], and Tan et al.'s forecast that it will reach 80% by 2050 [36], this study sets the urbanization rates for the high and low scenarios at 80% and 75%, respectively, by 2060. For per capita public building area, based on the Ministry of Housing and Urban-Rural Development's (MoHURD) forecast that the value will reach 22.3 m² by 2050, this study assumes that the per capita value in the high and low scenarios will be 23 m² and 21 m², respectively. For per capita urban residential building area, this study considers three main factors: first, the historical growth trend recorded by the National Bureau of Statistics [37]; second, the current data published by MoHURD showing an area exceeding 40 m²; and third, the higher levels of 40–70 m² identified by Tsinghua University's Building Energy Efficiency Research Center for developed countries [38]. Based on these, the study assumes that by 2060, the per capita urban residential building area will reach 55 m² and 50 m² in the high and low scenarios, respectively.

Table 1 Urbanization rate and per capita building area settings under high and low growth scenarios.

	Population (billion people)	High-growth scenario			Low-growth scenario		
		Urbanization rate (%)	Per capita building area (m^2/person)		Urbanization rate (%)	Per capita building area (m^2/person)	
			UR	PB		UR	PB
2020	1.41	64%	36	15	64%	36	15
2030	1.40	71%	44	18	68%	42	18
2040	1.37	76%	49	21	70%	46	19
2050	1.30	78%	53	22	73%	49	21
2060	1.19	80%	55	23	75%	50	21

(2) Renovation Scale

For the renovation of existing buildings, this study also constructs two scenarios—"high renovation scale" and "low renovation scale"—to reflect different policy intensities. The parameter settings fully consider the current reality in China, where renovation rates are generally low. According to the "13th Five-Year Plan for Building Energy Efficiency and Green Building Development," the average annual renovation area during the 13th Five-Year period accounted for only 0.2% of the total building stock [39]. Furthermore, several studies have confirmed that China's current renovation rate of less than 0.5% is much lower than the 1.0%-1.5% level seen in developed countries [40].

Given this context, this study sets the annual renovation rates for the "high" and "low" renovation scale scenarios at 0.4% and 0.2%, respectively. In the model, renovations will prioritize non-energy-efficient buildings, ensuring they meet current energy efficiency standards until the low-efficiency building stock is gradually upgraded.

(3) ZEBS Penetration Rate

For the promotion of ZEBS, this study designs three differentiated development scenarios: "No ZEBS implementation," "low penetration," and "high penetration." The "No ZEBS implementation" scenario serves as the baseline (BAU), assuming that no mandatory zero-carbon goals will be set by 2060 and building energy efficiency will only maintain the current standards. The "high penetration" scenario simulates a leapfrog development under strong policy support and technological maturity, with the ambition level referencing the promotion targets for ultra-low/near-zero energy buildings in the "14th Five-Year Plan for Building Energy Efficiency and Green Building Development." The "low penetration" scenario is more conservative, simulating a gradual promotion under cost and technological constraints.

Considering that the adoption of new technologies generally follows an "initial slow growth - accelerated growth in the middle stage - saturation in the later stage" pattern, this study argues that a simple linear growth model cannot accurately depict the penetration process of ZEBS. Therefore, this study uses an S-curve (Logistic) function to model the penetration rate of ZEBS over time, more realistically reflecting the accelerated growth and eventual long-term saturation as a result of technological maturity and policy support. The mathematical expression of this is given by Eq. (10):

$$P_t = \frac{P_{max}}{1 + e^{-k(t-t_0)}} \tag{10}$$

where, P_t represents the penetration rate in year t; $P_{\max}$ is the maximum penetration rate; k is the growth rate parameter, which can be set based on the desired medium-term growth speed; and t_0 is the midpoint year of the curve, where the penetration rate is approximately half of the maximum value. To reflect the differences in technological development, policy incentives, and market acceptance across regions, the study differentiates the three key parameters regionally: $P_{\max}$ represents the upper limit of promotion for each region, k reflects the strength of technological and policy support, and t_0 indicates the starting year for accelerated penetration in each region. By adjusting these parameters, the study generates distinct ZEBS penetration growth curves for different regions. **Table 2** displays the settings for different regions and ZEBS penetration levels.

Table 2 Settings for different regions and ZEBS penetration levels.

	ZEBS penetration rate (%)					
	Low			High		
	Developed	Moderately developed	Less developed	Developed	Moderately developed	Less developed
2020	-	-	-	-	-	-

2030	0.9%	0.5%	0.3%	2.3%	1.3%	0.8%
2040	9.1%	5.7%	3.8%	21.8%	13.8%	8.6%
2050	36.6%	29.9%	22.5%	76.2%	63.2%	50.6%
2060	48.5%	45.7%	37.6%	95.7%	89.5%	84.6%

2.2.2. Building carbon emission scenario design and parameter setting

(1) Energy efficiency improvement scenario (BAU)

In the baseline scenario (BAU), carbon emissions from the building sector are set to follow the current development trajectory. In this scenario, the reduction in EUI is primarily driven by periodic updates to existing energy efficiency standards. This study assumes that building design standards will be iteratively updated every 15 years, calibrated using historical data from the China Building Energy Efficiency Association (CABEE). At the same time, the evolution of the energy structure reflects the long-term impact of the national low-carbon transition and end-use electrification strategies: with the implementation of the low-carbon energy transition and end-use electrification strategies since the 13th Five-Year Plan, coal and oil consumption will gradually phase out, natural gas consumption will follow a "rise-then-decline" trend, and the share of clean electricity in end-use energy consumption will continuously increase.

(2) ZEBS promotion scenario

In the ZEBS promotion scenario, the decarbonization of the building sector is simulated as a phased and accelerated transformation process. This process begins with a demonstration phase, followed by scaling-up and mandatory promotion, ultimately progressing to stable implementation. This dynamic evolution will drive the internal upgrading of the high-efficiency building market, transitioning from low-carbon building (LCB) to higher standards, such as near-zero emission building (NZEB) and ZEB. The study also sets several key time points (e.g., 2025, 2030, and 2035) to assess the implementation progress and effectiveness of ZEBS promotion at different stages.

2.2.3. Data sources

The reliability and accuracy of data sources are crucial for ensuring the validity of the analysis results. In this study, socio-economic historical data and the supporting data for the building stock turnover model are sourced from the China Statistical Yearbook and the China Energy Statistical Yearbook. The population forecast data for 2021-2060 is based on the research by Zhang et al. [41], specifically using the Shared Socioeconomic Pathway SSP2 (a "business-as-usual" scenario maintaining historical development trends) for provincial population forecasting simulations. The historical data on national and provincial building energy consumption and carbon emissions come from the China Building Energy Consumption and Emission Database (CBEED), developed in collaboration between the research team at Chongqing University and the China Building Energy Efficiency Association.

3 Result analysis

3.1. Building area development scenario analysis

3.1.1. Building area development projections through 2060

(1) National level

This section presents the projected evolution of building area in China by 2060 under different new construction scale scenarios (**Fig. 3** and **Table 3**). The results show that, although the total building area continues to grow in both scenarios, there are significant differences in the scale and speed of growth. In the "High New Construction Scale" scenario, the urban residential and public building areas are expected to reach 52.2 billion and 22.2 billion square meters by 2060, respectively, representing a net increase of 20 billion and 8.5 billion square meters compared to 2020, with an average annual growth rate of 1.2%. In contrast, the expansion in the "Low New Construction Scale" scenario is more moderate, with the urban residential and public building areas projected to reach 44.9 billion and 18.9 billion square meters, respectively, with an average annual growth rate reduced to 0.8%. This trend is also reflected in per capita building area. By 2060, in the "High New Construction Scale" scenario, per capita residential and public building area will increase by 19.0 and 8.1 square meters, respectively, compared to 2020; whereas in the "Low New Construction Scale" scenario, the increase will be 14.5 and 6.0 square meters, respectively. The rapid increase in new construction area during the "13th Five-Year Plan" period (2016-2020) was driven by strong government support for urbanization and green building policies. However, during the "14th Five-Year Plan" period (2025-2030), as policy targets are gradually met and the market becomes more saturated, the growth rate of new construction begins to slow, and the increase in building stock becomes more stable.

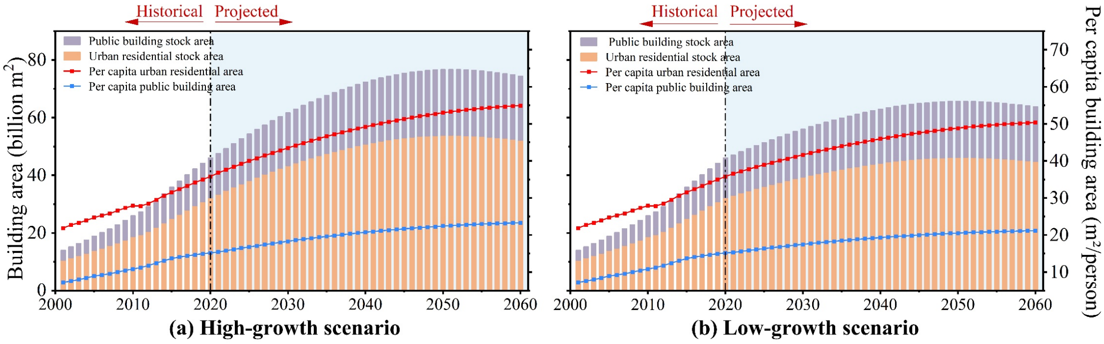

Fig. 3 Forecast of building area changes under high and low new construction scale scenarios.

Table 3 Statistical analysis of urban residential and public building areas under high and low growth scenarios.

	High-growth scenario			Low-growth scenario		
	UR	PB	Total	UR	PB	Total
2020	32.29	13.71	68.52	32.29	13.71	68.52
2030	43.39	18.26	81.96	39.44	16.57	77.20
2040	50.86	21.46	90.46	44.27	18.62	82.39
2050	53.85	22.78	92.77	46.22	19.43	83.13
2060	52.24	22.17	88.53	44.86	18.86	78.92

(2) Provincial level

Fig. 5 presents the projected building area in each province under different new construction scale scenarios up to 2060, showing significant regional disparities. In all scenarios, Guangdong Province has the largest building area nationwide, reaching 470 million m² under the "high construction scale" scenario, accounting for approximately 9.0% of the national total. In contrast, Qinghai Province has the smallest building area, representing about 0.4% of the total. Overall, eastern coastal provinces exhibit larger and faster-growing building stocks, whereas growth in western and sparsely populated regions is comparatively slower.

