Research on Implementation Pathways for Near-Zero Carbon Emissions in High-Density Urban Districts

Guoshu Yang*, Anni Guo, Gaijing Zhang

Shanghai Institute of Building Science Co., Ltd, Shanghai, China

Abstract. During the 14th Five-Year Plan period, the transition to low-carbon development in urban and rural construction has increasingly focused on achieving scalable low-carbon development and piloting near-zero carbon emission projects at the meso-scales and micro-scales. High-density urban districts in city centers serve as ideal settings for implementing near-zero carbon emission demonstration projects. Taking a high-density, high-quality urban districts in Shanghai as an example, this study proposes a pathway for implementing key technologies for near-zero carbon urban districts through a dual approach of "carbon source reduction" and "carbon sink enhancement," summarized as the "Two-Lows and Four-Aspects" strategy（low-energy buildings, low-emission transportation, resource circulation, ecological landscaping, energy maximization, and digital management）. Additionally, the feasibility of achieving near-zero carbon emissions in high-density urban districts is calculated and validated, providing a practical reference for similar high-density urban projects aiming for near-zero carbon emissions.

1 Introduction

In 2021, the State Council issued the Action Plan for Peak Carbon Dioxide Emissions Before 2030, emphasizing the acceleration of green and low-carbon transformation in urban and rural development and the creation of energy-saving, low-carbon industrial parks that meet international advanced standards. The same year, the Ministry of Ecology and Environment released the Guidelines for Coordinating and Strengthening Climate Change Response and Ecological Environment Protection, advocating for regions with solid foundations to explore pilot projects for near-zero carbon emissions and carbon neutrality. According to the 2023 China Building and Urban Infrastructure Carbon Emissions Research Report, the total life-cycle carbon emissions of the national construction sector in 2021 reached 5.01 billion tons of CO_2, accounting for 47.1% of the country's energy-related carbon emissions [1]. Thus, low-carbon transformation in urban and rural construction is pivotal to achieving the national carbon peaking and carbon neutrality goals.

With the growing demand for low-carbon urban transformation and the renovation of existing communities, carbon reduction strategies and pathways in urban construction are increasingly focused on the meso-scales and micro-scales, such as districts and neighborhoods [2,3]. Based on theoretical studies on urban morphology and factors influencing carbon emissions, researchers [4-6] have proposed that efficient land development, compact spatial layouts, and polycentric urban spatial structures are more conducive to low-carbon urban development. This article integrates theories and practical case studies related to high-density urban districts to establish an implementation pathway for achieving near-zero carbon emissions in central high-density districts. Using a block-level project in Shanghai as an example, the study applies scenario analysis to calculate and validate near-zero carbon emissions, aiming to provide a research framework for similar high-density districts pursuing near-zero carbon development.

2 Characteristics of High-Density Urban Districts and Carbon Emission Calculation Methods

2.1 Key Characteristics of High-Density Urban Districts

In the context of urban and regional planning, a district is typically defined as an area enclosed by roads, comprising one or more neighborhoods, and generally covering a space ranging from several hectares to 3 km^2 [3]. The term "high-density urban district" is more of a conventional concept, lacking a unified national standard. However, extensive research highlights four main features of such districts: high floor area ratio (FAR), high building coverage ratio, low undeveloped space ratio, and high population density [7]. The average FAR of high-density urban districts often exceeds 3.0, with some cases reaching above 10 (e.g., Hong Kong's average FAR is as high as 12–15). Building coverage ratios can range from 30% to 50%, and population densities can reach 15,000–20,000 people per square kilometer [8-11]. Therefore, high-density urban districts exhibit a certain degree of spatial

* Corresponding author: yangguoshu@sribs.com

heterogeneity compared to traditional urban environments, forming a new type of high-density, multi-dimensional urban spatial morphology.

