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From carbon emissions scenario simulation to source-sink integration technological pathways in central business districts

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Abstract

This study explores low-carbon transition strategies for central business districts (CBDs) using Qingpu New Town in Shanghai, China, as a case study. Employing a dual-path approach - combining top-down scenario simulation with bottom-up technological decarbonization potential accounting - we model carbon emissions from 2022 to 2040 under four scenarios: Business-As-Usual, General Development, Balanced Development, and High-Quality Development. Under the High-Quality Development scenario, carbon emissions peak in 2028 and decline by 47.3% compared with the Business-As-Usual scenario by 2040. Building on these results, six sectoral source-sink integration technological pathways - covering buildings, energy, transportation, solid waste, water resources, and carbon sinks - are evaluated. Results show that energy-efficient building design plays a leading role in emission reduction, while energy storage and optimization of green travel structures become increasingly important. All scenario-specific technology packages meet their projected reduction targets. The study recommends integrating scenario planning into CBD development processes, incentivizing multi-sectoral technological synergies, and fostering collaborative governance. These insights provide a practical roadmap for the low-carbon transformation



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of CBDs, aligning with China's carbon neutrality goals.

Keywords: Central business district, low-carbon technology, technological pathway

INTRODUCTION

Climate change represents one of the most pressing existential threats facing humanity today^[1-4]. In response, countries worldwide have committed to ambitious targets such as carbon peaking and carbon neutrality, signaling a paradigm shift toward systemic, strategic decarbonization^[2,4,5]. Urban areas, as centers of economic activity, population concentration, and infrastructure development, are at the forefront of this transition^[3,6-11]. Within cities, Central Business Districts (CBDs) are particularly significant due to their intensive energy use, high-density built environments, and concentrated carbon emissions^[12]. While CBDs are often regarded as engines of economic growth, they are also hotspots of carbon intensity, making them critical targets for emissions reduction strategies^[7]. CBDs concentrate high-rise offices, transport flows, and service industries, creating emissions hotspots but also high-leverage opportunities for integrated, district-scale decarbonization^[7,10,12,13].

Over the past decade, a growing body of literature has examined urban carbon emissions using two dominant methodological paradigms: top-down and bottom-up approaches^[14]. Top-down models assess the influence of macro-level variables - such as population growth, GDP per capita, urbanization rates, energy intensity, and energy structure - on carbon emissions. These models often employ frameworks such as the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model^[15,16], input-output analysis^[17-19], and integrated energy-economy-environment system models^[20,21]. These methods are valuable for projecting long-term trends under different development scenarios and analyzing interactions among sectors at regional or national scales^[22-24]. However, they are often criticized for insufficiently capturing technological specifics that are crucial at the urban and district levels, particularly in high-density environments such as CBDs. In contrast, bottom-up approaches estimate emissions from buildings^[13,25-27], transport^[28,29], energy^[30-32], water and solid waste systems^[33], and urban green-blue infrastructure^[34-36], enabling technology-level decarbonization roadmaps. Evidence shows substantial potential from deep energy retrofits and electrification of commercial buildings^[25], rooftop or building-integrated photovoltaics (BIPV)^[13,30], mobility demand management and electrified transit^[37,38], smart hybrid energy systems^[31,32], and nature-based carbon sinks^[34,35,39]. Nonetheless, many bottom-up studies are project- or sector-specific, with limited linkage to broader socioeconomic trajectories, rebound risks, and multi-sector synergies or trade-offs that shape outcomes over time^[40-42].

Most notably, both top-down and bottom-up studies have predominantly focused on city- or regional-scale analyses. Research specifically targeting CBDs - distinct spatial-functional units characterized by complex land use, vertical density, and interdependent systems - remains scarce. Existing CBD-focused studies typically examine building energy efficiency^[43,44] or traffic flow optimization^[45,46], while few have developed integrated frameworks that model emissions under multiple scenarios while aligning with concrete technological solutions and policy goals^[47,48]. As cities move toward carbon neutrality by mid-century, it becomes increasingly important to align long-term emissions reduction targets with feasible technological implementation pathways, particularly in high-potential areas such as CBDs^[5,47-49].

Addressing these gaps, this study proposes a comprehensive framework that integrates top-down and bottom-up approaches to explore and quantify carbon emissions trajectories and technological decarbonization potential in the Qingpu New Town CBD in Shanghai, China. From the top-down

perspective, we build a multi-scenario forecasting model for the period 2022–2040, incorporating key socioeconomic drivers such as economic growth, energy intensity, and energy structure. Four scenarios are constructed: Business-As-Usual (BAU), General Development (GD), Balanced Development (BD), and High-Quality Development (HQD), reflecting climate action and sustainable urban development objectives. From a bottom-up perspective, we conduct a comprehensive review of national, provincial, and municipal policy documents related to China's dual-carbon goals, identifying a portfolio of low-carbon technologies and green infrastructure strategies applicable to CBDs. These technologies encompass buildings, energy, transportation, water resources, solid waste management, and carbon sinks. Based on policy requirements, we then calculate the carbon reduction potential of these technology portfolios under different implementation intensities and compare the results with the emission reduction targets of each scenario for Qingpu New Town CBD. This approach verifies whether projected reductions from different technological configurations are sufficient to meet scenario-specific targets, providing quantitative and policy-aligned technological support for low-carbon development.

This study makes several key contributions. First, it proposes an integrated dual-pathway framework that bridges macro-level carbon scenario modeling with micro-level technology assessment, enhancing the coherence and practical relevance of carbon reduction planning. Second, it focuses on CBDs as a unique unit of analysis - an area underrepresented in the existing literature but highly significant for urban carbon governance. Third, by aligning emission targets from top-down modeling with bottom-up technological pathways and current policy frameworks, the study provides actionable insights for urban policymakers, planners, and infrastructure investors. Finally, the proposed methodology has broader implications beyond the case study area. As many global cities face similar challenges in balancing economic growth with environmental sustainability, this framework can serve as a replicable model for decarbonization planning in high-density urban cores, supporting science-based, technology-enabled, and policy-integrated pathways toward low-carbon cities.

METHODS

This study innovatively develops a dual-pathway analytical framework that integrates both bottom-up and top-down approaches. By combining socioeconomic data with multi-scenario simulations, we project future CBD carbon emissions with quantified uncertainty and conduct sensitivity analyses. Building on this foundation, and guided by policy directives and technological characteristics, we systematically evaluate the implementation potential of emission reduction technologies across sectors such as buildings, energy, transportation, solid waste, water resources, and carbon sinks, which can reduce carbon emissions and enhance carbon sinks. The framework quantifies carbon reduction benefits under varying levels of implementation intensity and ultimately formulates an integrated technological pathway for emission reduction and ecological enhancement.

Compared with traditional single-mode accounting frameworks, this approach overcomes key limitations and provides a scientifically robust and operationally feasible technological paradigm to support the low-carbon transition of CBDs. It offers significant practical value in guiding efforts to achieve urban carbon neutrality. The overall technical roadmap is shown in [Figure 1](#).