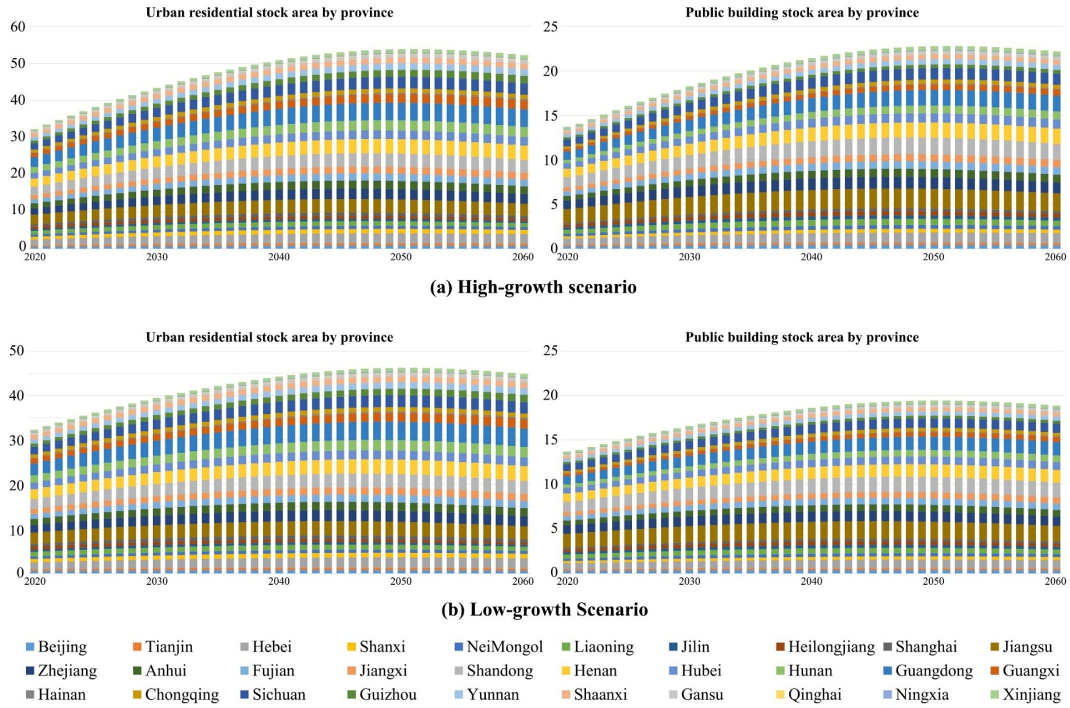

Fig. 4 Predicted building area for each province under high and low new construction scale scenarios.

3.1.2.Building area development projections compliant with ZEBS to 2060

To facilitate the subsequent scenario analysis, this study defines the symbols for 12 combined scenarios as follows: SC_{BAU-1} represents the scenario with high new construction scale and high renovation rate under the BAU scenario; SC_{BAU-2} represents the combination of high new construction scale and low renovation rate; SC_{BAU-3} represents the combination of low new construction scale and high renovation rate; SC_{BAU-4} represents the combination of low new construction scale and low renovation rate. Similarly, low ZEBS penetration scenarios (SC_{LP-1} to SC_{LP-4}) and high ZEBS penetration scenarios (SC_{HP-1} to SC_{HP-4}) correspond to different combinations of new construction scale and renovation rate.

(1) National level

Fig. 5 and **Table 4** reveal the future evolution paths of buildings that meet ZEBS standards. In terms of time, all promotion scenarios exhibit typical S-shaped growth, starting with a slow demonstration phase, followed by an accelerated scale-up and mandatory promotion phase, and ultimately reaching a high, stable level after 25 years. In terms of scenario differences, the level of promotion directly determines the final coverage scale. By 2060, under the SC_{LP}, the areas of ZEBS-compliant buildings in SC_{LP-1}, SC_{LP-2}, SC_{LP-3}, and SC_{LP-4} are expected to be 11.4, 10.4, 10.1, and 9.2 billion square meters, respectively. In contrast, under the SC_{HP}, the areas of ZEBS-compliant buildings in SC_{HP-1}, SC_{HP-2}, SC_{HP-3}, and SC_{HP-4} increase significantly to 24.4, 22.4, 21.6, and 19.9 billion square meters, respectively. These differences clearly demonstrate that new construction scale and renovation intensity have a decisive impact on the promotion of zero-carbon buildings. The "high new construction + high renovation" combination (SC_{LP-1}/SC_{HP-1}) can achieve the largest ZEBS coverage area, while the "low new construction + low renovation" combination (SC_{LP-4}/SC_{HP-4}) results in the smallest coverage. Additionally, the analysis shows that LCB area grows steadily in the early stages but slows down thereafter, while NZEB and ZEB areas rapidly increase during the mandatory promotion and stable development phases

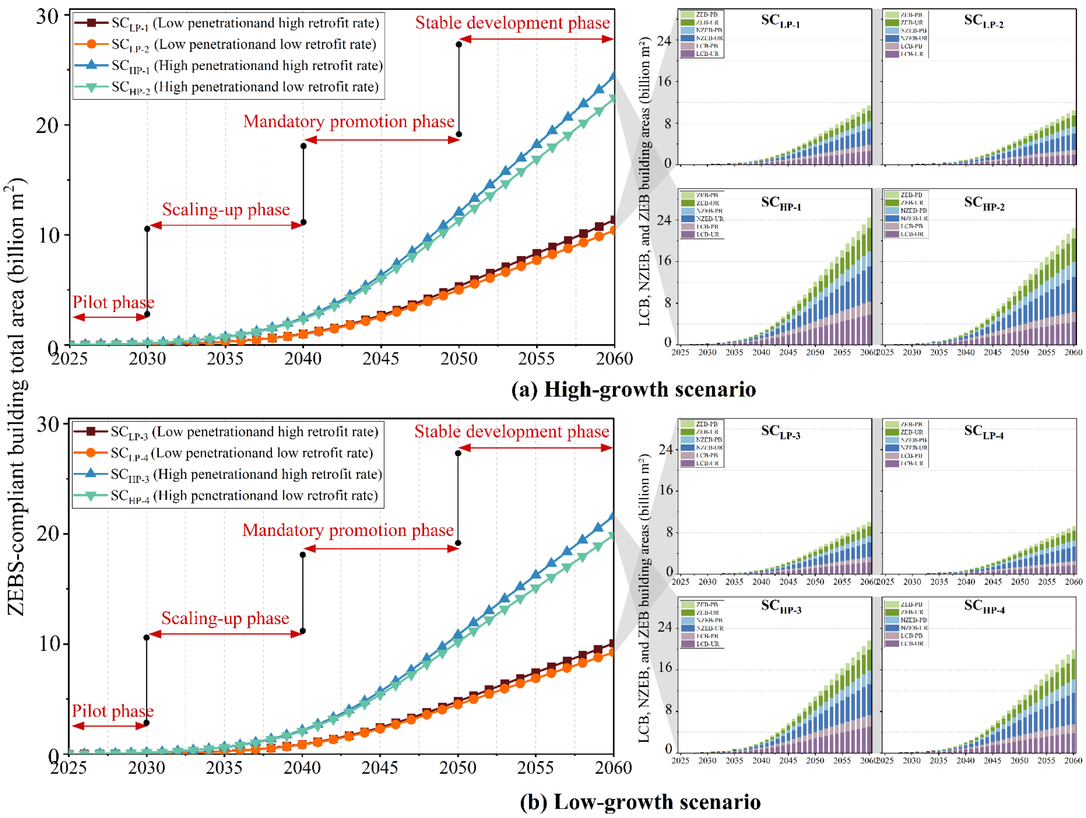

Fig. 5 Projections of the changes in the areas of LCB, NZEB, and ZEB nationwide.

Table 4 Statistics of the areas of LCB, NZEB, and ZEB nationwide (Million m^2).

Low ZEBS Penetration Rate																
	LP-1				LP-2				LP-3				LP-4			
	LCB	NZEB	ZEB	**Total**	LCB	NZEB	ZEB	**Total**	LCB	NZEB	ZEB	**Total**	LCB	NZEB	ZEB	**Total**
2030	50	10	5	**66**	48	10	5	**63**	42	8	4	**55**	40	8	4	**53**
2040	528	315	170	**1013**	484	315	170	**969**	464	280	151	**895**	426	280	151	**856**
2050	2024	2076	1237	**5337**	1692	2076	1237	**5004**	1794	1876	1119	**4789**	1507	1876	1119	**4502**
2060	3868	4513	2995	**11376**	2915	4513	2995	**10424**	3391	4014	2660	**10065**	2571	4014	2660	**9245**
High ZEBS Penetration Rate																
	HP-1				HP-2				HP-3				HP-4			
	LCB	NZEB	ZEB	**Total**	LCB	NZEB	ZEB	**Total**	LCB	NZEB	ZEB	**Total**	LCB	NZEB	ZEB	**Total**

2030	125	25	13	**163**	119	25	13	**157**	105	21	11	**137**	100	21	11	**131**
2040	1284	763	410	**2457**	1177	763	410	**2350**	1129	678	364	**2171**	1036	678	364	**2078**
2050	4617	4671	2777	**12065**	3873	4671	2777	**11321**	4091	4221	2511	**10823**	3450	4221	2511	**10182**
2060	8380	9666	6378	**24424**	6374	9666	6378	**22418**	7349	8600	5664	**21614**	5624	8600	5664	**19889**

(2) Climate zone level

Fig. 6 and **Table 5** present the predicted areas of LCB, NZEB, and ZEB buildings across five climate zones, showing significant regional differences. The areas of high-efficiency buildings are highest in the hot summer and cold winter (HSCW) region. In the high penetration scenario, the areas of LCB, NZEB, and ZEB in this region are 3.9, 4.3, and 2.9 billion square meters, respectively. In the low penetration scenario, the areas are 1.8, 2.1, and 1.4 billion square meters. The areas of high-efficiency buildings are lowest in the Cold Climate region. In the high penetration scenario, the areas of LCB, NZEB, and ZEB in this region are 0.4, 0.6, and 0.4 billion square meters, respectively. In the low penetration scenario, the areas are 0.3, 0.3, and 0.2 billion square meters.

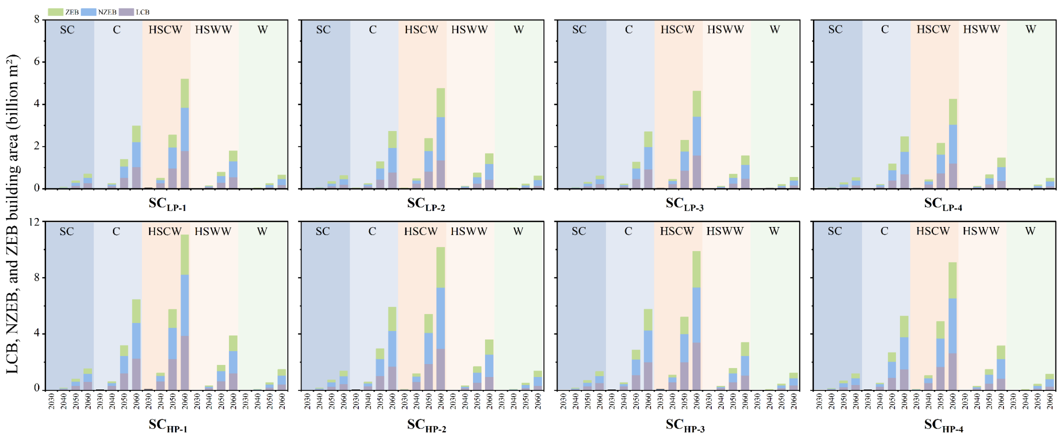

Fig. 6 Forecast of the area changes of LCB, NZEB, and ZEB across the five climate zones.

Table 5 Area statistics of LCB, NZEB, and ZEB across the five climate zones (Million m^2).

