

Article

Assessment of Carbon Emission Reduction Benefits of Infrastructure Systems in Urban Underground Space Development

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Abstract

Urban underground space is increasingly being developed to alleviate surface land constraints and support low-carbon urban development. However, carbon emission reduction (CER) benefits remain inadequately quantified and are not comparable across underground infrastructure types, largely due to the absence of a unified assessment framework, inconsistent system boundaries, and the omission of multi-pathway mitigation mechanisms such as carbon capture and storage and biological sequestration. This study proposes a CER benefit assessment framework for urban underground space that integrates mitigation mechanism identification, pathway analysis, and benefit accounting, explicitly incorporating biological carbon sequestration, carbon substitution, and carbon capture and storage within a unified accounting structure. Accounting models are then established for three representative underground infrastructure systems: transportation, public and commercial services, and municipal utilities. Using Nanjing as a case city to operationalize and validate the proposed assessment framework, we estimate CER across multiple pathways and compare regional differences. The results indicate that underground transportation infrastructure provides the largest benefit (8.74×10^5 tCO₂e per year), mainly driven by travel substitution and energy savings in station buildings. Underground public and commercial facilities achieve 6.64×10^5 tCO₂e per year, dominated by green-building energy savings and geothermal integration. Municipal utilities contribute a smaller but strategically important reduction, as they provide a long-term carrier for carbon capture and storage and are structurally integrated within underground utility corridors, totaling 0.98×10^5 tCO₂e per year citywide. Overall, the findings reveal differentiated mitigation mechanisms and spatial heterogeneity across underground infrastructure systems, providing a theoretical basis for optimizing urban spatial planning and informing low-carbon transition policies.



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Keywords: urban underground space; carbon emission reduction; infrastructure systems; carbon reduction mechanisms; assessment model

1. Introduction

In the context of intensifying global climate change, reducing urban carbon emissions is crucial for achieving carbon neutrality targets [1]. Urban areas, characterized by dense populations and intensive economic activities, are the primary sources of energy consumption and carbon emissions [2–4]. To advance the process of carbon peaking and carbon neutrality, countries worldwide are widely promoting urban green transitions. China has

also explicitly proposed its “dual carbon” goals, emphasizing the low-carbon development of urban spaces and infrastructure systems [5]. In this context, urban infrastructure is receiving increasing attention as it serves as both a significant source of emissions and a critical sector with carbon reduction potential [6].

Existing research on carbon emission reduction (CER) in urban infrastructure primarily focuses on building energy efficiency, green transportation systems, clean energy substitution, and water resource recycling, aiming to reduce carbon emissions by improving the operational efficiency of individual systems [7–9]. Methodologically, life cycle assessment, carbon footprint analysis, system modeling, and multi-objective optimization are commonly employed, contributing to the development of urban infrastructure CER assessment frameworks [10,11]. In recent years, research has shifted from single facilities to cross-sectoral and multi-system coordination. This shift emphasizes coupling mechanisms among infrastructure systems and the evaluation of integrated benefits. However, most of these studies are based on surface-level operational environments and technological pathways and have not yet adequately addressed the expanding underground infrastructure systems within urban spaces.

As an integral component of the urban infrastructure system, underground space plays an increasingly prominent role in expanding urban development space and enhancing resource utilization efficiency [12–14]. Possessing advantages such as a stable thermal environment, strong spatial substitution capability, and high integration of energy systems, it offers a solid foundation for achieving CER [15,16]. However, research on CER in underground infrastructure remains limited. Existing studies mainly focus on specific pathways, such as underground rail transit, geothermal energy utilization, and underground green space development. However, differences in analytical scope, system boundaries, and accounting assumptions across studies make their reported CER results difficult to compare [17,18]. Most studies rely on case analyses or theoretical deductions [19,20], lacking classification identification and the analysis of reduction mechanisms for multi-type underground facilities, and a unified assessment framework applicable to multiple types of underground infrastructure has not yet been established, resulting in CER estimates that are highly case-dependent and lack cross-system comparability. Meanwhile, the applicability and interaction of multiple mitigation pathways within underground space—such as carbon capture and storage, biological carbon sequestration, and energy substitution—are often treated in isolation or omitted altogether, leading to an incomplete representation of total CER potential [21]. The lack of clear quantification methods makes it difficult to effectively support policy formulation and empirical assessment. Therefore, a comprehensive analytical framework covering mechanism identification, pathway integration, and benefit assessment is required to support systematic CER research in underground space. Cities such as Tokyo and Seoul have accumulated extensive experience in the intensive development and utilization of urban underground infrastructure, particularly in transportation systems and public service facilities. These international practices highlight the increasing relevance of underground space as a strategic domain for urban sustainability, while also revealing the need for analytical frameworks that enable consistent assessment across different urban contexts.

To address these gaps, this study focuses on urban underground infrastructure systems and develops an analytical framework for CER that integrates mechanism identification, pathway analysis, and benefit accounting. It clarifies three reduction mechanisms, including biological carbon sequestration, carbon capture and storage, and carbon substitution, and develops CER benefit assessment models for underground transportation, public and commercial services, and municipal utilities based on facility functional attributes. Using Nanjing as a case study, data from representative underground space projects are collected

to estimate CER across multiple facility types, thereby validating the applicability and practicality of the proposed models.

The main contributions of this study are threefold. First, it categorizes the types of urban underground infrastructure and establishes an analytical framework for CER encompassing mechanism, pathway, and benefit. Second, by integrating three mitigation pathways, including biological carbon sequestration, carbon capture and storage, and energy substitution, it proposes quantifiable assessment models and extends the spatial boundaries of urban CER theory. Finally, based on an empirical study in Nanjing, it evaluates the CER benefits of different types of underground infrastructure, effectively verifying the validity and replicability of the proposed models.

The remainder of this paper is organized as follows. Section 2 reviews relevant literature and research progress. Section 3 presents the identification of CER mechanisms and the construction of the analytical model. Section 4 presents simulations and discussions based on a real-world case study. Section 5 concludes the study and outlines future research directions.

2. Literature Review

2.1. CER of Urban Infrastructure System

As global climate change intensifies, urban infrastructure systems play an increasingly critical role in achieving carbon neutrality targets, given that cities are concentrated areas of energy consumption and carbon emissions [22,23]. Infrastructure encompasses core sectors such as buildings, transportation, energy, and water services and accounts for a substantial share of urban life-cycle carbon emissions. From the perspective of building facilities, research on CER primarily focuses on the promotion of green building standards and the accounting of lifecycle carbon emissions. Du et al. [24] combined system dynamics with the long-range energy alternatives planning model to estimate energy consumption and carbon emissions across different building types. Zhao et al. [25] evaluated the carbon emissions of prefabricated buildings, identified their potential pathways for carbon reduction in urban renewal, constructed an influence mechanism based on the structural equation model, and established an assessment model by combining the system dynamics method. Regarding transportation infrastructure, relevant research is mainly conducted from three dimensions: modal shift, the development of intelligent transportation systems, and the optimization of infrastructure spatial layout. Chen et al. [26] integrated an origin–destination traffic flow model with a Monte Carlo approach to assess carbon emissions from urban refrigerated trucks. Taking Hefei, China, as a case study, they explored the carbon reduction potential of promoting electric refrigerated trucks and optimizing future power distribution modes. Zhou et al. [27] identified the key drivers of carbon emissions in the transportation sector and deeply analyzed the dynamic evolution of passenger and freight structures. By simulating 16 scenarios spanning from 2025 to 2040 that cover four dimensions, including economic growth, demographic changes, railway policies, and road freight policies, they predicted that carbon emissions in the transportation industry would peak around 2034. Energy and water infrastructure have also increasingly become key focal points in urban CER research. Qin et al. [28] collected data on water resource utilization, economic development, and social indicators across Chinese cities. They employed the life cycle assessment method to quantify the carbon emissions of urban water supply systems from 2005 to 2022 and analyzed their spatiotemporal evolution characteristics. The results indicate that the carbon emissions of urban water supply systems in China ranged from 162.01 million to 237.37 million tons of CO₂e, presenting a trend of decreasing, increasing, and then decreasing again.

Notably, research on CER in infrastructure systems has been shifting from individual component optimization to system-level coordination [29]. On one hand, multi-infrastructure coupling models are being gradually developed, emphasizing coordinated carbon reduction mechanisms across transportation, energy, and building systems [30]. On the other hand, the boundaries of carbon emission accounting have been continuously expanded to include indirect emissions throughout the entire life cycle and value chain of infrastructure systems [31].

2.2. CER of Urban Underground Space

Compared to traditional above-ground development, underground space possesses significant advantages in terms of space utilization efficiency, thermal environment stability, and energy coupling, making it an increasingly important component of low-carbon urban development [32]. Existing research primarily focuses on aspects such as CER pathways, accounting methods, and carbon expenditure of urban underground space [12,33].