Shanghai, as a representative megacity with high-density urban districts, exemplifies this development. Central districts in Shanghai are characterized by dual attributes of spatial intensification and high resource consumption, marked by high building densities, intensive energy and resource use, stringent environmental quality demands, and limited development space. Their spatial form, building density, functional layout, and construction-management models all have significant impacts on carbon reduction efforts. Districts, as the fundamental units of urban space, serve as key venues for embodying "people-centered" urban warmth and promoting "green and low-carbon" healthy lifestyles. They are the primary arenas for achieving dual-carbon goals in urban construction and management. Therefore, high-density urban districts shoulder the responsibility of driving innovation and establishing best practices for high-quality near-zero carbon emissions development.

2.2 Near-Zero Carbon Emission Calculation Methods at the District Scale

Currently, there is no standardized methodology for calculating near-zero carbon emissions at the district scale. However, numerous scholars, both domestically and internationally, have explored carbon emission calculation and evaluation methods at the park and community levels. Jones C. M., et al.[12] suggested that community carbon emissions primarily include transportation, energy, waste, water, embodied carbon in buildings, food, and services. Zuda Ye, et al.[13] reorganized detailed activity categories and emission factors from national greenhouse gas emission inventories to establish a carbon emission evaluation method suitable for the operational phase of green ecological urban districts in China. Yueyang Ma, et al.[14], using a commercial office block as an example, developed a carbon emission factor database for the construction phase and proposed a calculation and evaluation method for carbon emissions at the district scale. Gaijing Zhang, et al.[15], using a low-carbon eco-park in Shanghai as an example, conducted an analysis of operational phase carbon emissions through scenario analysis, finding that actual carbon reductions could reach 51% compared to conventional construction modes. Fang Li, et al.[16] developed a community carbon emission calculation method covering buildings and public facilities, transportation, waste treatment, and carbon sinks, validating the approach with data from a new community in Shanghai.

Currently, research on meso- and micro-scale carbon emission methodologies primarily focuses on near-zero carbon parks or communities, which can be adapted to district-scale near-zero carbon emission calculations. Therefore, near-zero carbon emission calculations for high-density urban districts mainly concentrate on areas such as buildings, energy, transportation, waste, and landscape carbon sinks. The specific focus for statistical calculations of energy activity data varies across fields. The most common calculation approach involves multiplying activity data by carbon emission factors.

3 Analysis of the Development Status of Near-Zero Carbon Emission Districts

3.1 Policy Trends for Near-Zero Carbon Emissions

The concept of "near-zero carbon emission district demonstration projects" was first introduced in the national *13th Five-Year Plan* in 2015, positioning near-zero carbon emission districts as a key focus for advancing various low-carbon pilot initiatives. With the ongoing implementation of "carbon peaking and carbon neutrality" policies, the development of near-zero carbon emission districts has entered a rapid growth phase during the *14th Five-Year Plan* period. As of October 2024, several local governments have issued implementation plans and policy documents related to the construction of near-zero carbon emission districts (**Table 1**). These documents outline carbon emission targets, evaluation metrics, and construction pathways, accelerating the development of near-zero carbon demonstration districts.

Table 1. Overview of Policies and Objectives Related to Near-Zero Carbon Emissions.

Province/City	Document Number	Document Name	Near-Zero Carbon Type	Carbon Emission Goals
Hubei Province	Hubei Environmental Protection Office [2020] Document No. 39	*Implementation Plan for Near-Zero Carbon Emission District Demonstration Projects in Hubei Province*	Near-zero carbon parks, near-zero carbon communities	Steady reduction in total carbon emissions; control of per capita carbon emissions for residents
Shanghai	Shanghai Environmental Climate [2021] Document No. 182	*Shanghai Low-Carbon Demonstration Creation Work Plan*	Near-zero carbon practice zones	Carbon intensity reaching the advanced level of similar areas citywide or reduced by over 50% from the baseline period
			Near-zero carbon communities	Per capita carbon intensity reaching the city's advanced level or reduced by over 40% from the baseline period