Low ZEBS Penetration Rate													
		LP-1			LP-2			LP-3			LP-4		
		LCB	NZEB	ZEB	LCB	NZEB	ZEB	LCB	NZEB	ZEB	LCB	NZEB	ZEB
SC	2030	3.6	0.7	0.4	3.4	0.7	0.4	3.1	0.6	0.3	2.9	0.6	0.3
	2040	38.1	22.5	12.1	34.8	22.5	12.1	33.6	20.0	10.8	30.7	20.0	10.8
	2050	150.9	138.8	82.4	122.5	138.8	82.4	125.6	119.1	70.7	103.0	119.1	70.7
	2060	275.9	257.9	168.9	198.5	257.9	168.9	239.4	222.7	145.2	172.8	222.7	145.2
C	2030	12.7	3.2	5.5	23.3	4.0	3.0	10.6	2.1	1.1	10.0	2.1	1.1
	2040	133.3	80.1	44.6	125.2	80.2	43.5	118.3	71.6	38.5	108.5	71.6	38.5
	2050	526.5	537.1	320.8	438.2	537.1	320.4	473.1	495.0	295.5	396.1	495.0	295.5
	2060	1036.3	1173.4	779.6	771.6	1173.4	779.5	922.6	1068.1	708.5	692.1	1068.1	708.5
HSCW	2030	25.8	5.2	2.6	24.5	5.2	2.6	21.7	4.3	2.2	20.5	4.3	2.2
	2040	264.8	157.1	84.4	242.4	157.1	84.4	233.7	140.2	75.4	214.1	140.2	75.4
	2050	976.1	984.7	585.9	815.6	984.7	585.9	870.8	899.1	535.3	732.1	899.1	535.3
	2060	1794.7	2046.6	1351.2	1356.8	2046.6	1351.2	1584.3	1837.7	1210.9	1205.8	1837.7	1210.9

HSWW	2030	6.9	1.4	0.7	6.6	1.4	0.7	6.0	1.2	0.6	5.7	1.2	0.6
	2040	73.1	44.2	23.8	67.3	44.2	23.8	64.2	38.9	20.9	59.1	38.9	20.9
	2050	289.3	315.3	188.5	245.4	315.3	188.5	254.1	279.0	166.8	216.1	279.0	166.8
	2060	558.5	741.8	496.5	432.7	741.8	496.5	487.3	652.1	436.2	378.7	652.1	436.2
W	2030	1.4	0.3	0.1	1.4	0.3	0.1	1.1	0.2	0.1	1.1	0.2	0.1
	2040	17.6	11.0	5.9	16.3	11.0	5.9	14.5	9.1	4.9	13.4	9.1	4.9
	2050	84.5	99.3	59.8	72.0	99.3	59.8	70.4	83.8	50.5	60.1	83.8	50.5
	2060	190.6	278.1	189.3	146.9	278.1	189.3	157.5	233.5	158.9	122.1	233.5	158.9
High ZEBS Penetration Rate													
		HP-1			HP-2			HP-3			HP-4		
		LCB	NZEB	ZEB	LCB	NZEB	ZEB	LCB	NZEB	ZEB	LCB	NZEB	ZEB
SC	2030	8.8	1.8	0.9	8.3	1.8	0.9	7.4	1.5	0.7	7.0	1.5	0.7
	2040	91.6	53.9	29.0	83.6	53.9	29.0	80.9	48.0	25.8	73.9	48.0	25.8
	2050	325.8	302.7	179.4	267.1	302.7	179.4	287.5	270.6	160.3	236.7	270.6	160.3
	2060	604.2	568.3	370.6	439.4	568.3	370.6	524.5	491.2	319.0	382.8	491.2	319.0
C	2030	31.3	6.3	3.2	29.8	6.3	3.2	26.3	5.3	2.6	24.9	5.3	2.6
	2040	327.5	195.6	105.1	300.3	195.6	105.1	288.2	174.0	93.6	264.5	174.0	93.6
	2050	1216.7	1226.6	729.9	1016.0	1226.6	729.9	1082.2	1117.9	665.6	909.5	1117.9	665.6
	2060	2260.1	2532.5	1671.0	1700.0	2532.5	1671.0	1990.7	2277.5	1500.4	1508.2	2277.5	1500.4
HSCW	2030	64.6	12.9	6.5	61.4	12.9	6.5	54.2	10.8	5.4	51.3	10.8	5.4
	2040	648.5	382.9	205.8	593.7	382.9	205.8	572.1	341.6	183.7	524.3	341.6	183.7
	2050	2228.0	2213.1	1313.0	1869.5	2213.1	1313.0	1987.0	2019.8	1199.0	1677.3	2019.8	1199.0
	2060	3870.3	4343.6	2846.8	2956.1	4343.6	2846.8	3418.8	3903.4	2553.5	2628.6	3903.4	2553.5
HSWW	2030	17.1	3.5	1.7	16.3	3.5	1.7	14.8	3.0	1.5	14.0	3.0	1.5
	2040	176.6	106.2	57.1	162.5	106.2	57.1	155.2	93.6	50.3	142.7	93.6	50.3
	2050	656.1	705.2	420.6	558.1	705.2	420.6	576.3	624.0	372.2	491.5	624.0	372.2
	2060	1216.2	1596.1	1063.7	948.3	1596.1	1063.7	1060.9	1402.5	934.0	830.0	1402.5	934.0
W	2030	3.3	0.7	0.3	3.1	0.7	0.3	2.5	0.5	0.3	2.4	0.5	0.3
	2040	39.6	24.8	13.4	36.6	24.8	13.4	32.6	20.6	11.1	30.1	20.6	11.1
	2050	190.2	223.4	134.5	161.9	223.4	134.5	158.3	188.6	113.6	135.3	188.6	113.6
	2060	428.8	625.6	425.9	330.5	625.6	425.9	354.5	525.3	357.5	274.6	525.3	357.5

3.2. Carbon emission scenario analysis

3.2.1. Analysis of energy consumption and carbon emission in the national building sector

This section presents the energy consumption and carbon emission forecast results for the national building sector (including rural buildings) to 2060 under 12 different scenarios (**Fig. 7**、**Fig. 8**、**Table 6** and **Table 7**). Overall, energy consumption and carbon emissions in all scenarios show a "rise then decline" trend, but the peak levels, peak years, and long-term trajectories vary significantly depending on the scenario settings. In terms of energy consumption, the predicted values for 2025 range from 738 to 783 Mtce, with differences mainly reflecting the combinations of new construction and retrofit scales. Energy consumption is expected to peak around 2040. Among all scenarios, the SC_{BAU} has the highest and latest peak (788−889 Mtce, 2038−2041), while the SC_{HP} has the lowest and earliest peak (782–877 Mtce, 2036–2038). Compared to the baseline year of 2020, although all scenarios show an increase in energy consumption in 2030 (14%–24%), by 2060, energy consumption in the SC_{HP} and SC_{LP} is expected to decrease by 0%–10%, while some SC_{BAU} will still see an increase of 4%–19%.

Regarding carbon emissions, driven by the continued optimization of the energy structure, the peak time for carbon emissions (2027 – 2030) occurs much earlier than for energy consumption (around 2040). Carbon emissions in all scenarios are expected to peak between 2027 and 2030 (2281–2483 $MtCO_2$), about 8–10 years earlier than the energy consumption peak. After reaching the peak, emissions will rapidly decline, reaching a range of 273–689 $MtCO_2$ by 2060. Compared to the 2020 baseline year, emissions are also expected to rise in 2030 (7%–18%), but by 2060, deep reductions of 79%–87% are achieved, particularly in the HP scenario, where reductions in residential and public buildings are as high as 86% and 87%, respectively. The results clearly indicate that the combination of "low new construction scale" and "high retrofit intensity," along with "high ZEBS penetration" (e.g., SC_{HP-3}), is the most effective path for achieving early peak carbon emissions and deep decarbonization in the building sector. In contrast, the combination of "high new construction, low retrofit" (e.g., SC_{BAU-2}) performs the worst in terms of energy consumption and emissions control.

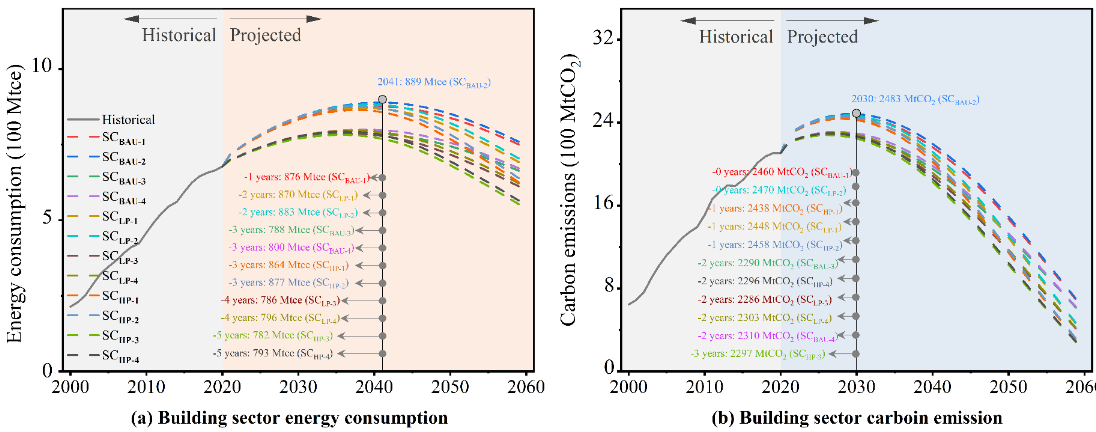

Fig. 7 Comparative analysis of the overall trends in energy consumption and carbon emissions across 12 scenarios at the national level.

Table 6 Energy consumption (Mtce) and carbon emissions ($MtCO_2$) statistics at the national level for 2025, peak carbon emission year, and 2060 under 12 scenarios.

	BAU-1	BAU-2	BAU-3	BAU-4	LP-1	LP-2	LP-3	LP-4	HP-1	HP-2	HP-3	HP-4
Building sector energy consumption												
2025	779	783	738	742	779	783	738	742	779	783	738	742
Peak value	876	889	788	799	870	883	786	796	864	877	782	793
Peak time	2040	2041	2038	2038	2039	2039	2037	2037	2038	2038	2036	2036
2060	740	748	654	661	679	689	600	609	608	622	538	550

Building sector carbon emission												
2025	2393	2405	2271	2283	2390	2402	2268	2280	2388	2401	2267	2279
Peak value	2460	2483	2293	2310	2447	2469	2285	2302	2440	2460	2281	2298
Peak time	2030	2030	2028	2028	2029	2030	2028	2028	2029	2029	2027	2028
2060	681	689	605	612	448	455	402	408	298	304	273	278

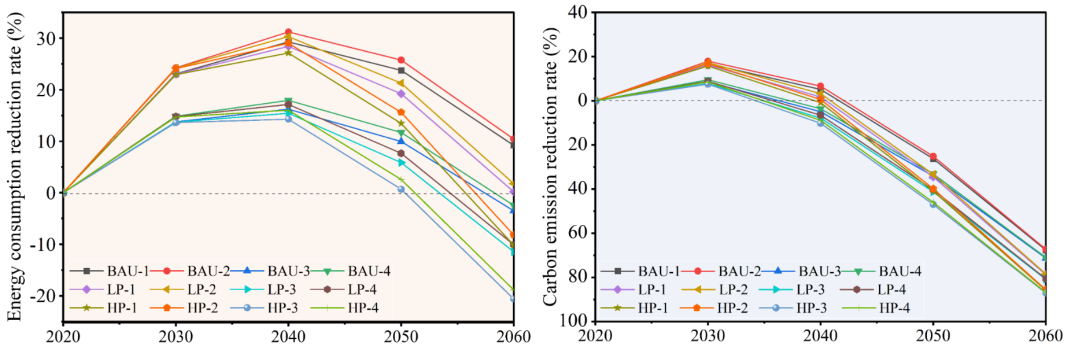

Fig. 8 Changes in energy consumption and carbon emissions in the building sector relative to 2020 under different scenarios at key years.