First, from the perspective of carbon emission pathways, underground space exhibits a certain level of carbon intensity during the construction phase but demonstrates significant CER potential during the operational phase through energy substitution, biological carbon sequestration, and system-level integration. In a life cycle carbon assessment of underground space development in China from 2001 to 2020, Wang et al. [34] identified underground buildings, rail transit, and geothermal systems as three typical structures for carbon emissions and reduction in underground space. Among them, although underground buildings entail high carbon emissions during the construction phase, substantial carbon sink gains can be achieved if the released surface space is converted into green vegetation. Wei et al. [21] quantitatively evaluated the ecological carbon sink potential of urban underground space by combining vegetation design strategies for urban blue-green spaces with carbon sequestration efficiency estimation methods. They constructed an estimation model converting underground development intensity into surface ecological space and established carbon sink calculation methods for partially open green spaces, closed green spaces, and partially open blue spaces.

Second, existing research shows a clear trend of shifting carbon emission accounting from the project level to the system level. Adopting life cycle assessment and scenario analysis methods at the national scale, Wang et al. [35] systematically evaluated the carbon reduction trends of three types of underground spaces, including underground buildings, rail transit, and geothermal systems, under different development scenarios. They pointed out that policy promotion and green technology integration would be key to enhancing the CER capability of underground space in the future. Furthermore, Wang et al. [35] explored the carbon footprint characteristics of urban underground highway tunnel facilities throughout their life cycles. Based on their functional positioning and design complexity, they constructed a carbon emission calculation model covering the full life cycle, revealing the overall carbon emission characteristics of such facilities. Additionally, Yang et al. [36] proposed four dimensions of CER efficiency and 21 assessment indicators. Based on the socio-technical systems theory, they constructed an analytical framework and conducted empirical verification through the Delphi method and confirmatory factor analysis. The results indicate that technological innovation, environmental protection, and ecological sustainability are prioritized, whereas aspects such as economic incentives, resource efficiency, social participation, and synergistic effects receive relatively lower attention.

Finally, it should be noted that underground space development still faces numerous challenges, such as high energy consumption during the construction phase and significant carbon expenditure for ventilation and lighting systems during the operational phase [11]. Based on data from the Xinjiekou underground space development in Nanjing since 2006,

Bian et al. [37] quantitatively analyzed the low-carbon benefits and carbon emission capabilities under different development intensities. They explored the influence of development intensity and urban socioeconomic factors on the dynamic evolution of carbon emissions and proposed recommendations for appropriate underground space development intensity.

In summary, existing research has conducted preliminary explorations into the CER mechanisms of urban infrastructure and underground space, focusing on the identification of carbon emission pathways, the delineation of accounting boundaries, and the improvement of system efficiency. A research framework covering multiple pathways, such as biological carbon sequestration, carbon capture and storage, energy substitution, and building energy conservation, has been initially established. However, there is currently a lack of classification and quantitative analysis of benefits for the CER pathways of different types of underground facilities. To this end, this study focuses on various types of urban underground infrastructure systems and constructs an analytical framework encompassing the mechanism, pathway, and benefit of CER. It proposes CER benefit assessment models covering rail transit, commercial services, and municipal utilities. Furthermore, taking Nanjing as a typical case, empirical simulation research is conducted to provide theoretical support and practical guidance for achieving urban dual carbon goals.

3. Methods

3.1. Research Framework

This study establishes a three-module research framework to systematically assess the carbon emission reduction benefits of infrastructure in urban underground space development. The first module identifies three applicable carbon reduction mechanisms in underground space, namely biological carbon sequestration, carbon capture and storage, and carbon substitution. The second module develops a benefit assessment model based on the core structure of “sequestration + substitution + capture – emissions,” which is applicable to different types of underground infrastructure. The third module applies Nanjing as an empirical case to conduct data collection, result estimation, and comprehensive analysis in order to validate the applicability of the model and extract policy implications. Figure 1 illustrates the research framework of this study.

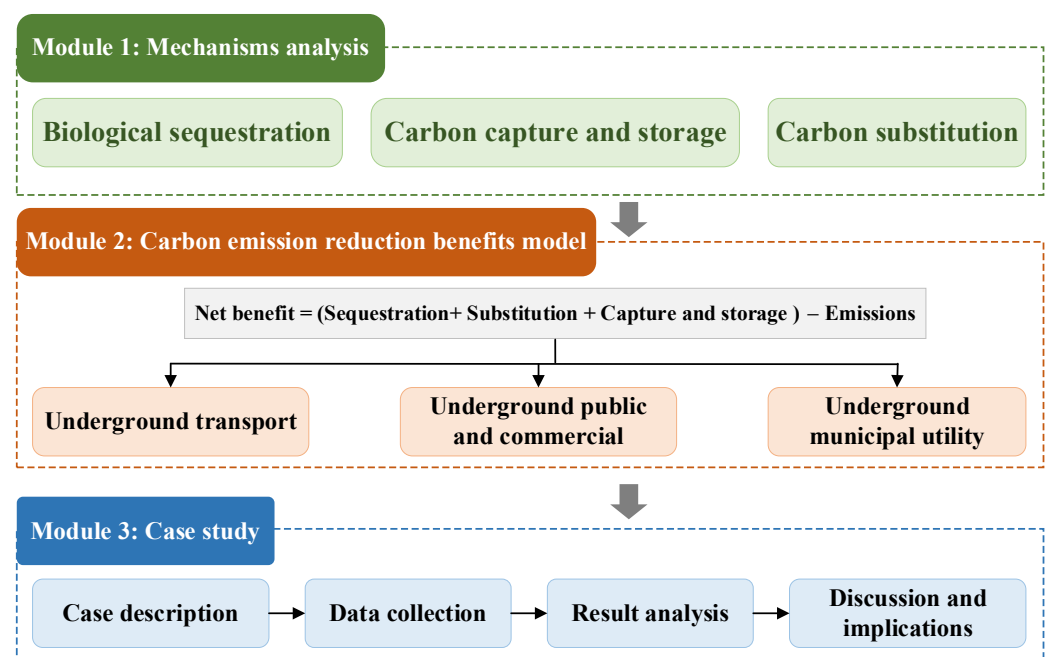


Figure 1. Schematic diagram of the research framework.

3.2. Assumptions and Accounting Rules

In this study, CER benefits are evaluated by comparing urban underground space infrastructure systems against clearly defined baseline scenarios. For transportation-related pathways, the baseline is defined as a functionally equivalent above-ground transport system dominated by private vehicles and surface roads, representing a mode-shift counterfactual. For public and commercial service facilities, the baseline refers to conventional above-ground buildings providing equivalent service capacity, with energy performance benchmarked against prevailing public building energy standards. For municipal utility systems, the baseline is defined as a no-project scenario in which carbon capture, storage, and energy substitution technologies are not implemented.

The system boundary of the assessment focuses on the operational phase of infrastructure systems, including energy consumption, carbon capture, and carbon sequestration effects during use. Due to data availability constraints, construction, maintenance, and end-of-life stages associated with underground infrastructure are not included in the quantitative accounting. To ensure comparability across different infrastructure types and mitigation pathways, all CER estimates are evaluated consistently within the same operational-phase system boundary.

To avoid double counting across mitigation pathways and infrastructure systems, this study applies accounting rules based on functional exclusivity and allocation principles. Energy efficiency improvements arising from the thermal stability of underground buildings and energy substitution achieved through geothermal systems are treated as mutually exclusive pathways for the same energy demand and are not counted simultaneously in CER estimation. When geothermal systems serve different infrastructure functions, the associated CER benefits are accounted for separately according to the energy demand scale of each system.

For surface land released through underground development, the corresponding greening-related carbon sequestration benefits are attributed only once, to the primary infrastructure system responsible for the spatial substitution, and are not allocated across multiple systems. Under these accounting rules, each unit of carbon emission reduction is included once in the assessment, ensuring internal consistency and methodological rigor.

Several coefficients and parameters play a dominant role in determining the magnitude of the estimated carbon emission reduction benefits, including green-building energy-saving rates, technology adoption rates, grid emission factors, travel mode-shift rates, and efficiencies of carbon capture, utilization, and storage. To improve transparency and reproducibility, all key parameters used in the analysis are consolidated into a master parameter table, which reports their symbols, values, units, data sources, plausible ranges, selection rationale, and local applicability. The full set of parameters is summarized in Table 1.

Operational parameters related to ventilation rates, lighting intensity, and energy efficiency are derived from prevailing design standards and local survey data, which reflect typical operating conditions of underground facilities in Nanjing. While actual operational performance may vary across facilities and over time, the adopted parameters provide a consistent and representative basis for comparative assessment. Variations in these assumptions would proportionally affect the magnitude of estimated CER values; however, the relative contribution of different mitigation pathways remains robust under reasonable parameter ranges.

3.3. CER Mechanisms of Urban Underground Space

Driven by the dual carbon strategy, urban underground space not only serves as a traditional spatial carrier but also increasingly exhibits its systemic potential in CER. Compared with above-ground systems, underground space possesses characteristics such

as strong structural enclosure, a stable thermal environment, and high integration of composite resources, offering a solid physical foundation for integrating multi-pathway carbon reduction mechanisms. Based on existing research and engineering practices, the CER mechanisms of urban underground space can be classified into three core pathways. The first is the biological carbon sequestration mechanism, which enhances urban carbon sink capacity through surface greenery replacement and underground artificial ecosystems. The second is the carbon capture and storage (CCS) mechanism, utilizing underground space as an integrated carrier for CO₂ capture, transportation, and long-term storage. The third is the carbon substitution mechanism, utilizing the constant underground thermal environment and renewable energy to replace traditional high-carbon energy to achieve source reduction. These three mechanisms are intertwined within the underground space, serving as significant support for the path of urban low-carbon development.