Province/City	Document Number	Document Name	Near-Zero Carbon Type	Carbon Emission Goals
Tianjin	Tianjin Environmental Climate [2021] Document No. 82	*Guidelines for the Preparation of Low-Carbon (Near-Zero Carbon Emission) Demonstration Construction Plans in Tianjin (Trial)*	Near-zero carbon demonstration zones	Per capita carbon emissions reaching 3.5 tCO_2/person
			Near-zero carbon communities	Carbon emissions reduced by ≥10% compared to the baseline year
Shenzhen	Shenzhen Environmental Protection [2021] Document No. 212	*Shenzhen Near-Zero Carbon Emission Zone Pilot Implementation Plan*	Near-zero carbon parks, near-zero carbon communities	Total carbon emissions reduced by over 40% compared to 2020
Sichuan Province	Sichuan Environmental Letter [2022] Document No. 409	*Work Plan for Near-Zero Carbon Emission Park Pilot Projects in Sichuan Province*	Near-zero carbon parks	Total carbon emissions reduced by 5%
Chengdu	Chengdu Environmental Development [2022] Document No. 15	*Work Plan for Near-Zero Carbon Emission Zone Pilot Projects in Chengdu (Trial)*	Near-zero carbon parks	Total carbon emissions steadily reduced compared to the baseline year
Chongqing	Chongqing Environmental Protection [2022] Document No. 93	*Chongqing Near-Zero Carbon Park Pilot Implementation Plan*	Near-zero carbon parks	Carbon intensity per unit of industrial added value reduced by ≥15%
Shandong Province	Shandong Environmental Development [2023] Document No. 16	*Implementation Plan for Demonstration Projects of Near-Zero Carbon Cities, Parks, and Communities in Shandong Province*	Near-zero carbon parks, near-zero carbon communities	Total CO_2 emissions reduced compared to 2020
Jiangsu Province	Jiangsu Development and Reform Commission, Resource and Environmental Department [2024] Document No. 366	*Jiangsu (Near) Zero Carbon Industrial Park Construction Guide (Provisional)*	Near-zero carbon industrial parks	CO_2 emissions per unit of industrial added value ≤0.6 tCO_2/10,000 RMB

Based on the above analysis, the construction of near-zero carbon emission zones currently focuses mainly on industrial parks, office parks, and residential communities. At the same time, there are differences in the existing evaluation systems. The carbon emission targets include four forms: reduction in total carbon emissions, reduction in carbon emission intensity, reduction in per capita carbon emission intensity, and reduction in carbon emission intensity per unit of industrial added value. Furthermore, the implementation of near-zero carbon emission zone construction mainly involves areas such as energy, buildings, transportation, industry, and ecology.

3.2 Case Studies of Near-Zero Carbon Emission Zones

Currently, there are successful domestic and international examples of near-zero carbon emission demonstration projects at the park/community scale (**Table 2)**. The Europark Zero Carbon Technology Park in Germany achieves an 80-95% renewable energy utilization rate through energy, buildings, transportation, and operations. The Hammarby EcoCity in Sweden mainly achieves the recycling of waste, water, and energy through sustainable planning and design concepts. The Shanghai Expo Park in China continues to practice low-carbon and energy-saving development concepts in areas such as buildings, energy, transportation, resources, and landscaping, with a carbon emission reduction rate exceeding 30%. The "International Sailing Center" in Qingdao, Shandong, China has achieved zero-carbon community construction in aspects such as zero-carbon heating, energy efficiency improvement, terminal optimization, and renewable energy utilization.

Based on the above analysis, the construction path for near-zero carbon emission zones should focus on six key aspects: green buildings, energy efficiency, low-carbon transportation, resource recycling, green industries, and smart operations. Through the integrated application of green and low-carbon technologies and innovative management practices, low-carbon energy saving and sustainable development can be achieved.

4 Challenges in Achieving Near-Zero Carbon Emissions in High-Density Urban Districts

There are several challenges in achieving near-zero carbon emissions in high-density urban districts. First, the high building coverage rate leads to high energy consumption in buildings, and it is difficult to implement ultra-low energy buildings or near-zero energy buildings in areas dominated by super-tall structures. Second, the low development space ratio can result in conflicts in the spatial layout of low-carbon technologies, such as competition for rooftop space between green roofing and photovoltaics. Third, the cost of utilizing energy resources is high, and the limited space in high-density urban districts makes it difficult to balance economic costs with carbon reduction outcomes when using technologies like photovoltaics and energy storage. Finally, the construction process of high-density urban districts often lacks coordinated planning for the systematic integration of low-carbon technologies and spatial matching.