Table 7 Energy consumption and carbon emissions statistics at the national level for 2025, peak carbon emission year, and 2060 under 12 scenarios.

	BAU-1	BAU-2	BAU-3	BAU-4	LP-1	LP-2	LP-3	LP-4	HP-1	HP-2	HP-3	HP-4
Building sector energy consumption (Mtce)												
2020	677	677	677	677	677	677	677	677	677	677	677	677
2030	834	842	771	778	833	841	770	778	833	841	770	777
2060	740	748	654	661	679	689	600	609	608	622	538	550
Energy consumption reduction rate (compare to 2020)												
2020	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2030	23%	24%	14%	15%	23%	24%	14%	15%	23%	24%	14%	15%
2060	9%	10%	-4%	-2%	0%	2%	-11%	-10%	-10%	-8%	-21%	-19%
Building sector carbon emission ($MtCO_2$)												
2020	2106	2106	2106	2106	2106	2106	2106	2106	2106	2106	2106	2106
2030	2460	2483	2284	2305	2446	2469	2271	2292	2437	2459	2263	2284
2060	681	689	605	612	448	455	402	408	298	304	273	278
Carbon emission reduction rate (compare to 2020)												
2020	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2030	17%	18%	8%	9%	16%	17%	8%	9%	16%	17%	7%	8%
2060	-68%	-67%	-71%	-71%	-79%	-78%	-81%	-81%	-86%	-86%	-87%	-87%

3.2.2.Analysis of energy consumption and carbon emissions at the climate zone level

At the regional level, the evolution of building energy consumption and carbon emissions exhibits clear regional differences (**Table 8**). The cold region (C) and HSCW are the largest sources of energy consumption and carbon emissions, followed by the severe cold region (SC). Although all scenarios predict a general decrease in energy consumption and emissions across all regions by 2060, the magnitude of the decline varies depending on the intensity of ZEBS promotion. For example, in the cold region (C), energy consumption in 2060 ranges from 216–247 Mtce under SC_{BAU}, while under SC_{HP}, it decreases to 178–206 Mtce. Carbon emissions in 2060 under SC_{BAU} range from 274–313 $MtCO_2$, whereas under SC_{HP}, they decrease significantly to 106–118 $MtCO_2$. In terms of emission reduction potential, the decline varies across different climate zones. SC exhibits the greatest emission reduction potential, with a reduction range between 67.6% (SC_{BAU-2}) and 90.7% (SC_{HP-3}). The C and HSCW regions also show significant reductions, with reductions reaching up to 86.5% and 86.8%, respectively. In contrast, HSWW and the warm region (W) have slightly lower maximum reductions, at 81.7% and 85.5%, respectively. This result indicates that in the high-energy consumption northern heating areas, the emission reduction effects achieved through ZEBS promotion are particularly significant.

Table 8 Predicted building energy consumption and carbon emissions in 2060 for different climate zones under various scenarios.

	BAU-1	BAU-2	BAU-3	BAU-4	LP-1	LP-2	LP-3	LP-4	HP-1	HP-2	HP-3	HP-4
Energy consumption (Mtce)												
SC	132	134	115	116	122	125	106	108	109	113	95	98
C	244	247	216	219	224	229	198	202	201	206	178	182
HSCW	233	236	207	209	215	220	191	194	195	198	173	176
HSWW	95	95	84	85	85	87	75	76	73	75	65	66
W	35	36	31	31	33	34	29	29	30	30	26	27
Carbon emission ($MtCO_2$)												
SC	144	146	125	127	73	74	64	65	47	49	42	43
C	309	313	274	278	199	202	178	181	115	118	106	108
HSCW	167	169	149	151	122	124	110	112	89	91	81	82
HSWW	45	46	42	42	40	41	38	38	35	35	33	33
W	16	16	14	14	14	14	12	12	12	12	11	11

3.2.3. Analysis of energy consumption and carbon emissions by building type

Fig. 9 and **Table 9** present the evolution of energy consumption and energy use intensity (EUI) for urban residential (UR) and public buildings (PB) under 12 different scenarios. The results show that the energy consumption of both building types exhibits a "rise and fall" pattern, with a significant reduction in peak energy consumption levels and an earlier peak time as the scenarios transition from SC_{BAU} to SC_{LP} and SC_{HP} optimizations. For urban residential buildings, under SC_{BAU}, energy consumption peaks around 2040-2041 at 40-41 Mtce. In SC_{LP}, the peak is brought forward to 2037-2039, with a reduced peak scale of 35-40 Mtce. SC_{HP} shows the most significant effect, with the peak further advancing to 2036-2038 (35-39 Mtce), a reduction of about 15% compared to SC_{BAU}. By 2060, the EUI under SC_{HP} could fall to 5.1-5.3 kgce/m^2, reflecting a 45% improvement in energy efficiency compared to 2020. Public buildings follow a similar pattern, but their peak time is generally later than that of urban residential buildings. Under SC_{BAU}, the peak energy consumption occurs around

2048-2049 (approximately 34 Mtce). In SC_{HP}, the peak time is significantly brought forward to 2039-2041, about 8-10 years earlier, with the peak scale dropping to 28-33 Mtce. By 2060, the EUI in the SC_{HP} could decrease to 11.2-11.7 kgce/m^2, representing a 35% improvement in energy efficiency compared to 2020. Overall, urban residential buildings' energy consumption is significantly lower across all scenarios compared to public buildings, but public buildings consistently have higher energy use intensity. With the comprehensive implementation of ZEBS standards and enhanced energy-saving retrofits, not only does the overall energy consumption peak level in the building sector decrease effectively, but the peak time is also significantly advanced.

Table 9 Predicted energy consumption (×10^4 tce) and peak time of urban residential and public buildings in key years under different scenarios.

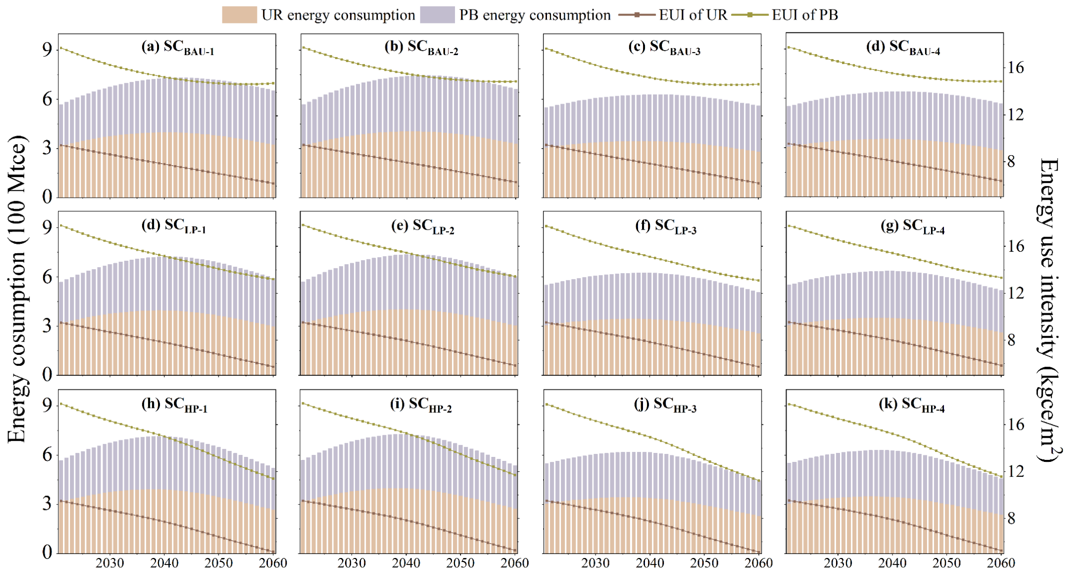

Fig. 9 Predicted energy consumption and energy intensity of urban residential and public buildings under different scenarios.

	UR		PB		UR		PB		UR		PB		UR		PB	
	EC	EUI	EC	EUI	EC	EUI	EC	EUI	EC	EUI	EC	EUI	EC	EUI	EC	EUI
	BAU-1				BAU-2				BAU-3				BAU-4			
2020	3.1	9.5	2.5	18.0	3.1	9.5	2.5	18.0	3.1	9.5	2.5	18.0	3.1	9.5	2.5	18.0
2030	3.8	8.7	3.0	16.4	3.8	8.8	3.0	16.6	3.4	8.8	2.7	16.3	3.4	8.8	2.7	16.6
Peak	4.0	7.9	3.4	14.8	4.1	7.9	3.4	15.1	3.5	8.1	2.9	15.1	3.5	8.1	2.9	15.1
Peak time	2040		2049		2041		2048		2038		2048		2039		2048	
2060	3.3	6.2	3.3	14.8	3.3	6.3	3.3	14.9	2.8	6.3	2.8	14.7	2.9	6.4	2.8	14.9
	LP-1				LP-2				LP-3				LP-4			
2030	3.8	8.7	3.0	16.3	3.8	8.8	3.0	16.6	3.4	8.7	2.7	16.3	3.4	8.8	2.7	16.5
Peak	4.0	7.9	3.3	14.9	4.0	8.0	3.3	15.0	3.5	8.1	2.8	14.9	3.5	8.3	2.9	15.2
Peak time	2039		2043		2039		2044		2037		2042		2037		2042	
2060	3.0	5.7	2.9	13.2	3.1	5.8	3.0	13.4	2.6	5.7	2.5	13.1	2.6	5.8	2.5	13.3
	HP-1				HP-2				HP-3				HP-4			

2030	3.8	8.7	3.0	16.3	3.8	8.8	3.0	16.5	3.4	8.7	2.7	16.3	3.4	8.8	2.7	16.5
Peak	3.9	7.9	3.2	14.8	4.0	8.1	3.3	15.1	3.5	8.2	2.8	15.1	3.5	8.3	2.8	15.4
Peak time	2038		2041		2038		2041		2036		2039		2036		2039	
2060	2.7	5.2	2.5	11.4	2.8	5.3	2.6	11.7	2.3	5.1	2.1	11.2	2.4	5.3	2.2	11.6

Fig. 10 and **Table 10** present the changes in total carbon emissions and carbon emission intensity for urban residential and public buildings under different scenarios. Overall, both types of buildings exhibit a "rise and fall" trend in carbon emissions, with the carbon emission peak generally occurring earlier than the energy consumption peak. Under SC_{BAU}, in 2020, the carbon emission for urban residential buildings was 830 $MtCO_2$, and the carbon emission intensity was 25.7 $kgCO_2/m^2$. By 2030, both energy consumption and carbon emission intensity significantly increased, reaching 960 $MtCO_2$ and 22.2 $kgCO_2/m^2$, respectively. The carbon emission peak occurred in 2031-2032. By 2060, carbon emissions for urban residential buildings decreased to 310 $MtCO_2$, a reduction of 65%, and carbon emission intensity decreased to 6.0–6.1 $kgCO_2/m^2$. In SC_{LP}, with the increase in clean energy proportion and building retrofitting efforts, the carbon emission peak is brought forward to 2027-2031, with a peak range of 860–970 $MtCO_2$. By 2060, carbon emissions drop to 170–200 $MtCO_2$, a reduction of 78%. In SC_{HP}, with the promotion of the ZEBS standard and energy decarbonization, the carbon emission peak is brought forward to 2030, with emissions decreasing to 100–120 $MtCO_2$. By 2060, emissions are reduced by 85%–90%. For public buildings, under SC_{BAU}, in 2020, the energy consumption was 850 $MtCO_2$, and the carbon emission intensity was 62.1 $kgCO_2/m^2$. By 2030, both energy consumption and carbon emission intensity significantly increased, with carbon emission intensity reaching 53.3 $kgCO_2/m^2$, and the carbon emission peak occurring in 2031-2032. By 2060, carbon emissions for public buildings decreased to 270 $MtCO_2$, a reduction of 70%, with carbon emission intensity decreasing to 13.1–13.2 $kgCO_2/m^2$. In SC_{LP}, the carbon emission peak for public buildings occurs between 2028-2031, reaching 870–990 $MtCO_2$. By 2060, emissions decrease to 150–180 $MtCO_2$, a reduction of 85%. In SC_{HP}, with the promotion of ZEBS standards, the carbon emission peak is brought forward to 2031, with emissions reducing to 80–100 $MtCO_2$, a reduction of 85%–90%. Overall, for both urban residential and public buildings, the peak of carbon emissions occurs approximately 5–10 years earlier than the peak of energy consumption. This trend is mainly driven by the decarbonization of the energy structure and the increase in the proportion of renewable energy. Meanwhile, with the widespread implementation of ZEBS standards and the continuous advancement of deep retrofits in existing buildings, the total carbon emissions and carbon emission intensity in the building sector continue to decline, significantly accelerating the transition of the building industry from the "carbon peak" to the "carbon neutrality" goal.