The CBD of Qingpu New Town is located at the intersection of the Yangtze River Delta Digital Mainline and the industrial-urban development axis of Waiqingsong Road. It is bordered by the Tongjiang-Sanya Highway to the east, Yinggang Road to the south, Shengli Road to the west, and Songze Avenue to the north, covering approximately 6.5 km², with a sample area of 3 km². As one of Shanghai's "Five New Towns", Qingpu New Town is planned as a comprehensive nodal city with a radiating influence within the

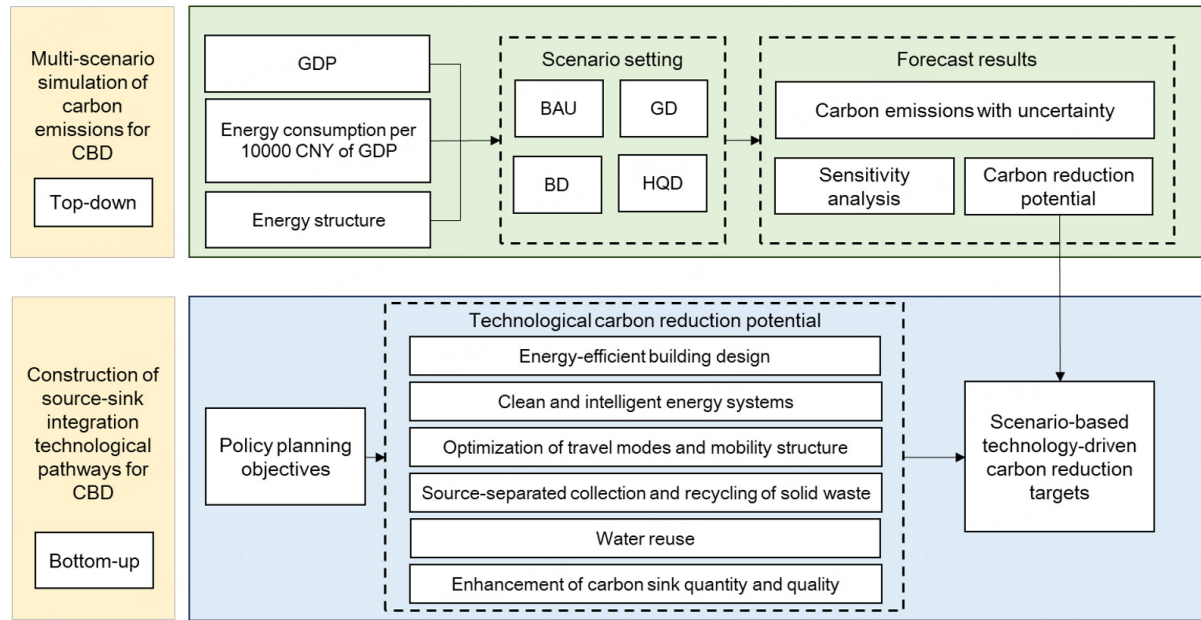


Figure 1. Technology roadmap. GDP: Gross domestic product; CNY: Chinese yuan; CBD: central business district; BAU: business-as-usual; GD: general development; BD: balanced development; HQD: high-quality development.

Yangtze River Delta urban agglomeration. The CBD, as its core area, plays an exemplary role in promoting green, low-carbon construction, transformation, and sustainable urban development.

Data for this study were collected from multiple official sources. GDP data were sourced from the Shanghai Statistical Yearbook and Qingpu Statistical Yearbook (2013 to 2022). Industrial land data were derived from the “Overall Plan and Land Use Master Plan of Qingpu District, Shanghai (2017-2035)” and “The Relocation Plan for Enterprises in the CBD Park”. Land use in the business district, population statistics, solid waste generation, and water consumption indicators were obtained from the “Partial Adjustment of the Control Detailed Plan for QPC1-0012, QPC1-0008, and QPC1-0009 Units in Qingpu New Town, Qingpu District, Shanghai”. Building energy consumption data were taken from the “Research Report on the Implementation Plan for Carbon Peak in the Building Sector of Qingpu District” and the “2022 Energy Consumption Monitoring and Analysis Report for Government Office Buildings and Large Public Buildings in Shanghai”. Travel mode share data came from the “Comprehensive Transportation Plan for Qingpu New Town (2021-2035)”, and power emission factors were based on the “Notice on Adjusting the Emission Factor Values in the Greenhouse Gas Emission Accounting Guidelines of Shanghai Municipality”.

Carbon emissions forecast method

This study simulates carbon emissions in the business district under different economic development scenarios using a scenario-analysis approach based on a top-down accounting method. The analysis focuses on three main energy types - gasoline, natural gas, and electricity - with carbon emissions calculated separately for each, as given in^[50]

$$CE = GDP \times E_{GDP} \times (\alpha_o \times \beta_o \times EF_o + \alpha_G \times \beta_G \times EF_G + \alpha_e \times (1 - P_{RE}) \times \beta_e \times EF_e) \quad (1)$$

where CE represents the carbon emissions of the business district (tCO_2eq), GDP is the gross domestic product of the business district (10,000 CNY), E_{GDP} denotes the energy consumption per 10,000 CNY of

GDP (tce/10,000 CNY), and α_o , α_g , and α_e are the shares of gasoline, natural gas, and electricity in total energy consumption (%), respectively; β_o , β_g , and β_e are the energy conversion factors for gasoline (t/tce), natural gas (m³/tce), and electricity (kWh/tce), respectively; EF_o , EF_g , and EF_e are the carbon emission factors for gasoline (tCO₂eq/t), natural gas (tCO₂eq/m³), electricity (tCO₂eq/kWh), respectively; P_{RE} is the share of renewable energy in total electricity consumption (%).

Due to data limitations, the base-year GDP of the business district is estimated based on the industrial GDP of the broader administrative region, scaled by area. As the region is currently dominated by secondary and tertiary industries, the calculation primarily considers GDP from these two sectors, as determined by^[51]

$$GDP = GDP_{SI,CBD} + GDP_{RI,CBD} \quad (2)$$

$$GDP_{SI}/S_{SI} = GDP_{SI,CBD}/S_{SI,CBD} \quad (3)$$

$$GDP_{TI}/S_{TI} = GDP_{RI,CBD}/S_{RI,CBD} \quad (4)$$

where $GDP_{SI,CBD}$ and $GDP_{RI,CBD}$ represent the secondary and tertiary industry GDPs of the business district (10,000 CNY), respectively; GDP_{SI} and GDP_{TI} are the secondary and tertiary industry GDPs of the broader administrative region (10,000 CNY), respectively; S_{SI} and S_{TI} are the land areas allocated to secondary and tertiary industries in the broader region (m²), respectively; $S_{SI,CBD}$ and $S_{RI,CBD}$ are the land areas used for secondary and tertiary industries within the business district (m²), respectively.

Key time-varying parameters - GDP growth and the share of renewable energy in total electricity consumption - are modeled with decreasing and increasing logistic functions, respectively, to capture long-run asymptotes and mid-term inflection points. Logistic parameters are determined through a two-point anchoring scheme using the base year, target year, and lower/upper bounds, as given in^[52]

$$P_{RE}(t) = L_p + \frac{U_p - L_p}{1 + \exp(-r_p [t - t_m^{(p)}])} \quad (5)$$

$$g(t) = L_g + \frac{U_g - L_g}{1 + \exp(+r_g [t - t_m^{(g)}])} \quad (6)$$

where $P_{RE}(t)$ denotes the share of renewable energy in total electricity consumption; $L_p < U_p$ are the long-run lower and upper bounds, $r_p > 0$ is the steepness parameter, and $t_m^{(p)}$ is the inflection year. Likewise, $g(t)$ denotes GDP growth; $L_g < U_g$ are the long-run lower and upper bounds, $r_g > 0$ is the steepness parameter, and $t_m^{(g)}$ is the inflection year.

GDP levels are projected by compounding annual growth from the base-year GDP. All other parameters and energy shares are taken from externally specified year-by-year deterministic schedules and normalized annually.

Uncertainty is concentrated at the target-year anchors. To balance interpretability and robustness, the target-year values are assumed to follow a triangular distribution: $\tilde{g}_1 \sim \text{Tri}(g_{\min}, g_{\text{mode}}, g_{\max})$, $\tilde{P}_{RE,1} \sim \text{Tri}(p_{\min}, p_{\text{mode}}, p_{\max})$, with (min, mode, max) specified by policy targets, while all other inputs are treated as deterministic trajectories/constants under the baseline specification. Monte Carlo simulations are conducted with N

independent draws per scenario (default $N = 100,000$) using a fixed random seed for reproducibility. Multiple policy scenarios are simulated independently. A one-at-a-time (OAT) sensitivity analysis is employed to evaluate the influence of key inputs on carbon-emissions outcomes. Holding all other parameters fixed, a single variable is perturbed slightly, full-year trajectories are recomputed, and emissions are calculated following Equation (1). For target years 2030 and 2040, both absolute and relative changes in emissions are recorded, perturbations are ranked by magnitude, and variable importance is visualized using tornado charts.