Table 2. Implementation Paths for Different Types of Near-Zero Carbon Emission Projects.

Location	Project Name	Scale	Zero-Carbon Honors	Energy/Carbon Reduction Goals	Key Initiatives
Germany	EUREF-Campus	5.5 hectares	Europe's first zero-carbon smart park	80% to 95% of the park's energy comes from renewable sources; the carbon emission reduction target of 80% was achieved ahead of schedule in 2014	Buildings: All new buildings are green energy-efficient buildings, with LEED Platinum certification;
					Energy: Solar, wind, geothermal; district heating; purchased agricultural biogas with an annual power generation of 2 MWh;
					Transportation: Entirely electric vehicles, with smart EV charging stations; retired batteries are recycled to create up to 1.9 MWh of energy storage;
					Operations: Energy management integrated with the overall digital solution for the smart park, based on microgrid EMA for photovoltaic, energy storage, and charging solutions.
Sweden	Hammarby Eco-Town	2.04 million square meters	Model for sustainable urban development	About 80% of total energy consumption is from renewable sources, 29-37% reduction in GHG emissions from the 1990s	Energy: Renewable energy; 100% district heating for buildings;
					Transportation: 80% of travel is by public transport;
					Waste: Precise waste sorting system, recyclable water treatment system.
Shanghai, China	Shanghai World Expo Park	5.28 square kilometers	Ministry of Housing and Urban-Rural Development peak carbon dioxide emissions and carbon neutrality case in 2021	Carbon reduction rate of 30% compared to the baseline scenario (2017)	Energy: Three distributed energy centers with a total photovoltaic installation capacity of 4.5 MW;
					Buildings: 100% of buildings meet the Green Building Two-Star standard or higher, with 61% of buildings reaching the Three-Star standard; one near-zero-energy building demonstration;
					Transportation: High-density bus + metro network, with a 10-kilometer riverside slow-traffic system;
					Resources: Water reuse initiatives; the Shanghai World Expo Park's rainwater utilization rate exceeds 20%;
					Landscaping: Roof greening on new buildings, and the Expo Cultural Park's landscaping area is expanded by 2 square kilometers.
Qingdao, Shandong Province, China	International Sailing Center" Zero-Carbon Community	45 hectares, with a building area of 227,000 square meters	Excellent case in "Zero Carbon China" in 2020	Directly reduces carbon emissions by 8,663 tons per year; building carbon emission intensity reduced to 25 kg CO_2/m^2	Energy: Uses clean energy technologies such as seawater-source heat pumps, solar photovoltaic and solar thermal energy, wind power, wastewater-source heat pumps, and industrial waste heat recovery;
					Buildings: Energy audits and energy-saving diagnostic analysis for 10 existing buildings;
					Transportation: Entirely electric vehicles, integrated charging stations with light storage, and smart street lighting;
					Operations: Establishment of a regional energy control platform (energy consumption monitoring, smart management).

5 Calculation and Verification of Near-Zero Carbon Emissions in High-Density Urban Districts

5.1 Overview of the Urban District Case

Fig. 1. Rendering of the urban block project.

This urban district project is an important transportation hub commercial complex in Shanghai, with a total land area of approximately 60,000 m² and a total building area of about 540,000 m². The buildings consist of six towers and podiums, with the tallest tower reaching 29 floors and a height of 100-140 meters (**Fig. 1**). The floor area ratio (FAR) of the entire block is 5.0, making it a typical high-density district block.