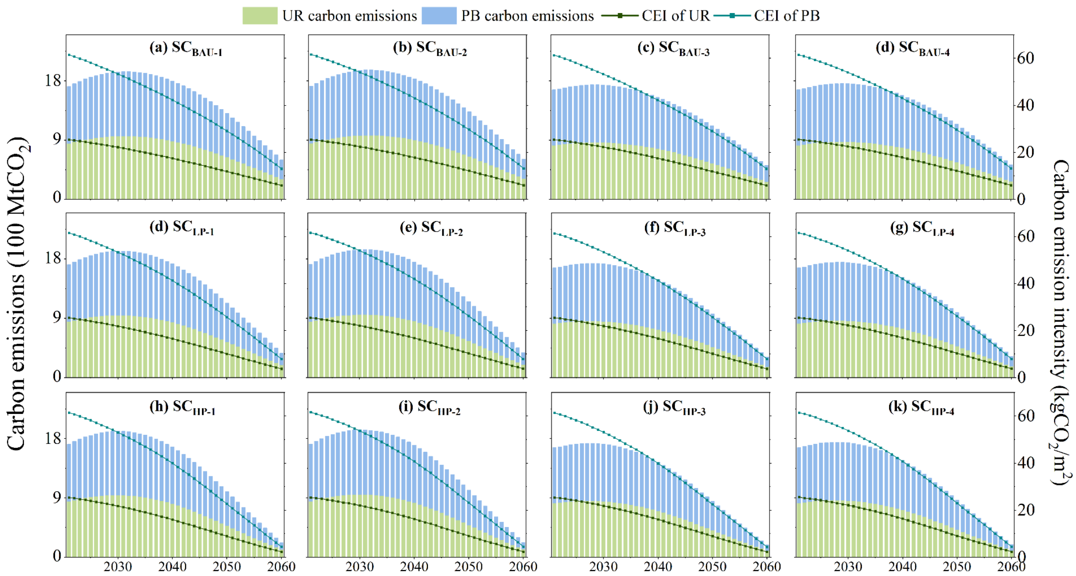

Fig. 10 Predicted carbon emissions and carbon intensity of urban residential and public buildings under different scenarios.

Table 10 Predicted carbon emissions and peak time of urban residential and public buildings in key years under different scenarios.

	UR		PB		UR		PB		UR		PB		UR		PB	
	CE	CEI	CE	CEI	CE	CEI	CE	CEI	CE	CEI	CE	CEI	CE	CEI	CE	CEI
	BAU-1				BAU-2				BAU-3				BAU-4			
2020	8.3	25.7	8.5	62.1	8.3	25.7	8.5	62.1	8.3	25.7	8.5	62.1	8.3	25.7	8.5	62.1
2030	9.6	22.2	9.7	53.3	9.7	22.4	9.9	53.9	8.7	22.3	8.7	53.4	8.8	22.6	8.8	54.0
Peak	9.6	21.8	9.7	52.3	9.8	21.6	9.9	52.0	8.7	22.7	8.7	55.0	8.8	23.0	8.8	55.0
Peak time	2031		2031		2032		2032		2029		2028		2029		2029	
2060	3.1	6.0	2.9	13.1	3.2	6.1	2.9	13.2	2.7	6.0	2.5	13.1	2.8	6.1	2.5	13.2
	LP-1				LP-2				LP-3				LP-4			
2030	9.5	21.9	9.7	53.3	9.6	22.1	9.9	53.9	8.5	22.0	8.7	53.4	8.6	22.2	8.8	54.0
Peak	9.5	21.9	9.7	52.2	9.6	21.7	9.9	52.9	8.6	23.3	8.7	55.4	8.7	23.1	8.8	55.0
Peak time	2030		2031		2031		2031		2027		2028		2028		2029	
2060	2.0	3.7	1.7	7.9	2.0	3.8	1.8	8.0	1.7	3.8	1.5	7.8	1.7	3.8	1.5	8.0
	HP-1				HP-2				HP-3				HP-4			
2030	9.4	21.8	9.7	53.0	9.5	22.0	9.8	53.7	8.5	21.9	8.7	53.1	8.6	22.1	8.8	53.8
Peak	9.4	21.8	9.7	53.0	9.5	22.0	9.8	52.6	8.6	23.3	8.7	55.3	8.7	23.0	8.8	55.8
Peak time	2030		2030		2030		2031		2027		2028		2028		2028	
2060	1.2	2.3	1.0	4.5	1.2	2.4	1.0	4.6	1.0	2.3	0.8	4.4	1.1	2.4	0.9	4.6

3.3. Carbon emission difference assessment

3.3.1. Scenario-based comparison of national building energy consumption and carbon emission

Fig. 11 and **Table 11** present a comparative analysis of energy consumption and carbon emission differences in the national building sector under various scenarios. At the national scale, energy consumption in the building sector exhibits significant differentiation across scenarios. With the intensification of ZEBS standard promotion and the acceleration of building retrofits, total energy consumption declines noticeably, energy-saving rates (ESR) increase progressively, and energy-saving potential is particularly pronounced in the mid-to-late stages. Under SC_{LP}, energy-saving effects gradually strengthen over time. For example, comparing SC_{BAU-1} to SC_{BAU-4} with SC_{LP-1} to SC_{LP-4}, the energy saved in 2030 ranges from 0.3 to 0.4 Mtce, with an ESR of 0.1%; in 2040, the saved energy ranges from 5.4 to 6.1 Mtce, ESR 0.8%–0.9%; in 2050, 27.4–30.9 Mtce (ESR 4.2%–4.5%); and by 2060, 51.7–61.1 Mtce (ESR 9.1%–9.6%). This indicates that in the medium- to long-term, the cumulative effects of building retrofits and energy efficiency measures become increasingly significant. Under SC_{HP}, the energy-saving potential is further unlocked. Comparing SC_{BAU-1} to SC_{BAU-4} with SC_{HP-1} to SC_{HP-4}, energy savings in 2030 range from 8.1 to 9.7 Mtce (ESR 0.1%); in 2040, 13.1–14.7 Mtce (ESR 2.0%–2.1%); in 2050, 61.9–69.8 Mtce (ESR 9.4%–9.9%); and by 2060, 111.2–131.2 Mtce (ESR 19.0%–20.6%). Compared with SC_{LP}, total energy savings under SC_{HP} in 2060 are roughly double, highlighting the substantial efficiency gains resulting from the mandatory implementation of ZEBS standards and accelerated retrofits.

Regarding national building sector carbon emissions, different promotion scenarios produce significant differences. The promotion of ZEBS standards and enhanced retrofit efforts significantly reduce peak emissions and advance the timing of the carbon peak. Under SC_{LP}, cumulative emission reductions (CERP) gradually increase over time, demonstrating progressively stronger mitigation effects. For instance, comparing SC_{BAU-1} to SC_{BAU-4} with SC_{LP-1} to SC_{LP-4}, carbon reductions in 2030 range from 13.0–14.6 $MtCO_2$ (CERP 0.8%); in 2040, 61.6–71.7 $MtCO_2$ (CERP 3.9%–4.0%); in 2050, 150.0–173.6 $MtCO_2$ (CERP 13.1%–13.4%); and by 2060, 202.3–234.5 $MtCO_2$ (CERP 38.4%–38.9%). This shows that under SC_{LP}, mid- to long-term carbon reduction potential is gradually realized, with cumulative reductions accounting for a significant portion of national emissions by 2060. Under SC_{HP}, carbon reduction effects are even more pronounced. Comparing SC_{BAU-1} to SC_{BAU-4} with SC_{HP-1} to SC_{HP-4}, reductions in 2030 range from 20.9–23.7 $MtCO_2$ (CERP 1.2%); in 2040, 109.8–127.5 $MtCO_2$ (CERP 7.0%–7.1%); in 2050, 269.8–310.8 $MtCO_2$ (CERP 23.4%–24.1%); and by 2060, 332.0–385.1 $MtCO_2$ (CERP 63.3%–63.8%). Compared with SC_{LP}, SC_{HP} achieves more than 1.6 times the carbon reduction by 2060, demonstrating the significant contribution of high-intensity ZEBS promotion and accelerated retrofits to decarbonization in the building sector.

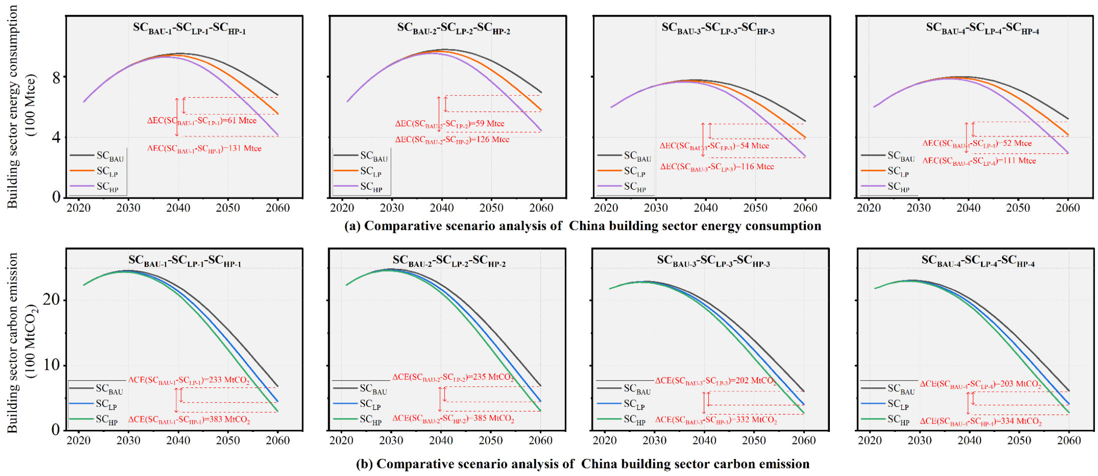

Fig. 11 Comparison and analysis of energy consumption and carbon emissions differences in the national building sector under different scenarios.

Table 11 Comparison of energy consumption and carbon emissions in the national building sector under different scenarios (with ESR and CERP).