Based on this foundation, various types of infrastructure within urban underground space have become key carriers for the implementation of carbon reduction mechanisms. By incorporating the aforementioned reduction pathways, facilities with different functions demonstrate structural contributions to carbon reduction during their operation. For example, underground transportation systems generate carbon reduction benefits through travel substitution by rail and surface greening. Underground public service facilities reduce energy consumption by utilizing constant-temperature building structures and geothermal systems. Underground municipal and industrial facilities can integrate CCS systems and renewable energy sources to achieve both emission control and spatial co-utilization. The conceptual framework of CER mechanisms in urban underground space is shown in Figure 2.

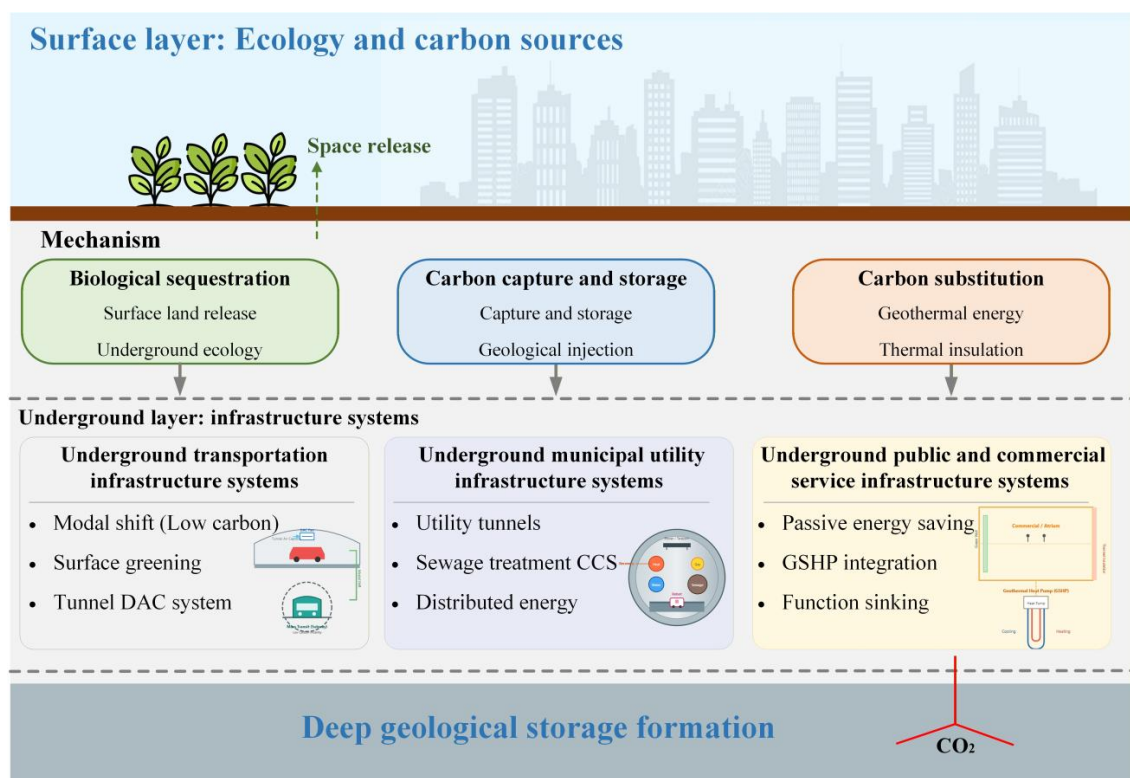


Figure 2. Schematic diagram of CER mechanisms in urban underground space.

3.3.1. Biological Carbon Sequestration

Biological carbon sequestration in urban underground space refers to the process of enhancing urban biological carbon sinks by releasing surface land through underground

development and expanding underground green systems. This mechanism primarily includes two approaches. The first is to relocate suitable facilities such as commercial spaces, transportation systems, and wastewater treatment plants underground, thereby freeing surface land for the construction of green vegetation and forming new carbon sink units. The second is to directly build artificial ecosystems within underground space that support plant growth, enabling plants and microorganisms to absorb and fix atmospheric CO₂ through photosynthesis and convert it into organic carbon stored in vegetation and soil. This approach achieves both CER and ecological benefits. In urban ecosystems, green space not only functions as a carbon sink but also enhances biodiversity and improves local microclimates. Therefore, under the dual carbon targets, its role in carbon sequestration is gaining increasing attention. The mechanism of biological carbon sequestration in urban underground space is illustrated in Figure 3.

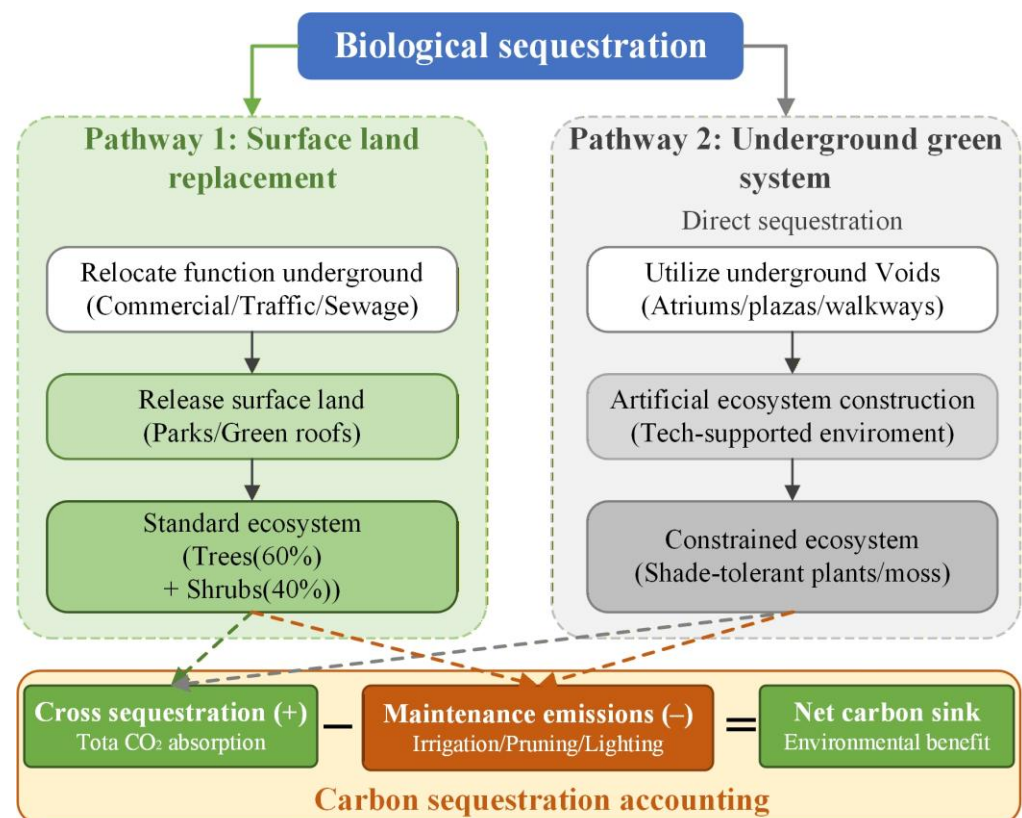


Figure 3. Framework of biological carbon sequestration mechanism in urban underground space.

For the quantification of carbon sink effects, this study adopts the mean biomass method to model the biological carbon sequestration mechanism of urban underground space. This method estimates total carbon sequestration by measuring the biomass density of vegetation per unit area and multiplying it by the corresponding greening area. It is characterized by its simplicity and strong applicability. Considering that urban green structures are primarily composed of trees and shrubs, while turfgrass vegetation generally acts as a carbon source due to its low biomass and short life cycle, only trees and shrubs are included in the model. According to the third national land survey of Nanjing, the ratio of green coverage by trees and shrubs is approximately 6:4. This study incorporates field monitoring data to determine representative values for plant density and carbon absorption per unit. The corresponding carbon sink accounting model is presented in Equation (1), which includes factors such as vegetation type, growth efficiency, proportion of planting area, and deductions for carbon emissions during maintenance. This model provides a

relatively comprehensive estimation of the net increase in carbon sequestration resulting from surface greening substitution.

$$C_{urbangreen} = \sum(\rho_i \times G_i \times S_1 \times 0.6 + \bar{\rho}_s \times \overline{LAI} \times \bar{q} \times S_1 \times 0.4) - \sum(\bar{\rho}_w \times S_1 \times 0.6 \times \bar{R} + \bar{\rho}_s \times S_1 \times 0.4 \times \bar{R}_1) \quad (1)$$

where ρ_i represents the planting density of urban greening trees (plants/hm²); G_i is the amount of CO₂ absorbed and fixed by a single tree per unit time through photosynthesis (g/d); S_1 denotes the total urban green area, measured in hectares (hm²); 0.6 is the proportion of the green area allocated to tree planting, based on the third national land survey of Nanjing; $\bar{\rho}_s$ refers to the average area density of shrubs in urban green spaces (m²/hm²); $\overline{LAI}$ is the average leaf area index of greening shrubs; $\bar{q}$ denotes the amount of CO₂ absorbed and fixed per unit time by shrubs through photosynthesis (g/(m²·d)); 0.4 is the proportion of the green area allocated to shrub planting, based on the third national land survey of Nanjing; $\bar{\rho}_w$ indicates the area density of greening trees, (m²/hm²); $\bar{R}$ represents the carbon cost associated with the maintenance of greening trees, including emissions from irrigation, pruning, fertilization, and other horticultural activities (kgC · hm⁻²); $\bar{R}_1$ refers to the carbon cost associated with the maintenance of greening shrubs, including emissions from irrigation, pruning, fertilization, and other horticultural activities, measured in kilograms of carbon per hectare (kgC · hm⁻²).