5.2 Implementation Path for Near-Zero Carbon Emission in the Urban District

Focusing on the goal of near-zero carbon emission in the urban district, this project proposes two core emission reduction pathways: "carbon reduction sources + carbon sinks enhancement." (**Fig. 2**). Through the "Two Low, Four Transformations" approach (low energy consumption, low emissions, circularity, ecological integration, maximization, and digitalization), six major green and low-carbon technological measures will be

implemented to reduce the carbon emission intensity of the district, leading the way in near-zero carbon emission urban district construction.

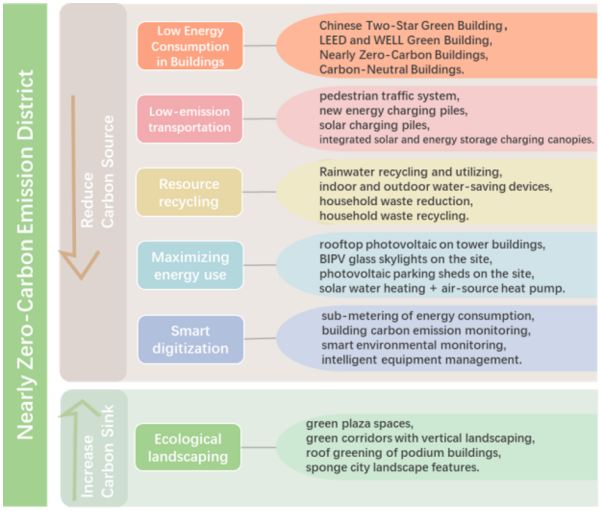

Fig. 2. Implementation Path for Near-Zero Carbon Emissions in the Urban District.

5.2.1 Low Energy Consumption in District Buildings

The buildings in the district have been constructed using an optimal technological strategy that meets the requirements of green building standards, as well as WELL and LEED Gold-level design specifications, to achieve high standards for low-carbon buildings. All new buildings fully comply with the Two-Star or higher green building standard, with office buildings T1-T6 meeting the LEED Gold-level design requirements. Additionally, the T1 commercial office building meets the WELL Gold-level requirements and serves as a demonstration for carbon-neutral buildings, while the T3-02 building is a near-zero carbon building demonstration. The new buildings integrate green, low-energy technologies through high-performance building envelopes, efficient mechanical and electrical systems, energy-saving elevators, and heat recovery for fresh air. A pilot project for high-efficiency machine rooms is also being implemented, with cooling plants achieving an EER energy efficiency ratio of $\geq$ 5.0, contributing to deep energy saving and carbon reduction in the buildings.

5.2.2 Low Emissions in District Transportation

The district's transportation system is organized with a focus on pedestrian networks as part of a multi-level urban traffic system. This includes a connected underground space, accessible ground-level district squares, and a two-story pedestrian corridor system, creating a multi-layered, integrated transportation network (**Fig. 3**), which allows for seamless one-stop transfers for pedestrians. Additionally, low-carbon transportation infrastructure within the district has been improved, with the proportion of new energy charging facilities reaching 15%. Two pilot projects for photovoltaic-storage-integrated parking shelters and two solar charging stations have been constructed. Furthermore, the district's public lighting system uses 100% LED energy-efficient lamps.

Fig. 3. Rendering of the District's Multi-Level Pedestrian System.

5.2.3 Resource Recycling in the District

The district implements the utilization of water resources and solid waste recycling. A rainwater reuse system has been set up to collect rainwater from rooftops, courtyards, and other areas. After treatment, the rainwater is used for landscaping irrigation and road cleaning. The rainwater collection pond has a capacity of 660 m^3, with a rainwater recovery utilization rate of 3%, achieving resource recycling of rainwater. Efforts are also made to reduce waste generation at the source and promote the recycling of household waste. All domestic waste is transported off-site for disposal, with a resource utilization rate of over 80%. In addition, both indoor and outdoor areas use high-efficiency water-saving facilities, and landscape irrigation employs water-saving methods. All indoor sanitary appliances are equipped with water-saving devices.

5.2.4 Ecological Landscaping in the District

Fig. 4. Central Park and Aerial Walkway Rendering.