	Comparison of energy consumption differences (Mtce)				**Comparison of carbon emission differences ($MtCO_2$)**			
	Δ SC_{BAU-1}-SC_{LP-1}	ESR	Δ SC_{BAU-1}-SC_{HP-1}	ESR	Δ SC_{BAU-1}-SC_{LP-1}	CERP	Δ SC_{BAU-1}-SC_{HP-1}	CERP
2030	0.4	0.1%	1.0	0.1%	14.5	0.8%	23.4	1.2%
2040	6.1	0.8%	14.7	2.0%	70.6	3.9%	125.8	7.0%
2050	30.9	4.3%	69.8	9.7%	171.9	13.2%	308.5	23.6%
2060	61.1	9.3%	131.2	20.1%	233.4	38.7%	382.9	63.5%
	Δ SC_{BAU-2}-SC_{LP-2}	ESR	Δ SC_{BAU-2}-SC_{HP-2}	ESR	Δ SC_{BAU-2}-SC_{LP-2}	CERP	Δ SC_{BAU-2}-SC_{HP-2}	CERP
2030	0.4	0.1%	1.0	0.1%	14.6	0.8%	23.7	1.2%
2040	6.1	0.8%	14.7	2.0%	71.7	3.9%	127.5	7.0%
2050	30.4	4.2%	68.8	9.4%	173.6	13.1%	310.8	23.4%
2060	58.6	8.9%	126.1	19.0%	234.5	38.4%	385.1	63.0%
	Δ SC_{BAU-3}-SC_{LP-3}	ESR	Δ SC_{BAU-3}-SC_{HP-3}	ESR	Δ SC_{BAU-3}-SC_{LP-3}	CERP	Δ SC_{BAU-3}-SC_{HP-3}	CERP
2030	0.3	0.1%	0.8	0.1%	13.0	0.8%	20.9	1.2%
2040	5.4	0.9%	13.1	2.1%	61.6	4.0%	109.8	7.1%
2050	27.8	4.5%	62.8	10.2%	150.0	13.4%	269.8	24.1%
2060	53.8	9.6%	115.7	20.6%	202.3	38.9%	331.9	63.8%
	Δ SC_{BAU-4}-SC_{LP-4}	ESR	Δ SC_{BAU-4}-SC_{HP-4}	ESR	Δ SC_{BAU-4}-SC_{LP-4}	CERP	Δ SC_{BAU-4}-SC_{HP-4}	CERP
2030	0.3	0.1%	0.8	0.1%	13.1	0.8%	21.2	1.2%
2040	5.4	0.8%	13.1	2.0%	62.6	4.0%	111.3	7.0%
2050	27.4	4.4%	61.9	9.9%	151.6	13.3%	271.9	23.8%
2060	51.7	9.1%	111.2	19.6%	203.3	38.5%	333.9	63.3%

3.3.2. Scenario-based comparison of urban residential and public building energy consumption and carbon emission

Fig. 12 and **Table 12** show a comparative analysis of energy consumption differences in urban residential and public buildings under different scenarios. In SC_{LP}, the energy-saving amount in urban residential buildings increases gradually over time. For example, comparing SC_{BAU-1} to SC_{BAU-4} with SC_{LP-1} to SC_{LP-4}, the energy saving in 2030 is approximately 0.2 Mtce, with an energy-saving rate (ESR) of about 0.1%. By 2040, the energy-saving amount reaches 2.9–3.2 Mtce, with an ESR of about 0.8%. In 2050, the energy-saving amount increases to 13.4–14.9 Mtce, with an ESR of 3.8%–4.1%. By 2060, the energy-saving amount is 22.8–26.3 Mtce, with an ESR of 7.7%–8.3%. The energy-saving effects for public buildings are slightly higher than for residential buildings, with the energy-saving amount in 2060 ranging from 28.9 to 34.8 Mtce, resulting in an ESR of 10.0%–10.9%. It is evident that in the low promotion scenario, the energy-saving potential in the later stages gradually increases, especially in public buildings where the energy-saving effect is more pronounced. In SC_{HP}, the reduction in building energy consumption is significantly higher. For example, comparing SC_{BAU-1} to SC_{BAU-4} with SC_{HP-1} to SC_{HP-4}, in 2030, the energy-saving amount for urban residential buildings ranges from 0.5 to 0.5 Mtce, with an ESR of about 0.1%. By 2040, energy savings increase to 7.1–7.9 Mtce, with an ESR of about 2.0%. In 2050, the energy-saving amount is 30.4–33.8 Mtce, with an ESR of 8.6%–9.3%. By 2060, the energy-saving amount reaches 48.9–56.3 Mtce, with an ESR of 17.1%–17.8%. Public buildings perform even better in the high promotion scenario, with energy savings in 2060 ranging from 62.3 to 74.9 Mtce, resulting in an ESR of 22.1%–22.9%.

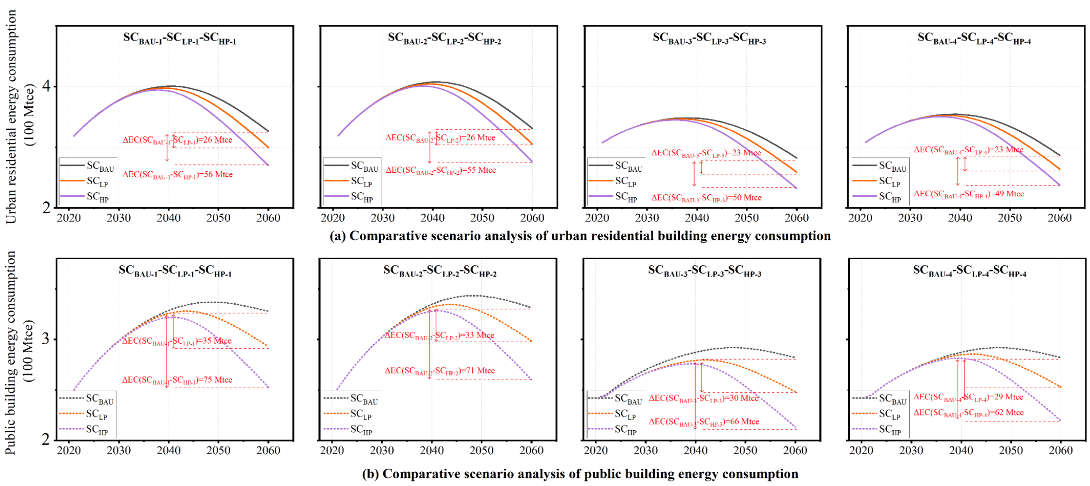

Fig. 12 Comparison and analysis of energy consumption differences between urban residential and public buildings under different scenarios.

Table 12 Comparison of energy consumption (Mtce) differences between urban residential and public buildings under different scenarios (with ESR and CERP).

	Urban residential				**Public building**			
	Δ SC_{BAU-1}-SC_{LP-1}	ESR	Δ SC_{BAU-1}-SC_{HP-1}	ESR	Δ SC_{BAU-1}-SC_{LP-1}	ESR	Δ SC_{BAU-1}-SC_{HP-1}	ESR
2030	0.2	0.1%	0.5	0.1%	0.2	0.1%	0.4	0.1%
2040	3.2	0.8%	7.9	2.0%	2.8	0.9%	6.9	2.1%
2050	14.9	3.9%	33.8	8.9%	16.0	4.7%	36.0	10.7%
2060	26.3	8.0%	56.3	17.3%	34.8	10.6%	74.9	22.9%
	Δ SC_{BAU-2}-SC_{LP-2}	ESR	Δ SC_{BAU-2}-SC_{HP-2}	ESR	Δ SC_{BAU-2}-SC_{LP-2}	ESR	Δ SC_{BAU-2}-SC_{HP-2}	ESR
2030	0.2	0.1%	0.5	0.1%	0.2	0.1%	0.4	0.1%
2040	3.2	0.8%	7.9	1.9%	2.8	0.8%	6.8	2.0%
2050	14.8	3.8%	33.5	8.6%	15.6	4.6%	35.3	10.3%
2060	25.6	7.7%	54.9	16.6%	33.1	10.0%	71.2	21.5%
	Δ SC_{BAU-3}-SC_{LP-3}	ESR	Δ SC_{BAU-3}-SC_{HP-3}	ESR	Δ SC_{BAU-3}-SC_{LP-3}	ESR	Δ SC_{BAU-3}-SC_{HP-3}	ESR
2030	0.2	0.1%	0.5	0.1%	0.1	0.1%	0.4	0.1%
2040	2.9	0.8%	7.1	2.0%	2.5	0.9%	6.0	2.1%
2050	13.5	4.1%	30.6	9.3%	14.2	5.0%	32.1	11.2%
2060	23.4	8.3%	50.1	17.8%	30.4	10.9%	65.5	23.5%
	Δ SC_{BAU-4}-SC_{LP-4}	ESR	Δ SC_{BAU-4}-SC_{HP-4}	ESR	Δ SC_{BAU-4}-SC_{LP-4}	ESR	Δ SC_{BAU-4}-SC_{HP-4}	ESR
2030	0.2	0.1%	0.5	0.1%	0.1	0.1%	0.4	0.1%
2040	2.9	0.8%	7.1	2.0%	2.5	0.9%	6.0	2.1%
2050	13.4	4.0%	30.4	9.1%	14.0	4.8%	31.5	10.8%
2060	22.8	8.0%	48.9	17.1%	28.9	10.3%	62.3	22.1%

Fig. 13 and **Table 13** present a comparative analysis of carbon emission differences in urban residential and public buildings under different scenarios. In SC_{LP}, the carbon reduction in urban residential buildings increases gradually over time. For example, comparing SC_{BAU-1} to SC_{BAU-4} with SC_{LP-1} to SC_{LP-4}, the carbon reduction in 2030 ranges from 12.9 to 14.5 $MtCO_2$, with a carbon emission reduction percentage (CERP) of approximately 1.5%. By 2040, the carbon reduction increases to 41.5–48.3 $MtCO_2$, with a CERP of around 5.3%–5.4%. In 2050, the carbon reduction reaches 82.7–96.0 $MtCO_2$, with a CERP of approximately 14.7%–14.9%. By 2060, the carbon reduction in urban residential buildings ranges from 102.9 to 119.2 $MtCO_2$, with a CERP of about 37.4%–37.8%. Although the carbon reduction in public buildings is slightly lower than in urban residential buildings, the potential for reduction is relatively higher. In 2060, the carbon reduction in public buildings ranges from 99.4 to 115.3 $MtCO_2$, with a CERP of around 39.4%–40.1%. In SC_{HP}, the reduction in building carbon emissions is significantly higher. For example, comparing SC_{BAU-1} to SC_{BAU-4} with SC_{HP-1} to SC_{HP-4}, in 2030, the carbon reduction in urban residential buildings ranges from 16.8 to 19.0 $MtCO_2$, with a CERP of approximately 1.9%. By 2040, the carbon reduction reaches 66.2–76.8 $MtCO_2$, with a CERP of around 8.5%–8.6%. In 2050, the carbon reduction increases to

141.0–162.9 $MtCO_2$, with a CERP of approximately 24.9%–25.5%. By 2060, the carbon reduction in urban residential buildings ranges from 167.7 to 194.4 $MtCO_2$, with a CERP of 61.0%–61.6%. The carbon reduction effect in public buildings is even more significant in the high promotion scenario, with the carbon reduction in 2060 ranging from 164.2 to 190.7