In the scenario simulation, the carbon reduction potential under the optimized scenario is calculated using Equation (7). The overall carbon emission reduction resulting from the decrease in the external electricity emission factor is not influenced by the technologies within the business district. Therefore, the technological carbon reduction target is expressed as Equation (8).

$$G = CE_B - CE_O \quad (7)$$

$$G_t = G - GDP \times E_{GDP} \times \alpha_e \times (1 - P_{RE}) \times \beta_e \times (EF_{e,B} - EF_{e,O}) \quad (8)$$

where G is the carbon reduction potential under the optimized scenario (tCO_2eq); G_t is the technological carbon reduction target (tCO_2eq); CE_B and CE_O are the carbon emissions in the baseline and optimized scenarios (tCO_2eq), respectively; GDP is the Gross Domestic Product of the business district (10,000 CNY); E_{GDP} is the energy consumption per 10,000 CNY of GDP ($\text{tce}/10,000 \text{ CNY}$); α_e is the proportion of electricity in total energy consumption (%); P_{RE} is the proportion of renewable energy in total electricity consumption (%); β_e is the conversion factor for electricity (kWh/tce); $EF_{e,B}$ and $EF_{e,O}$ are the electricity carbon emission factors in the baseline and optimized scenarios ($\text{tCO}_2\text{eq}/\text{kWh}$), respectively.

Carbon emissions scenario settings

(1) Scenario setting

The CBD of Qingpu New Town is in a stage of rapid construction and development, and total energy consumption is expected to continue increasing. However, with ongoing green upgrades and optimization of the energy structure, the CBD is projected to achieve relatively slow growth in carbon emissions while maintaining sustained and rapid growth of the social economy. Based on the current energy supply situation and trend prediction, four different scenarios have been designed, each corresponding to different rates of socioeconomic growth, energy efficiency improvements, and energy structure adjustments. These scenarios are summarized in Table 1. It provides a window for technological preparation following the 2030 carbon peak target and connects to the 2060 carbon neutrality vision. Therefore, the scenario simulations in this chapter cover the period from 2022 to 2040.

(2) Parameter settings

a. GDP growth rate

In 2022, the GDP of the CBD of Qingpu New Town was estimated at 2.722 billion CNY. Due to limitations in data availability, this study sets GDP growth rates based on historical data from Qingpu District over the past decade and relevant research reports. Between 2013 and 2023, Qingpu District's average annual GDP growth rate was 5.53%. According to Shanghai's 14th Five-Year Plan, the city's expected average annual GDP growth rate from 2021 to 2025 is projected to align closely with the national economic growth rate.

Table 1. Carbon emission scenario settings

Scenario name	Scenario description
Business-As-Usual (BAU)	The business-as-usual scenario assumes that socioeconomic development continues at the current average pace, and the carbon emission factor for electricity remains unchanged. Regional development and construction proceed without the implementation of any additional targeted policies
General Development (GD)	Building upon BAU, this scenario incorporates improvements in energy efficiency and energy structure, leading to a moderate reduction in electricity carbon intensity. It supports the development of local photovoltaics, moderate deployment of hydrogen energy, gradual electrification of end-use sectors, application of new energy storage technologies, construction of low-carbon buildings, green transportation systems, and enhanced ecological carbon sink capacity
Balanced Development (BD)	Based on GD, this scenario assumes accelerated economic growth, further enhancements in energy efficiency and structure, and additional reductions in electricity carbon intensity. It emphasizes large-scale photovoltaic deployment, appropriate hydrogen development, increasing electrification in end-use sectors, efficient reclaimed water reuse systems, application of new energy storage technologies, construction of low-carbon buildings, green transport systems, and strengthened ecological carbon sinks
High-Quality Development (HQD)	On top of BD, this scenario envisions substantial improvements in energy efficiency and structure, with a sharp reduction in the electricity carbon intensity and high-quality socioeconomic growth. It promotes full-scale photovoltaic deployment, active hydrogen energy utilization, increased procurement of clean external electricity, higher electrification of end-use sectors, establishment of efficient water reuse systems, adoption of new energy storage technologies, development of high-quality low-carbon buildings, people-oriented green transport systems, and the formation of high-capacity ecological carbon sinks

The State Information Center^[53] projects China's GDP to grow at an average annual rate of 5.0% between 2021 and 2035, and 3.5% between 2036 and 2050. Based on these data, the GDP growth rate of the CBD of Qingpu New Town, $g(t)$, is assumed to follow a decreasing logistic trajectory. Long-run bounds are set at $L_g = 1\%$ and $U_g = 7\%$. The base-year anchor is $g_0 = 5.53\%$ in 2023, and the target-year anchor is 2040. For 2040, the GDP growth rate follows a triangular distribution: Tri(0.032, 0.040, 0.048) for BAU and GD and Tri(0.040, 0.050, 0.060) for BD and HQD. Rates for core years are shown in [Supplementary Table 1](#).

b. Share of renewable energy generation

According to the 2022 National Renewable Energy Power Development Monitoring and Evaluation Report released by the National Energy Administration, the share of renewable energy in Shanghai's total electricity consumption was 29.8%. Future projections of this share are based on the Implementation Plan for Carbon Peaking in the Energy and Power Sector of Shanghai, which targets a renewable energy share of approximately 40% by 2030. In addition, the Implementation Plan for the Construction of the Chongming World-Class Ecological Island Carbon Neutral Demonstration Zone (2022 Edition) anticipates that by 2035, renewable energy will comprise more than 60% of Chongming Island's total electricity consumption. Considering these references and the specific characteristics of the CBD, the share of renewable energy in total electricity consumption, $P_{RE}(t)$, is modeled as an increasing logistic function. Long-run bounds are set at $L_p = 0$ and $U_p = 0.8$. The base-year anchor is $P_{RE}(2022) = 0.298$. The target-year anchor in 2040 follows a triangular distribution: Tri(0.277, 0.298, 0.319) for BAU, Tri(0.326, 0.350, 0.375) for GD, Tri(0.419, 0.45, 0.48) for BD, and Tri(0.465, 0.500, 0.535) for HQD. Rates for core years are shown in [Supplementary Table 2](#).

c. Annual decline rate of energy consumption per unit of GDP

Due to data limitations, the energy consumption per unit of GDP for Shanghai is used as a proxy for that of the CBD of Qingpu New Town. Based on this approach, the energy consumption per 10,000 CNY of GDP in 2022 was calculated as 0.26 tce. The national 14th Five-Year Plan calls for a 13%-14% reduction in energy consumption per unit of GDP, which corresponds to an average annual reduction of approximately 2.66%. The Implementation Opinions on Fully, Accurately, and Comprehensively Implementing the New Development Philosophy and Advancing Carbon Peaking and Carbon Neutrality and the Carbon Peaking

Implementation Plan of Shanghai both set a target of a 14% reduction in energy consumption per unit of GDP by 2025 relative to 2020. Given variations in energy intensity reduction across Shanghai's districts and the fact that the CBD of Qingpu New Town is in a phase of rapid development and construction from 2022 to 2040, the annual reduction rates of energy consumption per 10,000 CNY of GDP are set based on historical data, national targets, and the CBD's development trajectory: Under the BAU: 1% for 2023-2030 and 3% for 2031-2040; Under the GD: 1.5% for 2023-2030 and 3% for 2031-2040; Under BD: 2% for 2023-2030 and 3% for 2031-2040; Under HQD: 2% for 2023-2030 and 3% for 2031-2040. Rates for core years are presented in [Supplementary Table 3](#).