The district's landscaping focuses on creating three-dimensional urban public spaces, with the layout featuring a central city park, green plazas, green roofs on podium buildings, and elevated green corridors, among other green spaces. The green coverage rate exceeds 20%, with over 30% of the podium roofs dedicated to greening, creating a district environment where greenery is visible from every window (**Fig. 4**). A resilient sponge city

landscape is strategically planned, including approximately 5,800 m² of green roofs and a 60 m² rain garden, to create an ecologically sustainable and visually appealing sponge city demonstration district that is also highly people-friendly.

5.2.5 Maximization of Energy Use in the District

Energy carbon reduction is a key strategy for achieving near-zero carbon emissions in the district. The project aims to maximize energy utilization within the district. Due to significant shading from the podium buildings in this high-density district, photovoltaic panels are mainly installed on the rooftops of the towers. The photovoltaic capacity on the rooftops of T1 and T3 towers is approximately 0.12 MW, with a 70-kWh energy storage system, forming a carbon-neutral building and near-zero carbon building demonstration highlight (**Fig. 5**). The rooftop photovoltaic capacity on T2, T4, and T6 is approximately 0.18 MW. The district also includes two BIPV (Building Integrated Photovoltaic) glass skylights and two solar photovoltaic parking canopies to supply power for the underground garage lighting. The total annual green electricity generation for the project is approximately 840,000 kWh/year. Additionally, a 100 m² solar thermal panel system and air-source heat pump water heating system have been installed on the roof of the T1 podium to preheat water for the staff cafeteria.

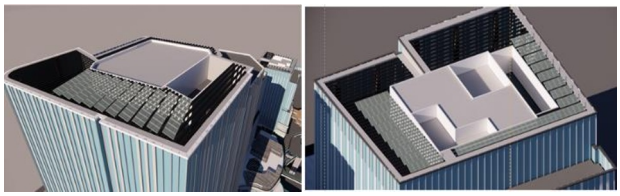

Fig. 5. Rendering of the Photovoltaic System on the Rooftops of T1 and T3 Towers.

5.2.6 Digitalization of District Management

The district adopts smart management by establishing a digital twin platform for carbon emission monitoring. This platform integrates real-time monitoring and management of building energy consumption, carbon emissions, and district environmental data. The digital platform is linked with the building's mechanical and electrical systems for interactive control, achieving intelligent group control of operational equipment and energy-saving management. Additionally, it is planned to integrate photovoltaic systems, charging stations, landscape lighting, and other energy usage into the digital platform, enabling comprehensive smart management of the district's operations.

5.3 Carbon Emission Calculation and Verification for the District

The carbon emission accounting boundaries for this project are defined in terms of buildings, transportation, resources, carbon sinks, energy, and other related sectors. A scenario analysis method is used to establish a baseline scenario and a near-zero carbon scenario, setting different levels of low-carbon target parameters for each sector (**Table 3)**. The carbon emission goals for the district are calculated and verified as follows:

Baseline Scenario: This assumes the carbon emissions of the district project under normal economic and social development trends, without any low-carbon measures being taken.

Near-Zero Carbon Scenario: This assumes the district project implements advanced carbon reduction technologies to significantly lower carbon emissions, achieving near-zero carbon levels or meeting the best practices for similar areas in the city.

Based on the research findings in Section 3.1 and Section 3.2, the minimum carbon reduction requirement for near-zero carbon emission districts in China is a carbon reduction rate of over 40%. Typical cases of near-zero carbon emissions at home and abroad can reduce carbon emissions by 30% to 80% (Different baseline scenarios).

After calculation and analysis, the carbon emissions for this district project under the baseline scenario are 36,000 tCO_2/a, and under the near-zero carbon scenario, the carbon emissions are 22,000 tCO_2/a. The total carbon reduction for the entire district is 15,000 tCO_2/a, achieving a reduction rate of 40.3% (**Table 4)**, meeting the target of over 40% and reaching the level of a near-zero carbon emission district in China. Approaching the carbon emission reduction targets of typical overseas near-zero carbon emission neighborhoods.

Table 3. Low-Carbon Parameters for Different Scenarios.