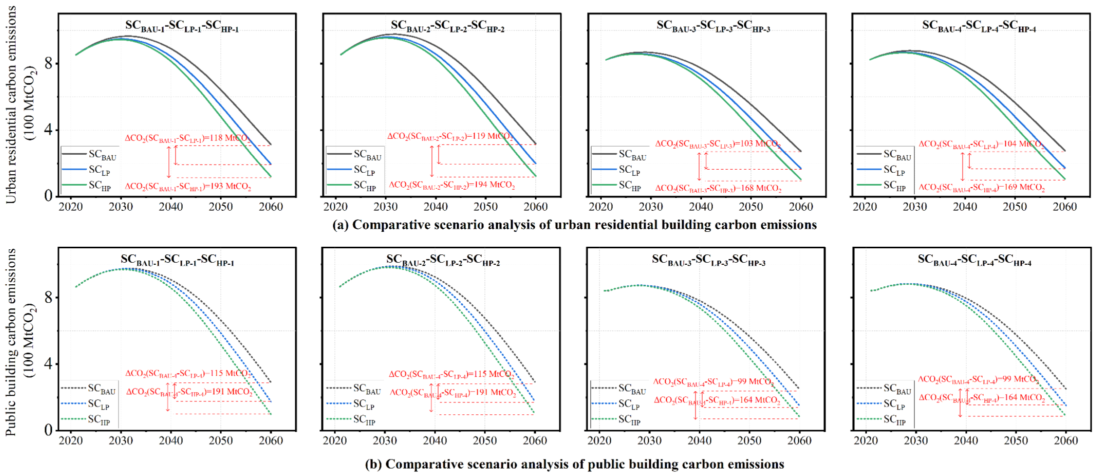

Fig. 13 Comparison and analysis of carbon emission differences between urban residential and public buildings under different scenarios.

$MtCO_2$, and a CERP of around 65.1%–65.8%.

Table 13 Comparison of carbon emission differences ($MtCO_2$) between urban residential and public buildings under different scenarios (with ESR and CERP).

	Urban residential				**Public building**			
	Δ SC_{BAU-1}-SC_{LP-1}	CERP	Δ SC_{BAU-1}-SC_{HP-1}	CERP	Δ SC_{BAU-1}-SC_{LP-1}	CERP	Δ SC_{BAU-1}-SC_{HP-1}	CERP
2030	14.3	1.5%	18.8	1.9%	0.1	0.0%	4.7	0.5%
2040	47.5	5.3%	75.7	8.5%	23.1	2.5%	50.1	5.5%
2050	94.7	14.7%	161.0	25.1%	77.3	11.6%	147.5	22.2%
2060	118.1	37.6%	192.5	61.3%	115.3	39.8%	190.5	65.8%
	Δ SC_{BAU-2}-SC_{LP-2}	CERP	Δ SC_{BAU-2}-SC_{HP-2}	CERP	Δ SC_{BAU-2}-SC_{LP-2}	CERP	Δ SC_{BAU-2}-SC_{HP-2}	CERP
2030	14.5	1.5%	19.0	1.9%	0.1	0.0%	4.7	0.5%
2040	48.3	5.3%	76.8	8.5%	23.4	2.5%	50.6	5.5%
2050	96.0	14.7%	162.9	24.9%	77.6	11.5%	147.9	21.9%
2060	119.2	37.4%	194.4	61.0%	115.3	39.4%	190.7	65.1%
	Δ SC_{BAU-3}-SC_{LP-3}	CERP	Δ SC_{BAU-3}-SC_{HP-3}	CERP	Δ SC_{BAU-3}-SC_{LP-3}	CERP	Δ SC_{BAU-3}-SC_{HP-3}	CERP
2030	12.9	1.5%	16.8	1.9%	0.1	0.0%	4.1	0.5%
2040	41.5	5.4%	66.2	8.6%	20.1	2.6%	43.6	5.6%
2050	82.7	14.9%	141.0	25.5%	67.3	11.9%	128.8	22.8%
2060	102.9	37.8%	167.7	61.6%	99.4	40.1%	164.2	66.2%
	Δ SC_{BAU-4}-SC_{LP-4}	CERP	Δ SC_{BAU-4}-SC_{HP-4}	CERP	Δ SC_{BAU-4}-SC_{LP-4}	CERP	Δ SC_{BAU-4}-SC_{HP-4}	CERP
2030	13.0	1.5%	17.0	1.9%	0.1	0.0%	4.1	0.5%
2040	42.2	5.4%	67.2	8.5%	20.4	2.6%	44.1	5.5%
2050	83.9	14.8%	142.7	25.3%	67.7	11.7%	129.2	22.4%
2060	103.9	37.6%	169.4	61.2%	99.4	39.6%	164.4	65.5%

4 Discussion

4.1. Analysis of the impact of cumulative carbon reduction under different scenarios

Fig. 14, **Fig. 15** and **Table 14** display the cumulative carbon reduction and their respective contributions by climate region under different scenarios. In SC_{LP}, the cumulative carbon reduction in the national building sector by 2060 ranges from 3340 to 3867 $MtCO_2$. The contributions of different climate regions show significant variation. The C region contributes the most, accounting for approximately 44% of the total, with a cumulative reduction of 1469–1701 $MtCO_2$. The HSCW region follows, with a cumulative reduction of 762–869 $MtCO_2$, contributing about 22.5%–22.8%. The SC region contributes 934–1097 $MtCO_2$, or around 28%, while the HSWW region and W region have smaller contributions, with reductions of 147–166 $MtCO_2$ (about 4.2%–4.4%) and 30–36 $MtCO_2$ (about 0.9%), respectively. It can be observed that in the low promotion scenario, the northern and central climate regions contribute the most to national carbon reduction. In SC_{HP}, the national building sector's cumulative carbon reduction significantly increases, ranging from 5837 to 6740 $MtCO_2$. The contribution trends by climate region remain similar to those in the low promotion scenario. The C region remains the leading contributor, accounting for about 46%, with a cumulative reduction of 2691–3117 $MtCO_2$. The HSCW region has a cumulative reduction of 1411–1609 $MtCO_2$, contributing about 23.9%–24.2%. The SC region contributes 1370–1604 $MtCO_2$, or around 23.5%–23.8%, while the HSWW region and W region show lower reductions, with values of 296–341 $MtCO_2$ (about 5.0%–5.2%) and 62–76 $MtCO_2$ (about 1.1%), respectively. Overall, in both the low and high promotion scenarios, the C region and HSCW region show the highest carbon reduction potential, followed by the SC region. On the other hand, the HSWW region and W region, with lower building energy consumption baselines, have relatively limited carbon reduction potential.

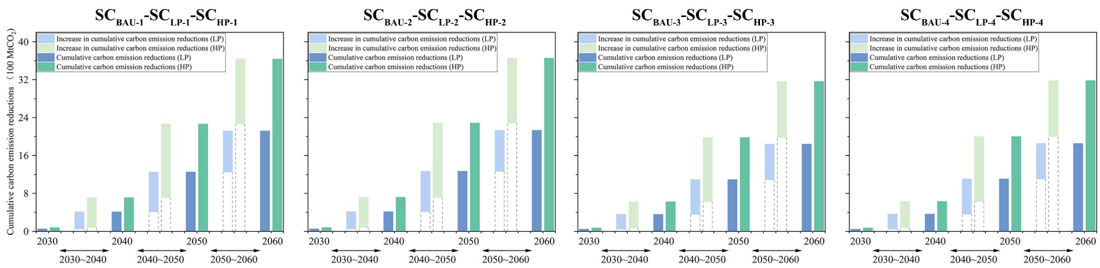

Fig. 14 Comparison of cumulative carbon emissions reductions in the national building sector under different scenarios.

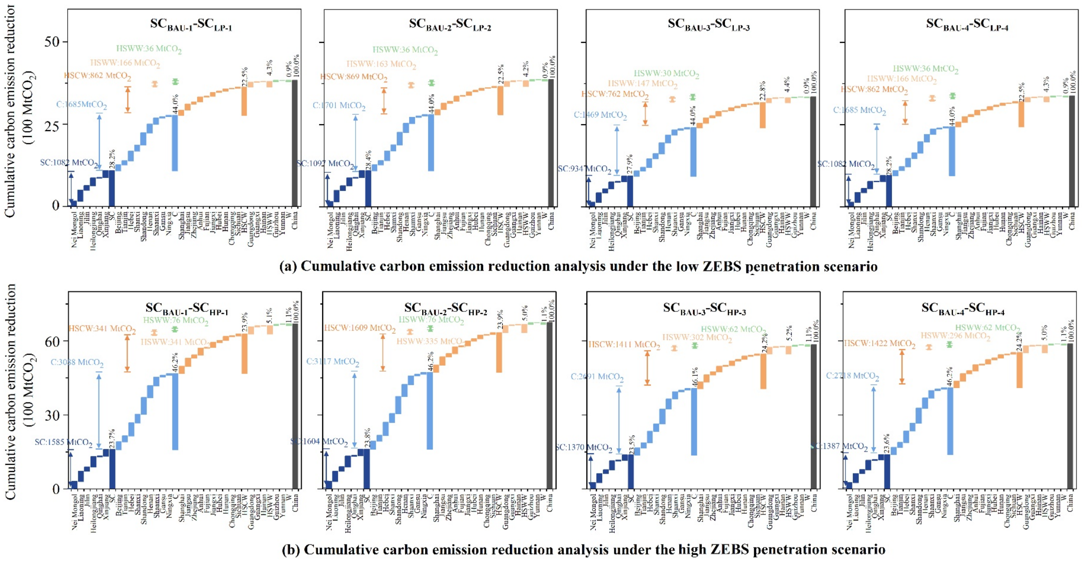

Fig. 15 Comparison of cumulative carbon emissions reductions in different climate zones under different scenarios.

Table 14 Comparison of cumulative carbon emissions reductions ($MtCO_2$) in the national building sector and different climate zones under different scenarios.

	Cum-CER	Ratio	Cum-CER	Ratio	Cum-CER	Ratio	Cum-CER	Ratio
	SC_{BAU1}-SC_{LP1}		SC_{BAU2}-SC_{LP2}		SC_{BAU3}-SC_{LP3}		SC_{BAU4}-SC_{LP4}	
China	3832	100.0%	3867	100.0%	3340	100.0%	3832	100.0%
SC	1082	28.2%	1097	28.4%	934	27.9%	1082	28.2%
C	1685	44.0%	1701	44.0%	1469	44.0%	1685	44.0%
HSCW	862	22.5%	869	22.5%	762	22.8%	862	22.5%
HSWW	166	4.3%	163	4.2%	147	4.4%	166	4.3%
W	36	0.9%	36	0.9%	30	0.9%	36	0.9%
	SC_{BAU1}-SC_{HP1}		SC_{BAU2}-SC_{HP2}		SC_{BAU3}-SC_{HP3}		SC_{BAU4}-SC_{HP4}	
China	6688	100.0%	6740	100.0%	5837	100.0%	5884	100.0%
SC	1585	23.7%	1604	23.8%	1370	23.5%	1387	23.6%
C	3088	46.2%	3117	46.2%	2691	46.1%	2718	46.2%
HSCW	1597	23.9%	1609	23.9%	1411	24.2%	1422	24.2%
HSWW	341	5.1%	335	5.0%	302	5.2%	296	5.0%
W	76	1.1%	76	1.1%	62	1.1%	62	1.1%

4.2. Impact of different timing of ZEBS promotion on cumulative carbon emissions reductions

Fig. 16 and **Table 15** analyze the impact of different ZEBS implementation start points on the cumulative carbon reduction in the national building sector. In SC_{LP}, if ZEBS is promoted starting in 2025, the national cumulative carbon reduction in that year ranges from 3340 to 3867 $MtCO_2$ (with differences between the four scenarios mainly arising from assumptions about different baseline scenarios). By 2030, the cumulative reduction drops to 2866–3345 $MtCO_2$, indicating that the first five years of ZEBS promotion could reduce an additional 474–531 $MtCO_2$. By 2035, the cumulative reduction further decreases to 2640–3098 $MtCO_2$, with the total saved amount reaching 688–782 $MtCO_2$. This shows that early promotion of ZEBS can significantly accelerate carbon reduction effects, with the first decade contributing approximately 15%–20% of the total reduction by 2025. In SC_{HP}, the carbon reduction effect of ZEBS is more significant. In 2025, the national cumulative reduction is between 5837 and 6740 $MtCO_2$. By 2030, it decreases to 4873–5676 $MtCO_2$, meaning that an additional 951–1079 $MtCO_2$ could be reduced during the first five years. By 2035, the cumulative reduction further drops to 4409–5168 $MtCO_2$, with the reduction over the first ten years totaling 1406–1598 $MtCO_2$. Compared to SC_{LP}, SC_{HP} shows that ZEBS promotion yields a higher reduction potential in the early years.