d. Energy structure

The Greenhouse Gas Emissions Inventory Report of Qingpu District indicates that, in 2022, the district's energy mix consisted of 32.7% gasoline, 7.3% natural gas, and 60.0% electricity. In the CBD, gasoline is primarily used in transportation, natural gas is mainly used for heating, cooling, and hot water, and electricity accounts for a significant share of building energy use, supporting functions such as lighting, air conditioning, elevators, and office equipment. Electricity is also the primary energy source for electric vehicles in transportation. Given the anticipated increase in electrification in both building and transportation sectors, and the already high share of electricity in buildings within the CBD, the projected energy mix for 2040 under GD, BD, and HQD is 12.0% gasoline, 15.0% natural gas, and 73.0% electricity. From the base year to 2040, the share of gasoline is projected to decline linearly, while natural gas and electricity shares increase linearly. Key values for milestone years are presented in [Supplementary Tables 4 and 5](#).

e. Electricity emission factor

In this study, the electricity emission factor primarily refers to the emission factor of purchased electricity. According to the Notice from the Shanghai Municipal Bureau of Ecology and Environment on Adjusting the Emission Factors in the Municipal Greenhouse Gas Accounting Guidelines, the current electricity emission factor in Shanghai is $4.2 \text{ tCO}_2\text{eq}/10^4 \text{ kWh}$. The Research Report on the Carbon Peaking Implementation Plan for the Building Sector in Qingpu District projects that Shanghai's electricity emission factor will decrease to $3.25 \text{ tCO}_2\text{eq}/10^4 \text{ kWh}$ by 2040. Furthermore, according to the latest forecasts from relevant experts and institutions, the emission factor is expected to decline to $2.25 \text{ tCO}_2\text{eq}/10^4 \text{ kWh}$ by 2040. Based on this information, the study assumes an electricity emission factor of $4.2 \text{ tCO}_2\text{eq}/10^4 \text{ kWh}$ throughout 2022-2040 under the Baseline Scenario. For the GD and BD Scenarios, the electricity emission factor is assumed to decrease linearly to $3.25 \text{ tCO}_2\text{eq}/10^4 \text{ kWh}$ by 2040, while under the HQD Scenario, it decreases linearly to $2.25 \text{ tCO}_2\text{eq}/10^4 \text{ kWh}$. Emission factors for core years are shown in [Supplementary Table 6](#).

f. Population

The population of the CBD in Qingpu New Town was 20,000 in 2022. According to the Shanghai New Town Planning and Construction Guidelines, population density in new cities should be no less than 12,000 people per square kilometer. Based on the planned area of 6.46 km^2 , the total population is expected to reach approximately 80,000. Therefore, this study sets the population at 20,000 in 2022 and 80,000 in 2040, with linear growth assumed for the intervening years. Population figures for core years are shown in [Supplementary Table 7](#).

Estimation of technological emission reduction potential

To achieve low-carbon development in the business district, it is essential to build an integrated system of technologies. This system should follow three core principles: systematic integration, practical feasibility, and problem-oriented focus, with the goal of establishing a low-carbon technology framework tailored to the specific needs of CBDs. First, the system should emphasize a comprehensive technological pathway by integrating technologies across multiple domains, including buildings, energy, transportation, solid waste, water resources, and carbon sinks. Second, practical feasibility must be considered by selecting low-carbon technologies that are well-suited to local resource conditions and the characteristics of the business district, ensuring strong adaptability and operational viability. Lastly, the approach should be problem-oriented, targeting key challenges such as suboptimal carbon emission structures and insufficient green infrastructure. By aligning technology integration with actual needs, this approach aims to drive an efficient and low-carbon transformation of the business district.

(1) Buildings

This study aims to reduce building operational energy consumption within the business district by incorporating nearly zero-energy buildings, ultra-low-energy buildings, three-star green buildings, and two-star green buildings. The potential energy savings of these building types are shown in Table 2. In the table, percentage values represent the reduction in energy consumption compared to current building standards, while numerical values represent the maximum allowable integrated energy consumption for each building type (unit: kWh/m²/a). The integrated energy consumption values exclude contributions from renewable energy generation. Therefore, the carbon reduction benefits from solar photovoltaic systems - detailed under energy technologies - are already accounted for in the carbon reduction attributed to this building-related strategy.

The carbon reduction is calculated as follows^[54]:

$$CER_{BES} = S \times (E_{GB} - E_{CS}) \times EF_e \times 0.001 \quad (9)$$

where CER_{BES} is the carbon emission reduction from building energy-saving design (tCO₂eq), S is the building area (m²), E_{GB} is the energy consumption per unit area of green/ultra-low energy/nearly zero-energy buildings (kWh/m²), E_{CS} is the current building energy consumption per unit area (kWh/m²), and EF_e is the electricity emission factor (kgCO₂eq/kWh).

(2) Energy

a. Solar Photovoltaic Technology, including rooftop photovoltaics and photovoltaic curtain walls. The carbon reduction is calculated using^[42,54]

$$CER_{SP} = CER_{RP} + CER_{PCW} \quad (10)$$

$$CER_{RP} = S \times \rho \times \alpha \times \beta \times AEG \times EF \quad (11)$$

$$CER_{PCW} = S \times FAR \times \gamma \times \delta \times AEG \times EF \quad (12)$$

Table 2. Energy consumption requirements for green/nearly zero-energy/ultra-low energy buildings

Type	Residential buildings	Public	Reference
Nearly zero-energy buildings	55	60%	Technical Standard for Nearly Zero-Energy Buildings
Ultra-low energy buildings	65	50%	Technical Standard for Nearly Zero-Energy Buildings
Three-star Green Buildings	15%	15%	Green Building Evaluation Standard
Two-star Green Buildings	10%	10%	Green Building Evaluation Standard

where CER_{RP} is the carbon reduction from rooftop photovoltaics (tCO_2eq), CER_{PCW} is the carbon reduction from photovoltaic curtain walls (tCO_2eq), S is the building land area (m^2), ρ is the building density, α is the rooftop utilization rate, β is the conversion coefficient, AEG is the average annual electricity generation per unit area (MWh/m^2), EF is the electricity emission factor (tCO_2eq/MWh), FAR is the floor area ratio, γ is the facade sunlight area coefficient, and δ is the installation area coefficient.

b. Combined Cooling, Heating and Power (CCHP) Technology, with its carbon reduction calculated as^[54]:

$$CER_{CCHP} = (E_{GPG} + E_H + E_C) \times EF_e - (C_{gas} \times EF_{gas}) \quad (13)$$

where CER_{CCHP} is the carbon reduction from the CCHP system (tCO_2eq), E_{GPG} is the electricity supplied to the grid (MWh), E_H is the heating output (MWh), E_C is the cooling output (MWh), EF_e is the electricity emission factor (tCO_2eq/MWh), C_{gas} is the natural gas consumption (m^3), and EF_{gas} is the natural gas emission factor (tCO_2eq/m^3).

c. Virtual Power Plant Technology, with its carbon reduction calculated as^[55]:

$$CER_{VPP} = S \times P \times EFL \times x \times T \times EF_e \quad (14)$$

where CER_{VPP} is the carbon reduction from the virtual power plant (tCO_2eq), S is the building area (m^2), P is the power load per unit building area (MW), EFL is the proportion of flexible, adjustable load (%), x is the proportion connected to the virtual power plant (%), T is the peak regulation time (hours), and EF_e is the electricity emission factor (tCO_2eq/MWh).

d. Energy Storage Technology, with its carbon reduction calculated as^[56]:

$$CER_{ES} = V \times P \times \frac{(M_P - M_V)}{M_U} \times 1000 \times EF_e \quad (15)$$

where CER_{ES} is the carbon reduction from energy storage technology (tCO_2eq), V is the storage capacity (MW), P is the annual storage time (hours), M_P is the peak period electricity price (CNY/kWh), M_V is the valley period electricity price (CNY/kWh), M_U is the normal period electricity price (CNY/kWh), and EF_e is the electricity emission factor (tCO_2eq/MWh).