Sector			Low-Carbon Parameters	
			Baseline Scenario	**Near-Zero Carbon Scenario**
Buildings	New office and commercial buildings		100% basic level	100% Two-Star Green Building certification, with T3-02 as a near-zero carbon building and T1 as a carbon-neutral building
Transportation	Transportation	Proportion of new energy charging stations	10%	Increased to 15%
	Lighting	Road lighting energy efficiency	100% energy-saving lighting	100% energy-saving lighting
Resources	Water resources	Non-traditional water source utilization rate	None	≥3%
	Solid waste treatment	Solid waste resource utilization rate	Current rate: 42%	Increased to 80%

Sector		Low-Carbon Parameters	
		Baseline Scenario	**Near-Zero Carbon Scenario**
Landscape	Ancillary green space	Green space ratio of 20%	Green space ratio of 20% + 30% green roof coverage on the podium buildings
Energy	Diversified photovoltaic systems	None	Photovoltaic capacity on T1 and T3 roofs is about 0.12 MW; on T2, T4, and T6 roofs about 0.18 MW; BIPV skylights, T5 + T6 photovoltaic carports

Table 4. District Carbon Emission Analysis.

Sector	Carbon Emissions		Carbon Reduction (tCO_2/a)
	Baseline Scenario Carbon Emissions (tCO_2/a)	Near-Zero Carbon Scenario Carbon Emissions (tCO_2/a)	
Buildings	29207	17186	12021
Transportation	2159	2073	86
Water Resources	213	141	72
Solid Waste	4845	2708	2137
Carbon Sinks	-17	-26	9
Energy	0	-357	357
Total	36407	21726	14682
Carbon Reduction Rate Compared to Baseline (%)			40.3%

6 Conclusion

High-density districts are a key area for achieving carbon peak and carbon neutrality goals in megacities. Urban center high-density districts are characterized by four main features: high building floor area ratio, high building coverage ratio, low development space ratio, and high population density. The near-zero carbon emission construction in these districts emphasizes the integrated application of green low-carbon technologies and innovative management mechanisms.

1. This article uses a high-density district project in Shanghai as a case study, exploring and establishing a near-zero carbon emission construction implementation path based on the "Two Low and Four Circular" approach. The study also employs scenario analysis to convert and analyze the numerical transformation of the district's near-zero carbon construction indicator requirements, further validating the feasibility of achieving a carbon emission reduction rate of over 40% in high-density districts.

2. The characteristics of different types of high-density neighborhoods vary, but there is consistency in the construction and implementation paths to achieve near-zero carbon emissions. That is, the technology path of "carbon reduction sources + carbon sinks enhancement", and the necessary market pathways for carbon offsets such as CCER carbon trading and Renewable Energy Certificate. The Market Pathway is primarily used for carbon-neutral building of small-scale volumes. District with higher average floor area ratios have greater difficulty in adopting technological measures to achieve near-zero carbon emissions, it need more efficient technological innovation practices.

3. Faced with the challenges of near-zero carbon transformation, the construction of high-density districts focuses on key measures such as low-energy buildings, low-emission transportation, resource circulation, ecological landscaping, energy maximization, and digital management. Through technical innovations such as near-zero carbon buildings, carbon-neutral buildings, integrated solar storage charging, BIPV (Building-Integrated Photovoltaics), and energy-carbon monitoring digital twin platforms, the study provides a path to lead high-density districts toward near-zero carbon emissions and green sustainable development, contributing valuable experience to the peak carbon dioxide emissions and carbon neutrality efforts in the field of urban and rural construction.

Acknowledgments

1 Shanghai 2022 "Science and Technology Innovation Action Plan" Technology Support for Carbon Peak and Carbon Neutrality Special Project: "Research on Carbon Emission Accounting Methods and Integrated Control Application Scenarios for High-Density, High-Quality Districts with Near-Zero Carbon Emissions" (22dz1207902)

2 National Key R&D Program Project: "Carbon Reduction Technology System for Building Urban Integration and Verticalized Land Use Based on Land Utilization and Spatial Compounding" (2023YFC3804104)

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