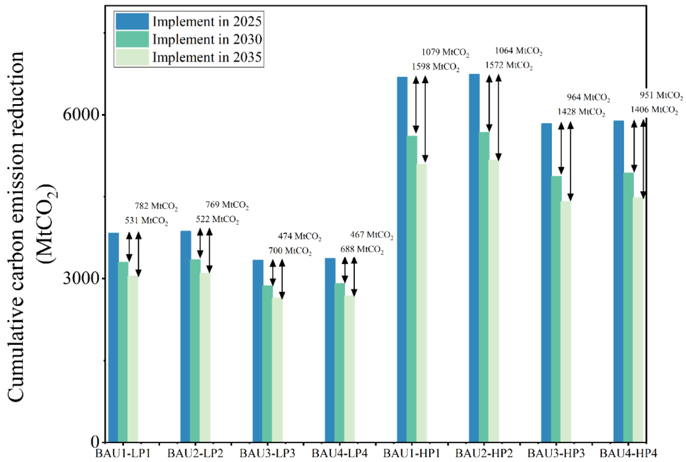

Fig. 16 Impact of different timing of ZEBS promotion on cumulative carbon emissions reductions.

Table 15 Impact of different timing of ZEBS promotion on cumulative carbon emissions reductions ($MtCO_2$).

	SC_{BAU1}-SC_{LP1}	SC_{BAU2}-SC_{LP2}	SC_{BAU3}-SC_{LP3}	SC_{BAU4}-SC_{LP4}	SC_{BAU1}-SC_{HP1}	SC_{BAU2}-SC_{HP2}	SC_{BAU3}-SC_{HP3}	SC_{BAU4}-SC_{HP4}
2025	3832	3867	3340	3372	6688	6740	5837	5884
2030	3301	3345	2866	2905	5609	5676	4873	4934
2035	3049	3098	2640	2684	5090	5168	4409	4478
ΔIT_{2025}-IT_{2030}	531	522	474	467	1079	1064	964	951
ΔIT_{2025}-IT_{2035}	782	769	700	688	1598	1572	1428	1406

4.3. Multi-scenario sensitivity analysis

This study uses Sensitivity Analysis to explore the extent to which changes in key driving factors impact the total carbon emissions from the national building sector. During the analysis, other factors are kept constant while a single factor is varied according to a predefined change rate. The change in carbon emissions before and after the perturbation is compared to assess the sensitivity of each factor. If the carbon emission change is larger under the same variation rate, it indicates that the factor has a more significant impact on carbon emissions; conversely, a smaller change indicates a weaker influence. The sensitivity analysis selects key exogenous variables as critical influencing factors, including population size, urbanization rate, per capita building area, building retrofit rate, electrification rate, and ZEBS penetration rate. The sensitivity (E) is calculated using Eq. 11:

$$E_{x,t} = \frac{\Delta y_t / y_t}{\Delta x_t / x_t} \tag{11}$$

where, $E_{(x,t)}$ represents the sensitivity of factor $x$to the total carbon reduction in the national building sector in year t; y_t is the dependent variable, i.e., the carbon reduction in the national building sector; x_t is the model factor, i.e., the selected key driving factor; Δy_t and Δx_t represent the changes in the dependent and independent variables in year t, respectively.

The sensitivity analysis results (**Fig. 17**) indicate that different input factors have significantly varying impacts on the national building sector's carbon reduction potential. Among these, the electrification rate (S5) is the most influential driver for carbon reduction, with a sensitivity coefficient of +0.140. This suggests that accelerating the electrification of end-use energy in buildings, under the premise of continued power system decarbonization, is the most crucial path to enhance emission reduction effects. In contrast, population size (S1) is the largest inhibiting factor, with a sensitivity coefficient of -0.108. This indicates that the expansion of building and energy demand driven by population growth poses the greatest challenge to achieving emission reduction targets. Other factors have relatively smaller impacts. The urbanization rate (S3) also acts as a promoting factor, with a sensitivity coefficient of +0.075. Per capita building area (S2) is an inhibiting factor, with a sensitivity coefficient of -0.023. The retrofit rate (S4) has a sensitivity coefficient of only +0.004, indicating that its impact on the cumulative reduction total is relatively small in this model.

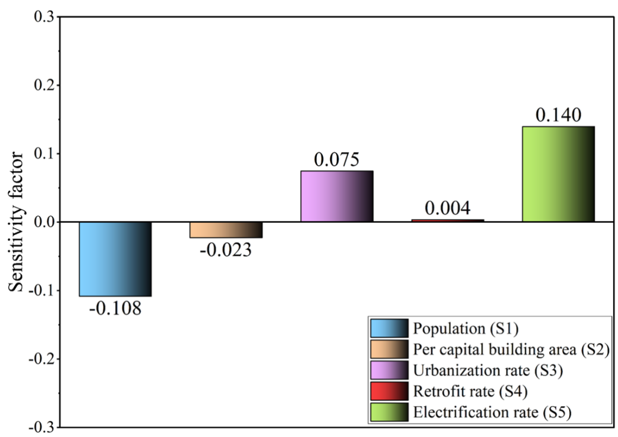

Fig. 17 Results of multi-scenario sensitivity analysis.

5 Conclusions and policy implications

5.1. Main conclusions

This study systematically evaluates the promotion effect of ZEBS in China from a macro-scale perspective, examining its far-reaching impact on the carbon-neutral pathway for the building sector. To achieve this goal, the study develops a comprehensive model integrating the dynamic evolution of building stock and multi-scenario analysis. This model adopts a top-down approach covering the period from 2021 to 2060, precisely simulating the processes of new construction, renovation, and stock turnover for urban residential and public buildings under various development pathways. Based on this, the core of the study quantifies the carbon emission trajectories and reduction potentials under different ZEBS promotion scenarios, providing a solid data foundation for assessing its emission reduction benefits at different stages. The key contribution of this study lies in systematically quantifying, for the first time, the long-term impact of different ZEBS promotion strategies (in terms of pace and intensity) on the decarbonization process of the building sector. The findings provide essential data support for policy-making, helping to translate strategic goals into specific implementation paths. The main conclusions of the study are as follows:

1. **Significant impact of different development scenarios on ZEBS coverage area**: In the "high penetration" scenario, the area of buildings complying with ZEBS standards is expected to reach approximately 199-244 billion square meters, whereas in the "low penetration" scenario, it is expected to be around 92-114 billion square meters. This difference indicates that urban construction scale, policy strength, and economic development levels will play a key role in constraining and guiding the promotion of zero-carbon buildings in the future.
2. **Increased ZEBS penetration significantly enhances emission reduction effects**: Strengthening the promotion of ZEBS can effectively reduce building energy consumption and carbon emissions. By 2060, the carbon reduction potential in the "high penetration" scenario is about 63% higher compared to the BAU scenario, and it can increase by an additional 25% compared to the "low penetration" scenario. This demonstrates a clear positive relationship between promotion intensity and emission reduction effects.
3. **The promotion effect of ZEBS varies across regions**: There are significant differences in the building energy consumption base and reduction potential across

different climate regions. Cold regions contribute the most to emission reduction, accounting for up to 46% of the total, while mild regions and low-energy consumption areas have relatively smaller emission reduction potentials, accounting for only about 1%. This implies that, when formulating promotion strategies, regional differences must be taken into account, and targeted measures should be implemented in each region.

4. **Macroeconomic uncertainties have a significant impact on ZEBS promotion effects**: Future uncertainties such as population growth and electrification rate will significantly influence the final promotion effect and emission reduction of ZEBS. Therefore, when formulating policies and promotion plans, these uncertainties must be fully considered, and flexible dynamic adjustment mechanisms should be established.

This study primarily focuses on the carbon emissions and reduction effects during the operation phase of buildings under ZEBS, but it somewhat overlooks the embodied carbon and cost factors over the entire building lifecycle. This limitation may affect the comprehensiveness and accuracy of the research results. First, the study does not include the embodied carbon from building material production, transportation, and construction, which could have significant impacts on the carbon emissions and reduction potential over the building's lifecycle, thereby limiting the assessment of carbon reduction effects. Second, this study mainly focuses on the carbon reduction effect of ZEBS promotion without considering changes in unit reduction costs and marginal costs. Although ZEBS can significantly reduce carbon emissions, the economic costs of its implementation and the cost differences under different penetration scenarios will directly impact the practical feasibility of the policy. Future research should integrate cost-benefit analysis and further explore changes in cost factors during ZEBS promotion to help policymakers make more informed decisions.

5.2. Policy implications

Based on the findings of this study, the following two core policy recommendations are proposed to accelerate the carbon-neutral process of China's building sector:

- Establish a clear and ambitious national zero-carbon building roadmap and timeline: The study finds that the intensity of ZEBS promotion is the key driver for the future depth of emission reductions in the building sector. Therefore, policymakers should seize the critical window during the 14th Five-Year Plan period to set clear targets for the area of zero-carbon buildings. This will create a demonstration effect and guide market investment. More importantly, a mandatory timeline for implementing zero-carbon standards in new buildings should be planned and introduced as soon as possible. This measure will provide the market with stable long-term expectations, lay the foundation for supply chain maturity, and reduce technology costs. It is a crucial step to ensure that long-term emission reduction goals are achieved.

- Implement regionally tailored and differentiated promotion strategies: This study reveals that there are significant differences in the potential for ZEBS promotion across different climate regions, with northern heating areas being key regions for emission reduction. Therefore, a "one-size-fits-all" promotion policy will not be effective. Future promotion strategies must fully consider the unique climate conditions of each region, the scale of new buildings, solar energy and other renewable resources, and the level of economic development. For example, in cold and severe cold regions, ultra-low-energy building envelope technologies should be prioritized, while regions with abundant solar resources should strongly encourage the integration of photovoltaic buildings (BIPV). By developing differentiated technical pathways and incentive policies, cost-effective emission reduction outcomes can be achieved nationwide.

6 Publications and other communications

Submitted - Wu, Z., Cai, W., Zhang, S., & Yang, X. China's building decarbonization: A top-down modeling analysis of the emissions impact of zero-emission building standards (ZEBS) implementation. Energy Policy

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