(3) Transportation

a. New Energy Vehicles, including new energy buses and electric cars, have their carbon reduction calculated as^[42,54]:

$$CER_{NEV} = (EF_{NEV} - EF_{NEV,o}) \times \gamma \times O_0 \times D \times 10^{-6} \quad (16)$$

where CER_{NEV} is the carbon reduction from new energy vehicles (tCO₂eq), EF_{NEV} is the carbon emission factor of new energy vehicles under the baseline scenario (gCO₂eq/person trips/km), $EF_{NEV,o}$ is the carbon emission factor under the optimized scenario (gCO₂eq/person trips/km), γ is the proportion of trips made by new energy vehicles (%), O_0 is the total daily trips by the resident population in the business district (person trips), and D is the trip distance (km).

b. Green Travel Structure Optimization Technology. Transit-Oriented Development (TOD) and slow traffic network systems function synergistically to improve the travel structure and reduce trip intensity, thereby supporting low-carbon transportation goals. Due to tight data coupling, these factors are calculated together^[42,54]:

$$CER_{tc} = (CE_t - CE_{t,o}) \times 10^{-6} \quad (17)$$

$$CE_t = S \times \sum_i (\alpha_{i,land} \times \beta_{i,land} \times x_{land}) \times \sum_n (\gamma_n \times D_n \times EF_n) \times 365 \times 10^{-6} \quad (18)$$

$$CE_{t,o} = S \times \sum_i (\alpha_{i,land} \times \beta_{i,land} \times x_{land}) \times \sum_n (\gamma_{n,o} \times D_{n,o} \times EF_n) \times 365 \times 10^{-6} \quad (19)$$

where CER_{tc} is the annual carbon reduction from green travel structure optimization (tCO₂eq), $CE_{t,o}$ and CE_t are annual traffic carbon emissions under the optimized and baseline scenarios (gCO₂eq), respectively, S is the total area of the business district (km²), $\alpha_{i,land}$ is the land use proportion of the i -th land type (%), $\beta_{i,land}$ is the travel correction coefficient per unit area, x_{land} is the average daily trips per unit area (person trips/km²/day), γ_n and $\gamma_{n,o}$ are the proportions of the n -th travel mode under the baseline and optimized scenarios (%), D_n and $D_{n,o}$ are the travel distances under the optimized and baseline scenarios (km), and EF_n is the carbon emission factor per unit distance for the n -th travel mode (gCO₂eq/person trips/km).

(4) Solid waste

In the solid waste management of the business district, the focus is placed on source-sorted recycling technologies, with carbon reduction calculated as^[57]:

$$CER_{sr} = CE_{wd} - CE_{wd,o} \quad (20)$$

$$CE_{wd} = (W_w - W_{wr}) \times EF_{wd} \times 0.001 \quad (21)$$

$$CE_{wd,o} = (W_w - W_{wr,o}) \times EF_{wd} \times 0.001 \quad (22)$$

where CER_{sr} is the carbon reduction from source-sorted recycling technologies (tCO₂eq), CE_{wd} and $CE_{wd,o}$ are the carbon emissions from solid waste treatment under the BAU and optimized scenarios, solid waste treatment (tCO₂eq), W_w is the amount of solid waste generated in the business district (kg), W_{wr} and $W_{wr,o}$ are the amounts of recyclable waste under the BAU and optimized scenarios (kg), and EF_{wd} is the carbon emission factor for waste treatment (kgCO₂eq/kg).

(5) Water reuse

This study adopts unconventional water reuse technologies, including reclaimed water reuse and rainwater utilization. The carbon reduction is calculated as^[57]:

$$CER_{WU} = V_{SW} \times EF_{TW} \times 0.001 \quad (23)$$

where CER_{WU} is the carbon reduction from water-saving technologies (tCO₂eq), V_{SW} is the volume of unconventional water sources substituting tap water (t), and EF_{TW} is the carbon emission factor for tap water production (kgCO₂eq/t).

(6) Carbon sink

Carbon sink technologies are divided into high carbon sink plant combinations and community design, rooftop greening, vertical greening, and affiliated green space construction technologies. For high carbon sink plant combinations and community design, the carbon reduction is calculated as^[54]:

$$CER_{pd} = (CF_{g,o} - CF_g) \times S_g \times 0.001 \quad (24)$$

where CER_{pd} is the carbon reduction from high carbon sink plant combinations and community design (tCO₂eq), $CF_{g,o}$ and CF_g are the optimized and baseline annual carbon absorption per unit green space area (kgCO₂eq/ m²), and S_g is the green space area (m²).

For rooftop greening, vertical greening, and affiliated green space construction, the carbon reduction is calculated as^[54]:

$$CER_{gt} = CF_{gt} \times S \times 0.001 \quad (25)$$

where CER_{gt} is the annual carbon absorption (tCO₂eq), CF is the annual carbon absorption factor per unit area under different scenarios (kgCO₂eq/m²), and S is the implementation area of the carbon sink technology (m²).

RESULTS

Carbon emissions scenario forecast analysis

According to the carbon emissions forecasts under different scenarios [Table 3 and Figure 2], the results show that under BAU, carbon emissions in the CBD of Qingpu New Town show an increasing trend in the planning timeframe. By 2040, total carbon emissions are projected to reach 23.82×10^4 tCO₂eq, with a carbon emission intensity of 0.38×10^4 tCO₂eq/10⁴ CNY. This indicates that continuing the current development model will lead to sustained emission growth, further intensifying the conflict between economic expansion and resource-environmental constraints. Under GD, the carbon emission peak occurs the latest (in 2035) and at a relatively high level. This outcome suggests that relying solely on conventional carbon reduction measures delays peaking and results in greater cumulative emissions. BD lies between BAU and GD, reflecting the stage-by-stage balance between economic growth and emission reduction. Compared with BAU, emissions in 2040 are 22.9% lower under GD and 28.8% lower under BD, demonstrating the limited effectiveness of incremental emission reduction pathways. HQD emphasizes economic development driven by a strong shift toward clean energy. It achieves a high-quality, low-level carbon peak in 2028, with a significant reduction in peak emissions compared with BAU. By 2040, total emissions under HQD decrease by 47.3% compared with BAU, with an emission intensity of only 0.18×10^4 tCO₂eq/10⁴ CNY, highlighting the role of green transformation in driving economic

Table 3. Scenario forecasting results (P50)

Scenario	Peak year	Carbon emission peak (10 ⁴ tCO ₂ eq)	2040 carbon emissions (10 ⁴ tCO ₂ eq)	2040 carbon emission intensity (tCO ₂ eq/10 ⁴ CNY)
BAU	/	/	23.82	0.38
GD	2035	18.73	18.36	0.29
BD	2034	17.26	16.96	0.25
HQD	2028	15.44	12.55	0.18

CNY: Chinese yuan, BAU: business-as-usual, GD: general development, BD: balanced development, HQD: high-quality development.