However, extending greening functions into underground space faces certain environmental constraints, such as limited light availability, restricted water supply, and inadequate ventilation, all of which significantly affect the photosynthetic efficiency and carbon fixation capacity of vegetation. To more accurately assess the carbon sequestration potential of underground greening systems, this study introduces correction coefficients for the daily carbon sequestration of trees and shrubs, as well as adjustment coefficients for leaf area index, into the accounting model. These correction coefficients range from 0 to 1 and reflect the extent to which underground environmental conditions suppress carbon absorption capacity. The values are determined by urban planners, botanists, and environmental engineers based on evaluations of actual underground environments, taking into account factors such as light intensity, air humidity, ventilation capacity, and nutrient availability [38]. In addition, underground greening typically requires more frequent artificial maintenance, including supplemental lighting, irrigation, and pruning, which generate indirect carbon emissions that should also be included in the accounting system. The net carbon sequestration benefit of urban underground greening is ultimately obtained by subtracting the carbon emissions from the maintenance phase, ensuring scientific rigor and accuracy in the assessment results.

Based on a comprehensive consideration of both surface greening substitution and underground greening systems, this study further develops an extended biological carbon sequestration model applicable to underground space development scenarios, as shown in Equation (2). The model introduces the urban greening ratio as an adjustment coefficient for substituted surface area and incorporates characteristic parameters of underground greening to estimate the potential increase in carbon sinks under different development intensities. It is applicable to various types of underground spaces, such as underground plazas, pedestrian streets, and parks, and allows for flexible parameter adjustment according to specific planning schemes.

$$\begin{aligned} C_{uug} = & GR \times \sum(\rho_i \times G_i \times S_1 \times 0.6 + \bar{\rho}_s \times LAI \times \bar{q} \times S_1 \times 0.4) \\ & + \sum(\rho_i^a \times G_i \times S_2 \times \alpha \times 0.6 + \bar{\rho}_s^a \times LAI \times \bar{q} \times S_2 \times \beta \times 0.4) \\ & - \sum(\bar{\rho}_w \times S_1 \times 0.6 \times \bar{R} + \bar{\rho}_s \times S_1 \times 0.4 \times \bar{R}_1) \\ & - \sum(\bar{\rho}_w^a \times S_2 \times \bar{R}_3 \times 0.6 + \bar{\rho}_s^a \times S_2 \times 0.4 \times \bar{R}_4) \end{aligned} \quad (2)$$

where ρ_i^a represents the planting density of underground greening trees (plants/hm²); S_2 is the total area of underground greening (hm²); α denotes the correction coefficient for the daily carbon sequestration of underground greening trees; $\bar{\rho}_s^a$ refers to the density of underground greening shrubs (m²/hm²); β is the correction coefficient for the daily carbon sequestration of underground greening shrubs; $\bar{\rho}_w^a$ indicates the area density of underground greening trees (m²/hm²); $\bar{R}_3$ represents the carbon cost of maintaining underground greening trees, including emissions from irrigation, pruning, fertilization, and other horticultural activities (kgC · hm⁻²); $\bar{R}_4$ represents the carbon cost of maintaining underground greening shrubs, including emissions from irrigation, pruning, fertilization, and other horticultural activities, (kgC · hm⁻²); GR denotes the urban greening ratio.

3.3.2. Carbon Capture and Storage

CCS is a key low-carbon technological pathway that involves the separation and purification of carbon dioxide generated from industrial processes, energy use, or ambient air, followed by its injection into underground geological formations for long-term storage or resource utilization. Both the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) have repeatedly emphasized that without large-scale deployment of CCS, most emission reduction scenarios are unlikely to meet the temperature control targets set by the Paris Agreement. Therefore, within the context of dual carbon goals, urban underground space offers a physical carrier characterized by enhanced safety, stability, and integration for CCS technology, thereby granting this technology higher feasibility and policy value in urban scenarios.

Compared with conventional surface-based CCS deployment, urban underground space offers several advantages, including a closed environment, stable temperature and humidity conditions, and well-controlled geological characteristics. These features can significantly reduce the risk of CO₂ leakage during the capture, transport, and storage stages, while improving the overall operational efficiency of the system. Moreover, in densely populated urban centers where land resources are highly constrained, locating CCS infrastructure within underground space can reduce surface land occupation and enhance land use efficiency. It also enables system-level integration with underground utility corridors, urban rail transit, and municipal pipelines, providing both spatial support and network connectivity for the application of CCS within urban energy systems.

From a technological perspective, CCS in industrial and energy systems is generally categorized into four types: direct air capture, pre-combustion capture, post-combustion capture, and oxy-fuel combustion capture. Direct air capture extracts CO₂ directly from the atmosphere, but due to the extremely low concentration of CO₂ in ambient air (approximately 0.04 percent), this approach is associated with high energy consumption and capture costs. It is currently more applicable near fixed sources or in high-carbon price regimes and is not considered a mainstream option for urban underground space deployment. Post-combustion and pre-combustion capture technologies are well established in coal-fired power plants, combined heat and power systems, and the chemical industry. These methods enable efficient CO₂ separation through chemical absorption, physical adsorption, and membrane separation, making them suitable for industrial sources and energy centers located near urban areas. Oxy-fuel combustion technology increases the oxygen concentration in the combustion process, significantly raising the CO₂ concentration in the flue gas, which facilitates subsequent compression and storage. It is suitable for scenarios requiring high-purity CO₂. In urban contexts, different CCS pathways can be applied in combination based on the industrial layout and energy structure. The mechanism of CCS in urban underground space is illustrated in Figure 4.

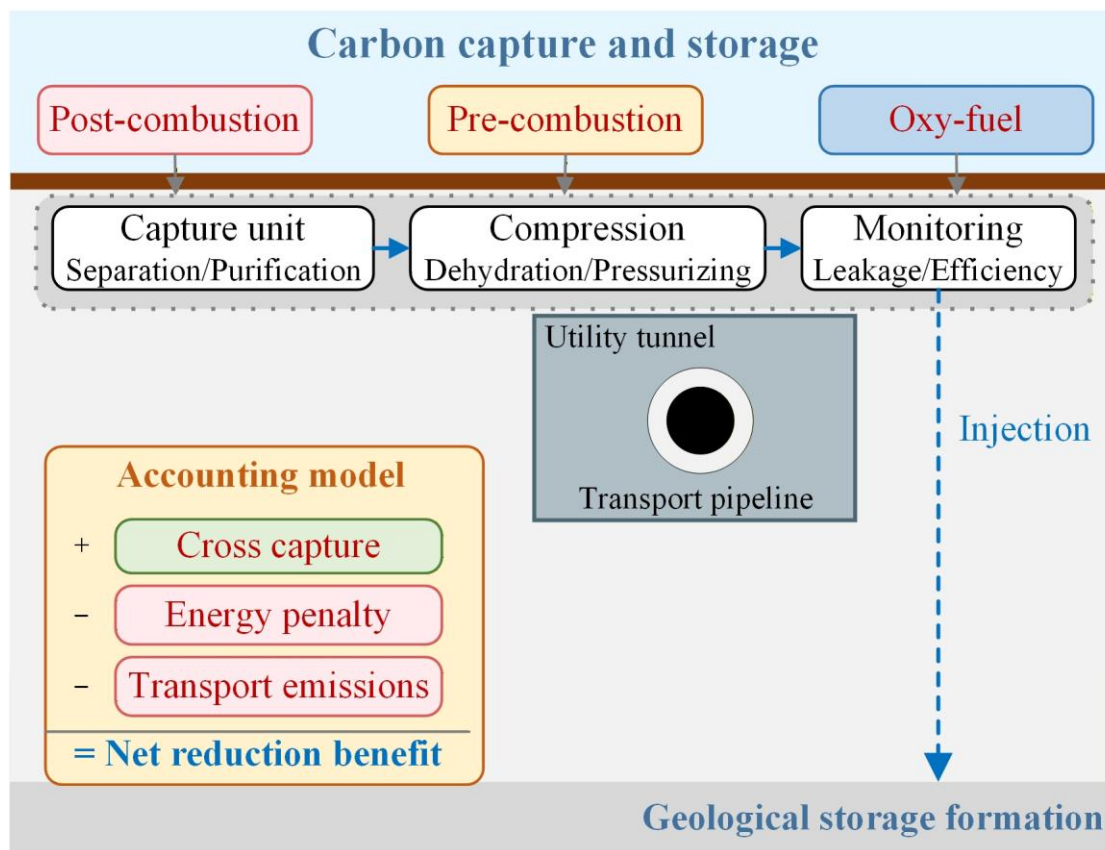


Figure 4. Framework of CCS mechanism in UUS.