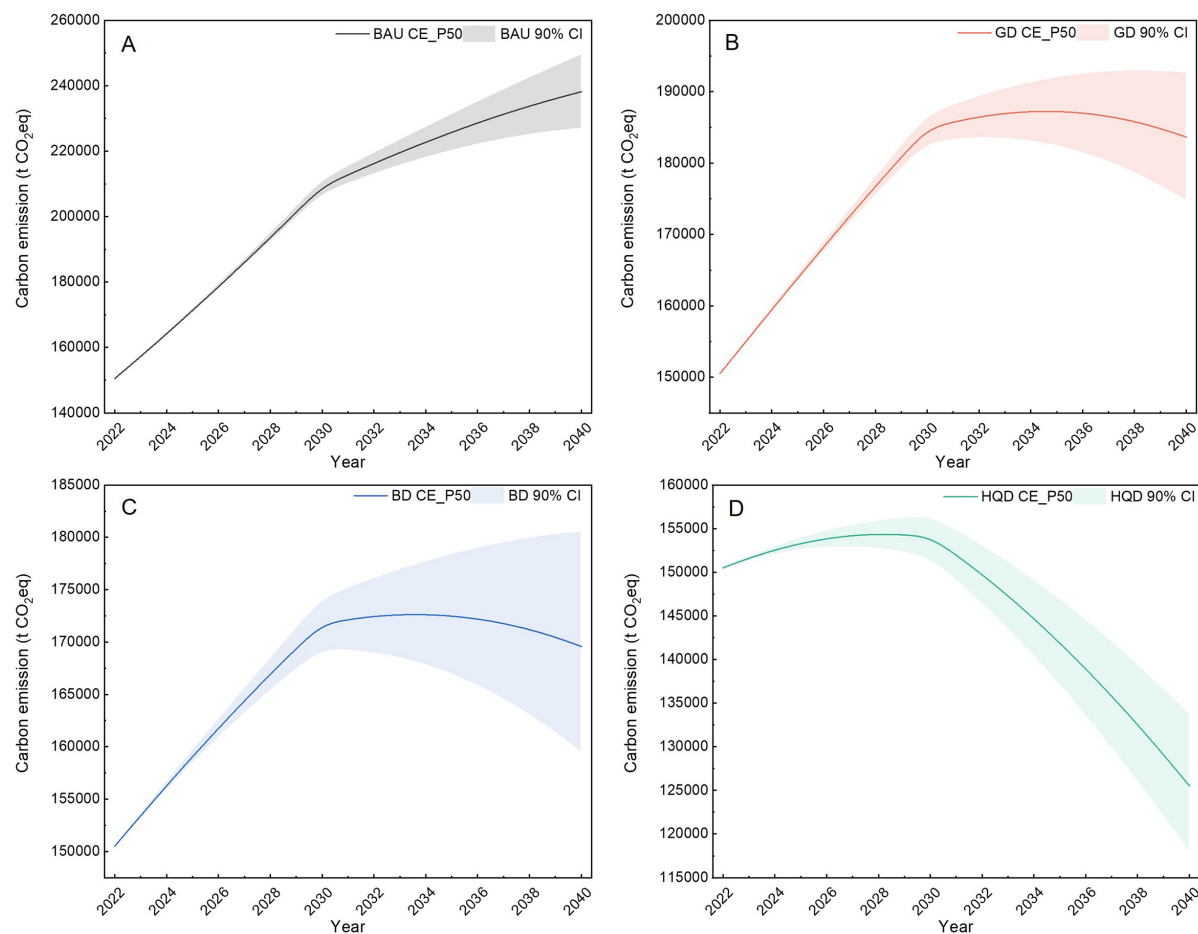


Figure 2. Carbon emission forecast trends in the CBD of Qingpu New Town. (A) BAU, (B) GD, (C) BD, (D) HQD. CBD: Central business district; BAU: business-as-usual; GD: general development; BD: balanced development; HQD: high-quality development.

decarbonization. Uncertainty bands widen over time, showing higher relative uncertainty in 2040 than in 2030. This suggests that mid- to long-term projections are more sensitive to assumptions on economic growth, energy mix, and technology uptake. Monte Carlo sampling around target-year anchors shows that uncertainty bands tighten when policy targets are closely aligned with base-year conditions but expand substantially when targets are more ambitious or loosely constrained.

The HQD scenario is selected as an illustrative case for further analysis. Parameter settings are presented in [Supplementary Table 8](#). Based on the OAT sensitivity results [[Figure 3](#)], the signs of parameter effects align

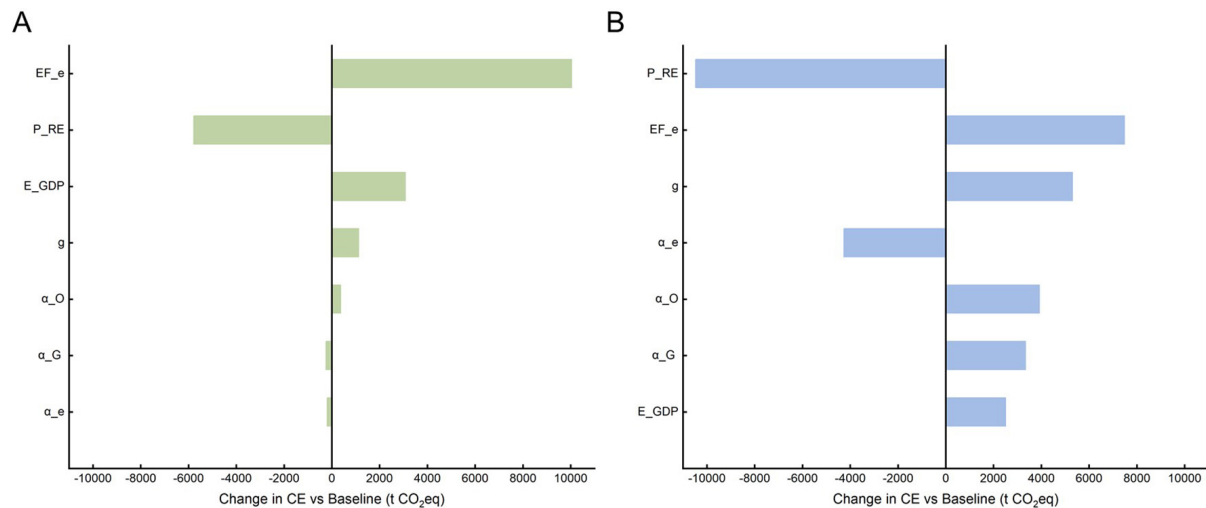


Figure 3. Sensitivity analysis. (A) Absolute changes in emissions in 2030. (B) Absolute changes in emissions in 2040. P_{RE}: Share of renewable energy in total electricity consumption; EF_e: carbon emission factor for electricity; g: GDP growth rate; α_e: proportion of electricity in total energy consumption; α_O: proportion of gasoline in total energy consumption; α_G: proportion of natural gas in total energy consumption; E_{GDP}: energy consumption per 10,000 CNY of GDP.

with theoretical expectations. In the near term, changes in the EF_e and P_{RE} are the most influential drivers of CBD emissions, while variations in E_{GDP} and g exert moderate effects. Over the long term, the influence of P_{RE} becomes even more pronounced, underscoring the central role of the electricity structure in shaping emission trajectories. In contrast, adjustments in the shares of gasoline, natural gas, and electricity within the total energy mix have only marginal impacts throughout the period.

Using BAU as the baseline for 2040, the emission reductions under GD, BD, and HQD from 2022 to 2040 are calculated to estimate the carbon reduction potential of the CBD in Qingpu New Town. If GD measures are adopted, the carbon reduction potential will reach 54,500 tCO₂eq by 2040. Under BD, more stringent measures will lead to a reduction of 68,600 tCO₂eq, while the HQD will achieve a reduction of 112,600 tCO₂eq. To eliminate the external emission reduction effects resulting from the decline in electricity emission factors, the study further calculates the technology-driven carbon reduction targets under different scenarios - i.e., the amount of carbon emissions reduced through structural optimization and technological measures. The results show that by 2040, the technology-driven carbon reduction targets derived from scenario simulations are 15,100 tCO₂eq under the GD scenario, 33,800 tCO₂eq under the BD scenario, and 47,800 tCO₂eq under the HQD scenario.

Analysis of multi-scenario source-sink integration technological pathways

To quantitatively assess the contribution of various low-carbon technologies under different development scenarios, this study calculates the emission reduction potential of a comprehensive set of Source-Sink Integration technologies for the Qingpu New Town CBD by the year 2040, as shown in Figure 4A. The evaluation includes three scenarios: GD, BD, and HQD, with total technology-driven emission reductions reaching 59,467 tCO₂eq, 72,038 tCO₂eq, and 77,547 tCO₂eq, respectively.

Under all scenarios, building-related technologies emerge as the dominant contributors to emission reduction. Energy-efficient building design alone accounts for approximately 34,599 tCO₂eq (GD), 36,496 tCO₂eq (BD), and 36,646 tCO₂eq (HQD), making it the single most effective measure. This highlights the substantial potential of enhancing building envelope performance and adopting low-energy

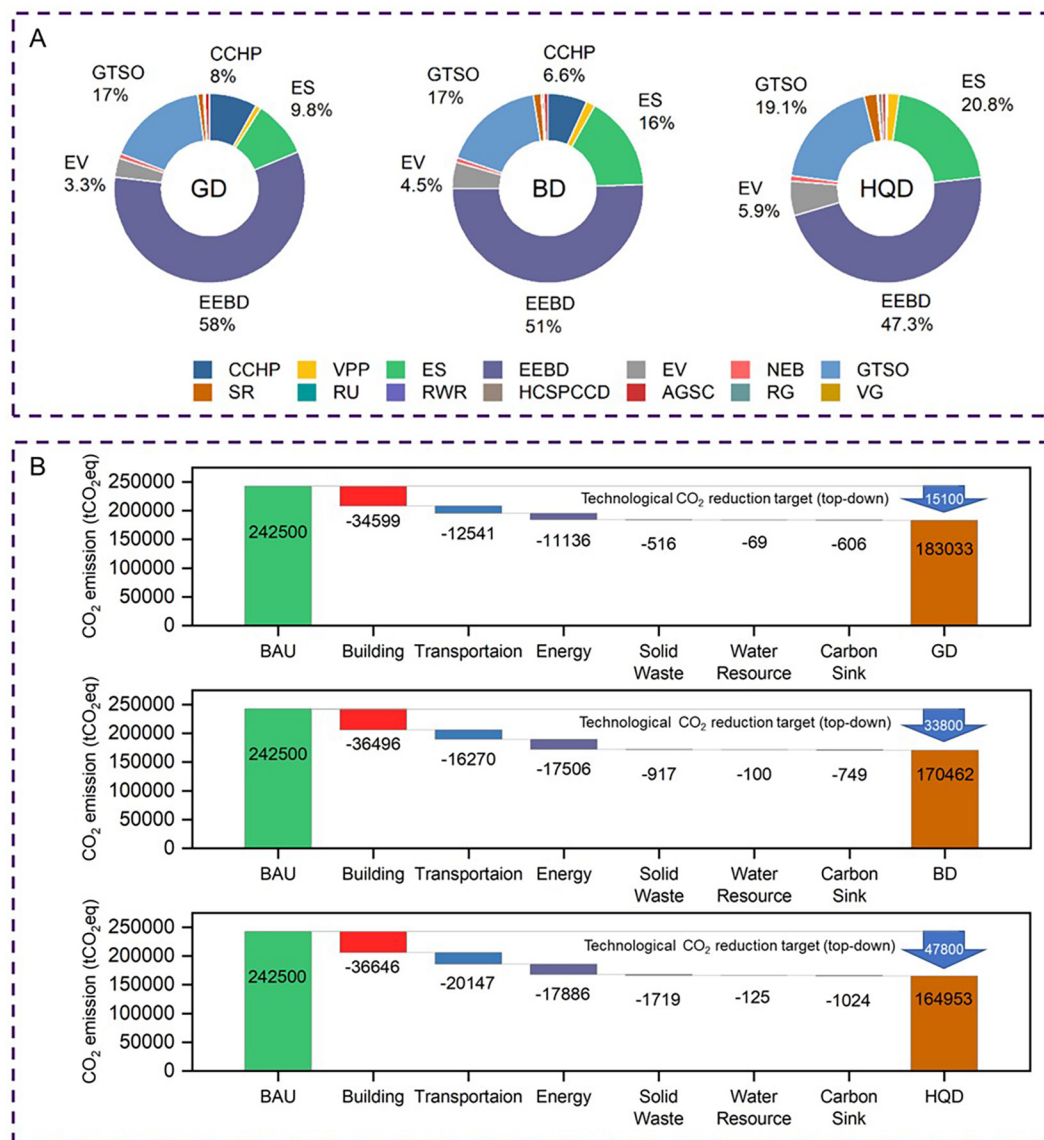


Figure 4. Carbon Emission Reduction potential of a comprehensive set of Source-Sink Integration technologies. (A) Proportion of Carbon Reduction from Technologies under Different Scenarios in 2040. (B) Comparison of 2040 Technology Portfolios with Scenario Simulation Results. BAU: Business-as-usual; GD: general development; BD: balanced development; HQD: high-quality development; CCHP: combined cooling, heating and power; VPP: virtual power plant; ES: energy storage; EEBD: energy-efficient building design; EC: electric car; NEB: new energy bus; GTSO: green travel structure optimization; SR: source-sorted recycling; RU: rainwater utilization; RWR: reclaimed water reuse; HCSPCCD: high carbon sink plant combinations and community design; AGSC: affiliated green space construction; RG: rooftop greening; VG: vertical greening.

architectural practices within high-density CBD environments. In the energy sector, distributed energy technologies show varying contributions across scenarios. Trigenation systems based on natural gas (CCHP) achieve reductions of 4,765 tCO₂eq in both BAU and BD, but only 198 tCO₂eq in HQD due to a presumed shift away from fossil-based systems. Meanwhile, emerging smart grid technologies, including virtual power plants and energy storage, show a consistent increase in effectiveness with scenario ambition. Energy storage systems, for example, contribute 5,809 tCO₂eq (GD), 11,618 tCO₂eq (BD), and 16,133 tCO₂eq (HQD), indicating strong potential to support renewable integration and demand-side management. Transportation-related measures also exhibit significant contributions, particularly under the

more ambitious development scenarios. The promotion of electric cars results in emission reductions ranging from 1,960 tCO₂eq (GD) to 4,573 tCO₂eq (HQD). Similarly, new energy buses and green travel structure optimization lead to cumulative reductions of 10,581 tCO₂eq (GD), 16,270 tCO₂eq (BD), and 20,147 tCO₂eq (HQD). Additional carbon reduction benefits stem from improvements in solid waste and water resource management. Source-separated waste recycling contributes up to 1,719 tCO₂eq in HQD, while rainwater utilization and reclaimed water systems provide smaller, but important, reductions that enhance system resilience. Carbon sink technologies related to landscape design also play a supplementary role. The design of high carbon sequestration plant communities, combined with rooftop and vertical greening, contributes modest yet valuable emission reductions. For instance, these greening strategies collectively account for 606 tCO₂eq in the BAU scenario and up to 1,024 tCO₂eq in HQD.

Overall, this analysis underscores the importance of integrating multiple technological pathways to meet scenario-specific carbon reduction targets, as shown in Figure 4B. While energy-efficient building design remains the backbone of the carbon reduction technological strategy, scalable improvements in energy, transportation, and carbon sink are essential to achieving a comprehensive and resilient low-carbon CBD by 2040.

DISCUSSION

The scenario analysis clearly shows that operational emissions in the CBD are jointly driven by macroeconomic demand scale and the pace of power-sector decarbonization. Relative to BAU, the GD, BD, and HQD scenarios exhibit progressively greater efficiency gains and cleaner power penetration, yielding earlier and lower peaks. Among these, HQD achieves earlier peaking and larger reductions under higher clean-power targets and steadier intensity improvements. Monte Carlo draws around target-year anchors indicate that uncertainty bands are narrower when targets are coherent with the base year and policy bounds are clear, but widen markedly when anchors are more ambitious or weakly constrained - highlighting the decisive influence of policy implementation tempo and external clean-power supply on scenario realization. OAT results indicate that in the short term, EF_e and P_{RE} dominate CBD emissions, while E_{GDP} and g have moderate influence. In the long run, the effect of P_{RE} grows stronger, whereas changes in fossil fuel shares show only minor impacts.