A CER accounting model is constructed based on core parameters such as capture efficiency, combustion emissions, energy consumption during capture and compression processes, and emissions from CO₂ transport and storage processes. The CER equations for post-combustion capture, pre-combustion capture, and oxy-fuel combustion capture are provided in Equations (3)–(5), which are used to calculate net captured amounts, boundary emissions from energy consumption, and ultimately the actual emission reduction per unit system. Building upon this, the study incorporates the processes of underground pipeline transport and geological storage, and employs Equation (6) to comprehensively estimate the captured, compressed, transported, and stored CO₂, along with the carbon trading value. This establishes a full-process CCS carbon reduction accounting framework applicable to urban scenarios.

$$E_1 = (CE_{so} - CE_{ca} - CE_{co} - CE_{ut}) / CE_{so} \quad (3)$$

where E_1 refers to the net amount of CO₂ captured during post-combustion; CE_{so} denotes the amount of CO₂ equivalent generated during the combustion process of the feedstock for post-combustion capture; CE_{ca} represents the CO₂ emissions produced during the CO₂ capture process; CE_{co} refers to the CO₂ emissions generated during the compression process; and CE_{ut} indicates the CO₂ emissions produced during the combustion of the feedstock.

$$E_2 = (CE_{so}^{pc} - CE_{ca}^{pc} - CE_{co}^{pc} - CE_{ut}^{pc}) / CE_{so}^{pc} \quad (4)$$

where E_2 represents the net amount of CO₂ captured during pre-combustion; CE_{so}^{pc} denotes the CO₂ emissions generated during the combustion of feedstock in the pre-combustion capture process; CE_{ca}^{pc} refers to the CO₂ emissions produced during the CO₂ capture

process; CE_{co}^{pc} indicates the CO₂ emissions generated during the compression process; CE_{ut}^{pc} represents the CO₂ emissions produced during the CO₂ utilization process.

$$E_3 = (CE_{so}^{onc} - CE_{cb}^{onc} - CE_{ca}^{onc} - CE_{co}^{onc} - CE_{ut}^{onc}) / CE_{so}^{onc} \quad (5)$$

where E_3 represents the net amount of CO₂ captured during oxy-fuel combustion; CE_{so}^{onc} denotes the CO₂ emissions generated from the combustion of feedstock in the oxy-fuel process; CE_{cb}^{onc} refers to the CO₂ emissions produced during the oxy-fuel combustion process itself; CE_{ca}^{onc} indicates the CO₂ emissions generated during the CO₂ capture process; CE_{co}^{onc} represents the CO₂ emissions produced during the compression process; CE_{ut}^{onc} denotes the CO₂ emissions generated during the CO₂ utilization process.

$$C_{ccs} = E_{\Delta} \times C_{co} - (CO_{ca} + C_t + C_s) / r \quad (6)$$

where C_{ccs} represents the net economic benefit of CER through CCS; E_{Δ} denotes the net amount of CO₂ captured from pre-combustion, post-combustion, and oxy-fuel combustion processes (t), $E_{\Delta} = E_1 + E_2 + E_3$; C_{co} refers to the concentration of CO₂ (%); CO_{ca} represents the cost of CO₂ capture (\$/t); C_t denotes the cost of CO₂ transportation (\$); C_s indicates the cost of CO₂ storage (\$); r represents the carbon trading rate (\$/t).

It should be noted that CCS systems in urban underground space still face challenges, such as substantial equipment investment, high energy consumption, and complex monitoring systems. Furthermore, storage safety varies under different urban geological conditions. Therefore, their deployment needs to be in deep alignment with urban geology, energy structures, and industrial layouts.

3.3.3. Carbon Substitution

Carbon substitution refers to the process of reducing greenhouse gas emissions by developing and utilizing renewable energy or improving energy efficiency to replace traditional fossil fuels. In the context of urban underground space development, this mechanism is mainly reflected in three aspects. First, it involves the full utilization of geothermal resources within underground space to achieve clean substitution for conventional high-carbon energy sources. Second, it leverages the thermal stability of underground environments to promote the development of green buildings with constant-temperature characteristics, thereby significantly reducing energy consumption for heating and cooling. Third, it enhances the efficiency and carbon reduction capacity of urban energy systems through the systematic integration of underground energy corridors and intelligent management systems. Compared with carbon capture and carbon sequestration mechanisms, carbon substitution represents a source-based reduction pathway, characterized by strong continuity, high system integration, and clear long-term cost advantages. The carbon substitution mechanism based on urban underground space is illustrated in Figure 5.

As one of the most representative types of renewable energy in urban underground space, geothermal energy offers several advantages, including wide availability, high stability, a long-life cycle, and extremely low carbon emissions. According to data from the China Geological Survey, the annual exploitable potential of shallow geothermal resources nationwide is equivalent to 700 million tons of standard coal, far exceeding the total current energy consumption of urban buildings [39]. In practical applications, shallow geothermal energy is typically harnessed through ground source heat pump systems, which can provide heating, cooling, and domestic hot water services for urban buildings. Since ground source heat pump systems can be integrated with underground structures, their construction costs are relatively manageable, making them suitable for wide deployment in newly built underground facilities. Compared with coal-fired systems, the operational

carbon emissions of geothermal systems are only about one-tenth. Based on this, the study establishes a CER model for geothermal substitution in underground space. Taking a reference emission intensity of 0.1 for coal-fired systems, the model proposes an estimation formula based on the number of heat pumps, unit energy efficiency, and the electricity carbon factor, as shown in Equation (7).

$$C_{le} = N_{pump} \times E_{vae} \times TR_{elec} - 0.1 \times E_u \times TR_{elec} \quad (7)$$

where C_{le} represents the amount of carbon reduction resulting from the use of clean energy in urban underground space; N_{pump} denotes the number of geothermal heat pumps; E_{vae} refers to the average energy provided by each heat pump from shallow geothermal sources for building heating and cooling (J/pump); TR_{elec} is the carbon conversion factor of electricity (kg/J); E_u represents the electricity consumption for heating and air conditioning in aboveground buildings (J).

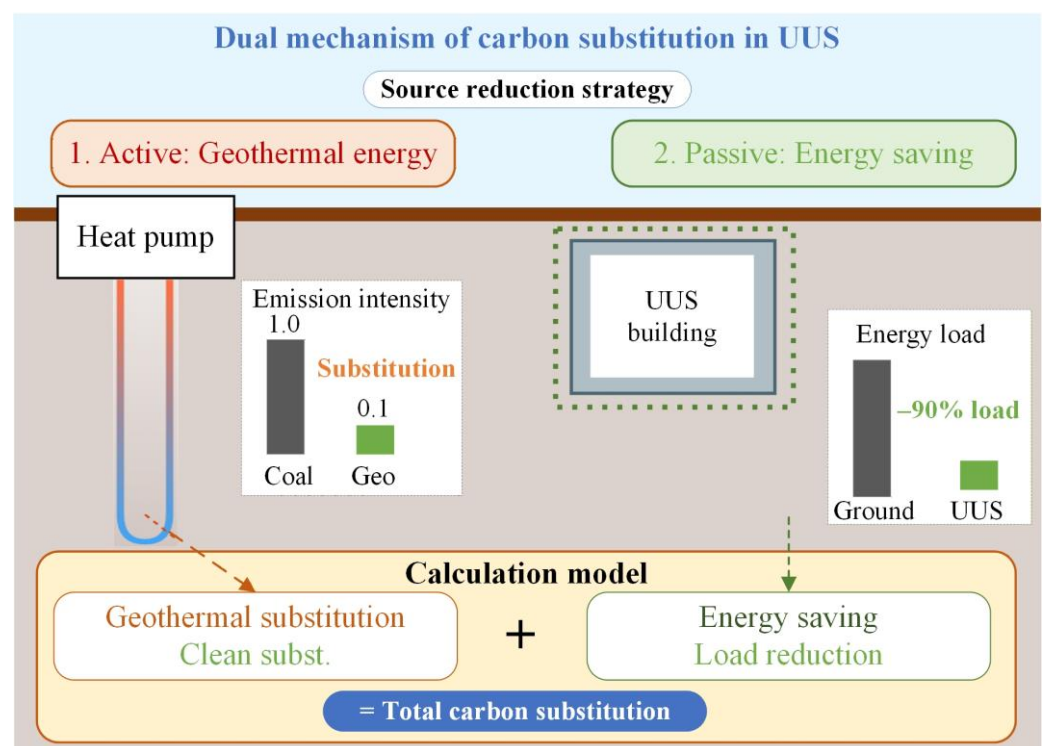


Figure 5. Framework of carbon substitution mechanism in UUS.

In addition to energy substitution, urban underground space also demonstrates significant energy-saving potential in green building applications. Due to their passive thermal insulation structure and stable temperature and humidity conditions, underground buildings can substantially reduce heating demand in winter and cooling load in summer. Relevant studies have shown that the energy consumption of air conditioning systems in underground buildings is only about 10 percent of that in aboveground buildings. Therefore, this study introduces a reduction coefficient of 0.9 for underground green buildings and assumes that public buildings account for 60% of total energy consumption. Based on these assumptions, a CER accounting model for underground green buildings is established, as shown in Equation (8). This model comprehensively considers underground floor area, electricity carbon emission factor, and energy consumption characteristics by

building type and can be used to evaluate the carbon substitution effect of various types of underground buildings during the operational phase.

$$C_{pub} = S_{pub} \times (0.9 \times 0.6 \times TR_{elec} \times ECE_{ave}) \quad (8)$$

where C_{pub} represents the amount of carbon reduction achieved by utilizing the constant-temperature characteristics of public buildings in urban underground space; S_{pub} denotes the total floor area of underground space (m^2); ECE_{ave} refers to the average energy consumption of public buildings ($GJ/(m^2 \cdot year)$).

In terms of system integration, urban underground space often contains a large number of infrastructure corridors for heating, cooling, electricity, and communication. By constructing integrated utility tunnels and green intelligent systems, it is possible to achieve efficient energy transmission while enabling real-time monitoring and optimized scheduling. The intelligent and coordinated regulation of energy systems can further reduce redundant losses and system inefficiencies, thereby enhancing overall carbon reduction benefits. In addition, the composite spatial layout of underground space provides physical interfaces for the integrated application of green technologies such as solar energy, air-source heat pumps, and rainwater harvesting, offering a high degree of scalability.

Although the carbon substitution mechanism has demonstrated promising potential in both theory and practice, its application in urban underground space still faces several challenges. These include geological adaptability constraints in geothermal development, relatively high construction costs of underground buildings, and increased energy consumption for lighting and ventilation during the operational phase. Therefore, practical implementation should be based on integrated planning and site-specific conditions. The selection of carbon substitution pathways and optimization of system parameters should be carried out scientifically, taking into account building functions, types of underground space, and the urban energy structure.

Table 1. Key parameters and values used in the CER assessment.

Symbol	Parameter	Value	Unit	Source
ρ	Air density	1.29	kg/m^3	[40]
TR_{elec}	Electricity emission factor	0.997	$kg\ CO_2e/kWh$	[25]
ECE_{ave}	Average energy consumption intensity of urban buildings	1.51	$GJ/(m^2 \cdot year)$	[21]
pd_{up}	Lighting power density	9	W/m^2	[24]
c	Specific heat capacity of air	1	$kJ/(kg \cdot ^\circ C)$	[21]
GR	Urban green space ratio	0.45	/	[24]
ECE_{car}	Energy consumption efficiency of motor vehicles	0.050	$(L \cdot person^{-1})/km$	[24]
ECE_{rail}	Energy consumption efficiency of rail transit	0.176×10^6	$(J \cdot person^{-1})/km$	Survey
D_{com}	Commuting distance	10	Km	Survey
-	Operational energy-saving rate of underground buildings	0.9	/	[41]
-	Adoption rate of green building technologies	0.6	/	[25]
COP	Coefficient of performance	3.8	/	[25]
$\bar{R}/\bar{R}_1$	Carbon sink efficiency (Trees, Shrubs)	3.18; 1.72	$kg\ CO_2e/(m^2 \cdot year)$	[40]

3.4. CER Benefits Assessment Model

3.4.1. CER Benefits Assessment Model of Underground Transportation Infrastructure Systems

Urban underground transportation infrastructure systems, as a key component of urban CER, include various spatial forms such as metro systems, underground parking facilities, tunnels, and pedestrian passages. These systems not only serve transportation functions but also demonstrate multiple CER benefits in terms of spatial substitution, energy substitution, and carbon capture.

First, underground transportation facilities can effectively substitute a portion of surface-based motor vehicle travel, optimize the structure of urban transportation modes,

and reduce both commuting distances by private cars and the carbon intensity per trip. By taking the rail transit system as the core, an energy efficiency comparison model between passenger cars and metro systems can be constructed. Combined with data on the size of the urban commuting population and the average travel distance, the model can estimate the reduction in daily exhaust emissions resulting from modal shifts. Second, the construction of underground transportation systems releases surface land, facilitating the creation of new urban green spaces and enhancing the carbon sequestration capacity per unit area through biological carbon sequestration. At the same time, carbon sequestration within underground space itself can be enhanced through the implementation of underground green belts and green roofs.

Second, in terms of carbon capture, underground parking facilities and large underground transfer spaces possess enclosed and stable air environments, making it feasible to introduce direct air capture devices for localized carbon concentration control and CO₂ capture. Based on capture efficiency, operational energy consumption, and storage pathways, the net emission reduction benefits of such systems in the carbon storage stage can be further estimated. For underground parking lots and tunnel-type facilities, an energy consumption and emission accounting model for the ventilation and lighting phases can be developed. Key parameters such as fan power, illumination standards, and operating duration are used for estimation, and the resulting emissions are included as carbon expenditure in the overall emission reduction assessment.

In summary, the CER benefits of underground transportation systems consist of the mitigation effects generated by underground parking facilities, underground tunnels and pedestrian passages, and rail transit systems, as shown in Equation (9).

$$\Delta E_{trans} = \Delta E_p + \Delta E_t + \Delta E_r \quad (9)$$

where ΔE_{trans} represents the total CER benefits of the urban underground transportation system; ΔE_p , ΔE_t , ΔE_r denote the CER benefits of underground parking facilities, underground tunnels and pedestrian passages, and underground rail transit systems, respectively, as referenced in Equations (10), (13) and (14).

$$\Delta E_p = \Delta E_{DAC} + \Delta E_{green}^p - \Delta C_{vent} \quad (10)$$

where ΔE_{DAC} represents the amount of carbon emission reduction achieved through CO₂ recovery using direct air capture technology in underground parking facilities, as referenced in Equation (6); ΔE_{green}^p denotes the carbon sequestration benefits generated by surface greening substitution in underground parking facilities, as referenced in Equation (2); ΔC_{vent} refers to the carbon emissions produced by ventilation and lighting in underground parking facilities, as referenced in Equations (11) and (12).

$$\Delta C_{vent} = (Q_1 + Q_2 + Q_3) \times t \times 3600 \times TR_{elec} \quad (11)$$

$$Q_1 = G \times \frac{P}{\eta_1} \times \eta_2; Q_2 = G \times \rho \times c(t_R - t_0); Q_3 = Pd_{up} \times S_3 \quad (12)$$

where t represents the operating duration of lighting and ventilation systems in urban underground parking facilities; 3600 is the conversion factor between kilowatts and joules; Q_1 denotes the energy consumption of the ventilation fan motor in underground parking facilities; G is the ventilation volume; P represents the total pressure of the fan; η_1 and η_2 are the fan efficiency and motor efficiency, respectively; Q_2 refers to the heat loss due to exhaust air; ρ is the air density, taken as 1.29 kg/m³; c is the specific heat capacity of air, taken as 1 kJ/(kg·°C); t_R represents the indoor air design temperature, and t_0 represents

the outdoor air temperature; Q_3 denotes the energy consumption for lighting; Pd_{up} is the power density of lighting in underground parking facilities (W/m^2); S_3 refers to the total area of urban underground parking facilities (m^2).

$$\Delta E_t = \Delta E_{green}^t - \Delta C_{light} \quad (13)$$

where ΔE_{green}^t represents the carbon sequestration benefits generated by surface greening substitution through underground tunnels and pedestrian passages, as referenced in Equation (2); ΔC_{light} denotes the carbon emissions produced by lighting in underground tunnels and pedestrian passages, with the calculation method referenced in Equations (11) and (12).

$$\begin{aligned} \Delta E_r = D_{com} \times & \left[N_r \times (ECE_{car} \times TR_{fos} - ECR_{rail} \times TR_{elec}) \right] \\ & + GR \times \sum (\rho_i \times G_i \times S_5 \times 0.6 + \bar{\rho}_s \times LAI \times \bar{q} \times S_5 \times 0.4) \\ & - GR \times \sum (\bar{\rho}_w \times S_5 \times 0.6 \times \bar{R} + \bar{\rho}_s \times S_5 \times 0.6 \bar{R}_1) \\ & + N_{num} \times E_{vae} \times TR_{elec} + 0.1 \times E_u \times TR_{elec} \end{aligned} \quad (14)$$

where N_r represents the estimated number of users of the underground rail transit system; D_{com} refers to the estimated average commuting distance for users of the system (km/person); ECE_{car} is the energy consumption efficiency of motor vehicles ($L \cdot person^{-1}/km$); ECR_{rail} represents the energy consumption efficiency of the rail transit system ($J \cdot person^{-1}/km$).

In summary, underground transportation infrastructure systems generate carbon reduction benefits encompassing spatial, energy, and engineering dimensions through multiple pathways, including transportation modal shift, ecological space release, carbon capture and storage, and energy system optimization. Consequently, they serve as a vital carrier and policy instrument for supporting the low-carbon transition of future cities.