Comparing technology pathways with scenario targets suggests that building energy efficiency constitutes the foundational abatement wedge; distributed resources, storage, and flexibility provide system-level support; travel-mode shifts and electrification deliver steady long-run gains; and solid waste, water systems, and carbon sinks offer complementary contributions. Under HQD, the scenario-specific technology bundle can match and even exceed the required “technical abatement” gap, indicating that coordinated source-grid-load-storage-mobility strategies combining “strong efficiency + high clean-power share + demand-side management” can deliver substantial reductions without compromising development quality.

Limitations and future directions

This analysis is primarily district-scale and top-down, so it only partially captures intra-sector heterogeneity, rebound effects, and endogenous feedbacks along technology-adoption paths. The S-curve identification strategy favors interpretability and may be conservative under shocks or structural breaks. Although we quantify parameter uncertainty using OAT and Monte Carlo sampling, structural uncertainty warrants deeper treatment. Data constraints, particularly the lack of systematic building-level energy records and other high-resolution inputs, may underrepresent spatial and structural variability within the CBD. In addition, the absence of material ledgers, process parameters, and end-of-life pathways prevents the inclusion of Life Cycle Assessment (LCA) at this stage. Future research could move toward single-building

resolution via sub-metering and digital twins, assemble a Life Cycle Inventory and implement hybrid LCA, and couple this framework with bottom-up engineering models to better reflect sectoral heterogeneity and system feedbacks - thereby improving robustness and policy relevance under uncertainty.

Policy implications

To promote the low-carbon transition of the CBD, multi-scenario carbon emission simulations should be systematically embedded into urban planning and evaluation systems. This would enable the early assessment of carbon impacts under different development pathways, thereby supporting informed and scientific decision-making. Meanwhile, a coordinated incentive mechanism based on the integration of “technology-scenarios-benefits” should be established to foster the deep integration of low-carbon technologies into specific application contexts and to strengthen the quantifiable evaluation and dynamic feedback of emission reduction outcomes. At the regional level, a cross-departmental coordination mechanism is needed to break down sectoral silos, promote resource integration and data sharing, and build a unified and efficient joint regulatory system. On this basis, diversified policy tools, such as fiscal subsidies, carbon points, green credit, and credit evaluation, should be employed to incentivize active participation from the public, enterprises, and social organizations, thereby building a collaborative governance model that provides strong support for green, low-carbon, and high-quality CBD development.

At the operational level, it is recommended that all CBD projects submit a concise Carbon Impact Statement (CIS) that tests several “what-if” scenarios and ensures compliance with two conditions: (1) the project fits within the CBD’s overall carbon budget; and (2) it meets basic fairness criteria. Responsibilities are kept simple: the Planning Department incorporates the CIS into permitting procedures, the Environmental Bureau oversees Measurement, Reporting, and Verification (MRV) and enforcement, the Finance Bureau manages the Equity Retrofit Fund (ERF) and green finance, utilities upgrade the grid and share data, and Energy Service Companies (ESCOs) conduct retrofit work under standardized performance contracts. Results should be published regularly, and adjustments made through a rapid Plan-Do-Check-Act cycle.

To safeguard fairness, public infrastructure is financed through city budgets and green bonds, while building retrofits are repaid through shared-savings contracts with ESCOs or via on-bill repayment mechanisms. The ERF should prioritize higher levels of grants and credit guarantees for low-income groups and Small and Medium Enterprises (SMEs). An affordability index should be adopted to ensure repayment capacity, while rent-protection rules should prevent landlords from passing costs to tenants without corresponding benefits. The CBD management committee should further support SMEs through bulk procurement, a one-stop help desk, tiered compliance pathways, and green lease mechanisms that fairly distribute verified savings between landlords and tenants. In this way, CBD decarbonization can achieve efficiency, fairness, and sustainability simultaneously. Stakeholder Participation Matrix is shown in [Table 4](#).

CONCLUSION

CBDs hold particular significance due to their high energy consumption, densely built environments, and concentrated carbon emissions. While they are frequently viewed as engines of economic growth, CBDs also represent hotspots for carbon intensity, rendering them critical targets for emission reduction strategies. Based on the current development and planning goals of Qingpu New Town CBD, this study constructed four carbon emission scenarios - BAU, GD, BD, and HQD - and conducted a top-down simulation and carbon reduction potential assessment for 2022-2040. The results indicate that under BAU, emissions continue to rise without reaching a peak, highlighting the unsustainability of traditional development models. In contrast, GD and BD show progressively earlier and lower emission peaks, while

Table 4. Stakeholder participation matrix

Who	What they do	Their tools
Planning Bureau	Put CIS into permits; apply the two-gate rule	Permit conditions; CIS checklist
Environment Bureau	Set standards; do MRV; enforce compliance	Codes, audits, public disclosure
Finance Bureau	Run ERF; arrange green finance	Grants/rebates, guarantees, green bonds
Utilities	Provide enabling infrastructure & data	Grid upgrades, connection terms, open data
CBD Committee	Orchestrate and help SMEs	Bulk buying; one-stop technical assistance; vendor lists
ESCOs/Developers	Deliver retrofits end-to-end	Shared-savings & on-bill contracts
Owners & Tenants (including SMEs)	Join programs; sign green leases	Green lease templates; technical assistance kits
Community/Low-income groups	Co-design protections; give feedback	ERF grants; rent safeguards

CIS: Carbon impact statement; MRV: measurement; reporting; and verification; ERF: equity retrofit fund; CBD: central business district; ESCOs: energy service companies; SMEs: small and medium enterprises.

HQD peaks in 2028 and achieves a 47.3% reduction in total emissions and a 52.6% decline in carbon intensity compared with BAU by 2040. OAT analysis shows that in the near term, EF_e and P_{RE} are the primary determinants of CBD emissions, with E_{GDP} and g exerting secondary effects. Over the longer term, the role of P_{RE} becomes increasingly significant, while adjustments in fossil fuel shares contribute only marginally. After excluding the external effects of grid decarbonization, the 2040 technology-based carbon reduction targets for GD, BD, and HQD are calculated at 15,100, 33,800, and 47,800 tCO₂eq, respectively.

A systematic assessment of sectoral carbon reduction potentials was conducted across six key areas: buildings, energy, transport, solid waste, water resources, and carbon sinks. Energy-efficient building design emerges as the dominant contributor, with a maximum share of 58.2% among all scenarios. The energy system exhibits a transition toward storage-led and smart-grid solutions, with storage technologies contributing up to 20.8% in HQD. In the transport sector, decarbonization is driven by electric vehicle adoption and optimization of urban mobility patterns. Solid waste and water-related carbon reductions rely on improved recycling and reuse efficiencies. Carbon sink strategies focus on vertical greening and high carbon sequestration plant communities. By 2040, the total technological carbon reduction potentials for GD, BD, and HQD reach 59,500, 72,000, and 77,500 tCO₂eq, respectively, all aligning with their scenario-based emission reduction targets. These findings demonstrate the feasibility and policy relevance of a multi-scenario low-carbon transition pathway for CBDs.

DECLARATIONS

Authors' contributions

Conceptualization, methodology: Wang, L.; Guo, R.; Li, A.; Peng, K.; Xu, C.; Jing, X.; Zhang, Y.; Liu, J.; Chen, B.; Ma, T.; Huang, X.

Data curation, writing - original draft, formal analysis: Wang, L.; Li, A.; Xu, C.; Jing, X.; Zhang, Y.

Funding acquisition, supervision: Guo, R.; Peng, K.; Liu, J.; Chen, B.; Ma, T.; Huang, X.

Validation: Wang, L.; Guo, R.; Li, A.; Peng, K.; Xu, C.; Jing, X.; Zhang, Y.

Visualization: Wang, L.; Wu, H.; Cai, A.

Writing - review & editing: Wang, L.; Guo, R.; Li, A.; Peng, K.; Shi, X.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of interest

Xu, C. and Chen, B. are affiliated with Shanghai Tongji Urban Planning & Design Institute Co., Ltd., while the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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