3.4.2. CER Benefits Assessment Model of Underground Public and Commercial Infrastructure Systems

Urban underground public and commercial service infrastructure, as a key carrier of functional integration and vertical spatial intensification, encompasses a variety of multifunctional zones such as underground commercial districts, office spaces, educational and cultural facilities, and associated transit hub areas. This system is characterized not only by high population density and energy consumption but also by its potential for multiple carbon reduction pathways through building typology, thermal environment adaptability, and geothermal energy integration.

First, underground public and commercial service infrastructure possess a naturally stable thermal environment, making them well-suited for the deployment of ground source heat pump systems. These systems can replace conventional air conditioning, electric resistance heating, and gas water heating equipment, forming a stable and clean solution for heating and cooling. Based on building area and energy demand, a CER model for geothermal energy substitution is developed. By incorporating the operational efficiency of ground source heat pump systems and the regional electricity carbon emission factor, the emission reduction benefits resulting from energy substitution can be quantitatively assessed. In addition, compared with aboveground buildings, underground buildings offer energy efficiency advantages in terms of passive enclosure, diurnal temperature control, and heat loss mitigation, which can reduce energy consumption per unit area.

Second, in terms of ecological carbon sequestration, underground public and commercial service infrastructure can enable the full relocation of surface building functions below ground, thereby releasing valuable surface land in urban centers for transformation into ecological green spaces, pocket parks, or urban forest systems. Additionally, the

incorporation of enclosed greening systems such as plant walls and ecological light courts within underground facilities provides a supplementary micro-scale carbon sink function, enhancing the endogenous carbon reduction capacity of the space. For high energy consumption areas, such as underground shopping malls and convention centers, lighting and ventilation energy consumption accounting modules should be introduced. Parameters such as illumination standards, operating duration, and load factors are used to estimate operational carbon emissions, thereby establishing a comprehensive assessment framework that integrates emission reduction benefits with associated carbon expenditures.

In summary, underground public and commercial service infrastructure systems generate carbon reduction benefits through three primary pathways: geothermal energy substitution, green building energy efficiency, and ecological surface substitution for carbon sequestration. At the same time, a carbon expenditure model is constructed based on the energy consumption during the operational phase. Together, these components form a comprehensive accounting framework for evaluating the CER benefits of underground multifunctional service spaces, as presented in Equation (15).

$$\Delta E_{com} = \Delta E_{green}^{com} + \Delta E_{sub}^{com} + \Delta E_{si} - \Delta C_{com} \quad (15)$$

where ΔE_{com} represents the total CER benefits of underground public and commercial service infrastructure; ΔE_{green}^{com} denotes the carbon sequestration benefits generated by surface greening substitution, as referenced in Equation (2); ΔE_{sub}^{com} refers to the CER benefits derived from underground green building design, as referenced in Equation (8); ΔE_{si} indicates the CER benefits from geothermal energy substitution, as referenced in Equation (7); ΔC_{com} represents the carbon emissions from lighting ($\text{kgCO}_2\text{e/year}$), as referenced in Equations (11) and (12).

3.4.3. CER Benefits Assessment Model of Underground Municipal Utility Infrastructure Systems

Urban underground municipal infrastructure systems encompass essential service functions such as water supply, heating, electricity, drainage, communication, waste treatment, and resource recovery. The facility types include underground utility tunnels, reclaimed water treatment plants, pumping stations, waste transfer stations, stormwater storage tanks, substations, and communication equipment rooms. Compared with surface deployment, underground installation offers higher land use efficiency and stronger environmental adaptability. It allows for the conservation of surface space while enhancing the resilience and safety of urban operations. At the same time, underground deployment alters the energy consumption structure of facility operations, bringing both significant opportunities and challenges for carbon emission reduction. It therefore constitutes a critical component of the urban carbon neutrality pathway.

From the perspective of CER pathways, underground municipal infrastructure can reduce emissions through carbon capture and storage mechanisms by capturing CO_2 generated during operation and storing it in subsurface geological formations for long-term containment, thereby preventing its release into the atmosphere. Representative scenarios include the capture of metabolically emitted CO_2 during wastewater treatment and the treatment of flue gasses from oxy-fuel combustion following waste incineration. In addition, the construction of underground pipeline networks for long-distance CO_2 transport can effectively link industrial emission sources with storage sites, enabling the formation of a multi-node CER network. The second pathway is carbon substitution, which involves replacing high-carbon energy sources with geothermal energy, renewable energy, or waste heat recovery systems to meet temperature control, power, and lighting demands in underground systems, thereby reducing carbon emission intensity at the source.

The third pathway relates to surface greening substitution. By deploying infrastructure underground, surface green space can be preserved or restored, and additional green roofs or surface parks can be installed above the facilities to generate biological carbon sequestration benefits.

During the operational phase, lighting and ventilation are the primary sources of carbon emissions in underground municipal facilities. Due to the fully enclosed nature of these spaces, ventilation must rely on mechanical systems to maintain air quality, and lighting must continuously meet operational and safety standards. As a result, energy consumption is significantly higher than that of aboveground facilities. Literature indicates that lighting energy consumption in underground facilities is more than four times that of surface facilities, while ventilation energy consumption can be approximately six times higher [11]. To accurately assess the associated carbon emissions, it is necessary to model the ventilation power load and lighting power density separately, taking into account key variables such as operating duration and electricity carbon emission factors.

Based on the aforementioned carbon reduction pathways and emission sources, this study models the CER benefits of urban underground municipal infrastructure systems as a weighted net value comprising two carbon reduction mechanisms and operational carbon emissions. Specifically, this includes (1) the carbon sequestration benefit ΔE_{ccs}^{util} generated through CO₂ capture, pipeline transport, and underground storage, as referenced in Equation (6); (2) the carbon reduction benefit ΔE_{sub}^{util} from substituting conventional energy with green energy sources such as geothermal energy, as referenced in Equation (8); and (3) the carbon emission cost ΔC_{util} associated with ventilation and lighting systems, as referenced in Equations (11) and (12). Accordingly, the estimation formula for the CER benefits ΔE_{util} of urban underground municipal infrastructure systems is presented in Equation (16).

$$\Delta E_{util} = \Delta E_{ccs}^{util} + \Delta E_{sub}^{util} - \Delta C_{util} \quad (16)$$

4. Case Study

4.1. Case Description and Data Preparation

Nanjing is one of the earliest cities in China to systematically promote urban underground space development, supported by strong historical continuity and institutional frameworks. Since the Republican era, the development of underground space in Nanjing has undergone multiple stages, including civil air defense-oriented construction, dual-purpose designs for peace and wartime, transportation-led expansion, and integrated multifunctional utilization. This evolution has gradually shaped a well-structured and functionally integrated underground space system. According to the Blue Book of Urban Underground Space in China, Nanjing has consistently been ranked among the leading cities in underground space development since 2015. In 2019, it was recognized as one of the cities with the highest overall capacity in this field. By the end of 2024, the total developed area of underground space in the city had reached 80 million square meters, with a per capita area of 7.72 square meters, placing it at the forefront among large and medium-sized cities in China (see Figures 6 and 7). In addition, Nanjing is located in the hilly region of the lower Yangtze River and belongs to the northern subtropical monsoon climate zone. It benefits from stable ground temperatures and abundant shallow geothermal resources, which provide favorable natural conditions for the green and low-carbon utilization of underground space.

This study selects Nanjing as the case city and focuses on three major functional underground infrastructure systems: transportation, public and commercial services, and municipal utilities. Based on a systematic review of Nanjing's underground space utilization structure, metro network coverage, distribution of public buildings, utility tunnel

layout, and surface greening substitution potential, a unified framework for CER benefit assessment is established.

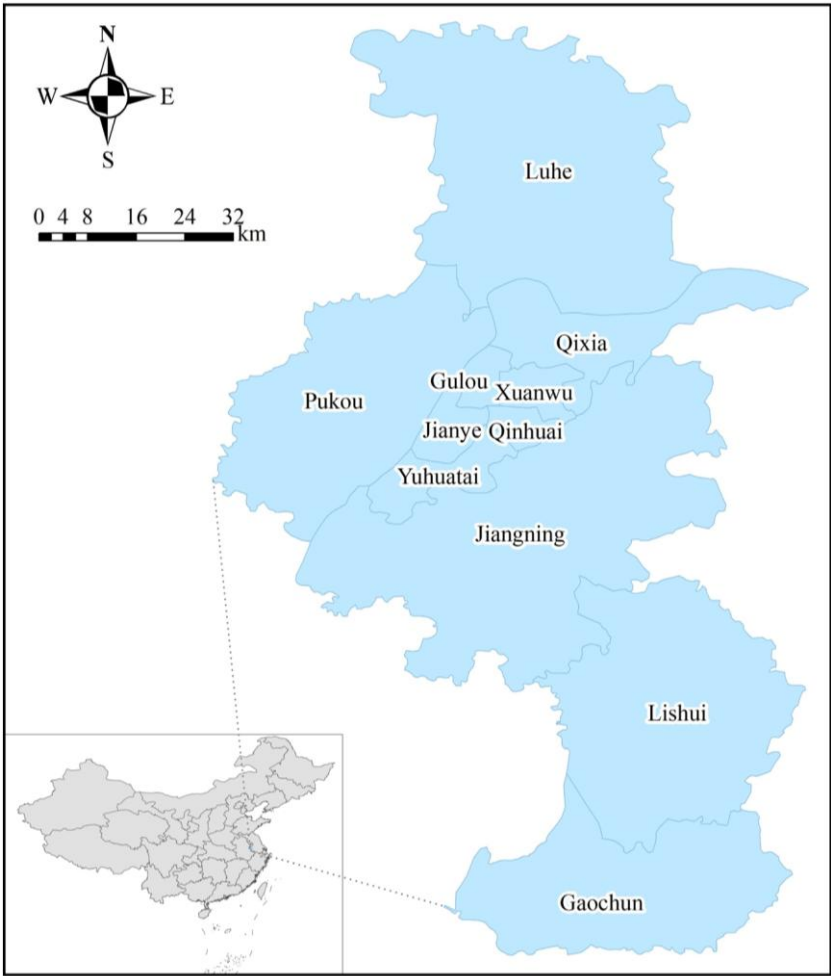


Figure 6. Overview of Nanjing urban region.

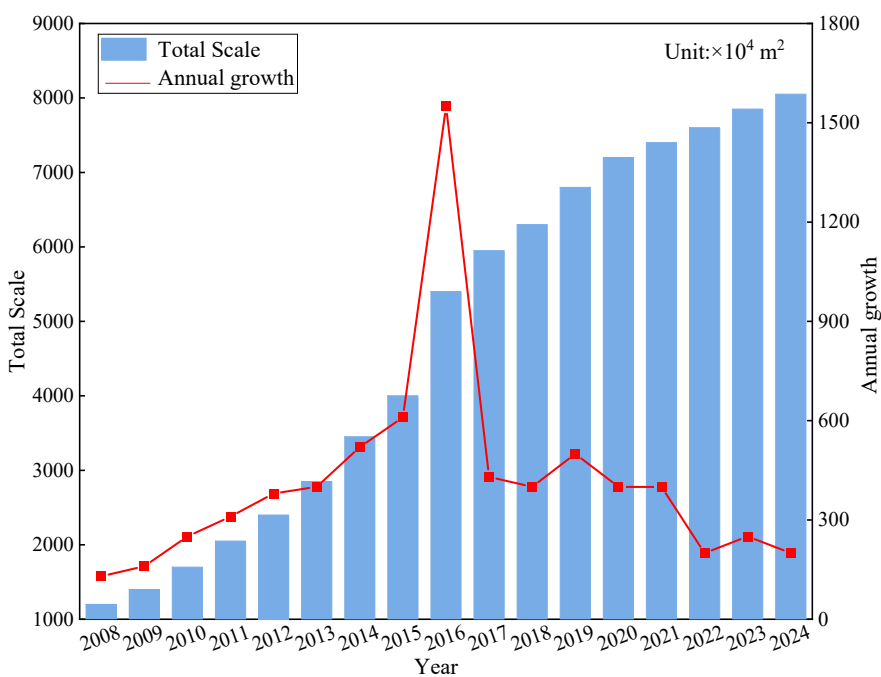


Figure 7. Development scale and annual growth trend of underground space in Nanjing.

The carbon emission accounting parameters adopted in this study are primarily derived from three categories of data sources. First, data from public documents, including the Report on Building Energy Consumption and Energy Conversion Factors, green space carbon sink parameters and relevant empirical studies released by the Nanjing Greening and Landscape Bureau, and the calculation basis for geothermal systems and soil thermal properties in the Research on Development and Utilization of Shallow Geothermal Energy Resources in Nanjing. Second, data obtained through field surveys and expert interviews conducted from June to August 2025. The surveys covered underground commercial, transportation, and geothermal facilities, while the interviews involved multiple experts in the fields of urban carbon emissions, energy, and greening. These data were primarily used for the calibration and verification of key model parameters and boundary assumptions. Third, supplementary data derived from relevant domestic and international literature [21,24,25,39,40], which were used to refine the model structure and enhance the regional adaptability and scientific rationality of the parameters.

4.2. Result Analysis

4.2.1. Calculation of Underground Transportation Infrastructure Systems CER Benefits

1. Underground Rail Transit Infrastructure

As the backbone of the city's public transportation network, Nanjing's urban rail transit system is characterized by high line density, large passenger volume, clean energy propulsion, and intensive spatial utilization. It is one of the underground infrastructure systems with the most significant CER potential. By 2025, the Nanjing Metro operated 13 lines, with a total length of 508 km and 255 stations. The daily average passenger flow of the operational network has reached 2.9 million trips, and the public transportation mode share is close to 60 percent. This study establishes a comprehensive evaluation framework for the CER benefits of underground transportation infrastructure, considering four dimensions: travel mode substitution, biological carbon sequestration, building energy efficiency, and geothermal energy substitution.

First, we will discuss the CER benefits of the travel mode substitution mechanism. As an electricity-powered system, urban rail transit produces significantly lower carbon emissions per passenger than private cars, taxis, and conventional diesel buses. Based on the annual operational volume of private cars, buses, and taxis, and their respective mode shares (approximately 10.7:8.3:1), the metro system can replace an estimated 1.296 million car trips, 0.996 million bus trips, and 0.108 million taxi trips per day. Assuming an average commuting distance of 10 km and applying modal-specific emission factors (gasoline: 2.3 kg/L; diesel: 2.63 kg/L; electricity: 0.997 kg/kWh), the metro system reduces approximately 8.26×10^5 tCO₂e annually through travel mode substitution.

Second, we will discuss the CER benefits from surface greening substitution. Most sections of the metro system are constructed underground, thereby freeing up substantial land previously used for surface roads and transportation facilities and enabling its conversion into potential green space. Based on the current total length of underground metro lines in Nanjing (306.939 km) and a typical land occupancy coefficient, the corresponding surface area is converted into effective green space using the city's average greening rate of 45.06%. Assuming a reasonable vegetation composition ratio of 6:4 between trees and shrubs and applying the carbon sequestration efficiency of urban greenery, the annual CER benefit from greening substitution associated with the metro system is estimated at approximately 42.41 tCO₂e.

Third, there are CER benefits from energy savings in underground transport buildings. Metro stations and tunnel structures are located within a thermally stable zone at a depth of 10 to 20 m, where the impact of external climate is minimal. As a result, these structures

exhibit excellent thermal stability and reduced heating, ventilation, and air conditioning loads. Based on the average annual energy consumption intensity of public buildings in Nanjing ($1.51 \text{ GJ/m}^2\cdot\text{year}$), and taking into account the energy consumption of different types of underground facilities as shown in Table 2, the annual CER benefit resulting from energy savings in underground buildings is approximately $3.16 \times 10^4 \text{ tCO}_2\text{e}$. Potential overlaps in energy substitution benefits across different infrastructure systems are controlled by assigning each renewable energy application to its primary functional system based on actual service scope and energy use records. In cases where shallow geothermal energy supports multiple facilities, CER benefits are allocated proportionally according to system-specific energy demand, ensuring that the same emission reduction is not counted more than once. At the city scale, the CER magnitude on the order of $10^5 \text{ tCO}_2\text{e}$ per year indicates that underground transportation infrastructure can contribute a meaningful share of near-term urban emission mitigation, as these reductions are primarily achieved through immediate energy-saving mechanisms such as travel mode substitution and operational efficiency improvements.

Table 2. Energy consumption of all kinds of facilities.

Category	Number	Total Floor Area (m^2)	Proportion (%)	Energy Consumption Intensity ($\text{GJ}/(\text{m}^2\cdot\text{year})$)
Office	56	366.86	61.5	1.43
Shopping mall	12	53.55	9.00	1.89
Hotel	19	103.51	17.4	1.73
Hospital	7	29.16	4.90	1.80
Theater	2	7.70	1.30	0.81
Others	4	35.68	6.00	1.00
Total	100	596.46	100	1.51

Finally, the CER contribution of the geothermal energy substitution mechanism. Some metro stations in Nanjing have adopted ground source heat pump systems that utilize the stable underground temperature for cooling and heating purposes. The coefficient of performance (COP) of these systems typically ranges from 3.5 to 4.0. Table 3 presents the contribution of shallow geothermal energy utilization to CO_2 emission reduction in 2022. Assuming a COP of 3.8 and an energy supply load of 75 kWh/m^2 , the annual CER benefit from geothermal energy substitution in underground urban rail transit is estimated to be approximately $2430 \text{ tCO}_2\text{e}$.

Table 3. Estimated contribution of shallow geothermal energy utilization to CER in 2022.

Proportion of Geothermal in Renewable Energy	20%	40%	60%
Total building floor area (10^4 m^2)	8470.9	8470.9	8470.9
Share of renewable energy buildings	17%	17%	17%
Geothermal-supplied building area (10^4 m^2)	288.0	576.0	864.0
CO_2 emission reduction (10^4 t)	5.0	9.9	14.9

2. Underground Parking and Tunnels Infrastructure

As vital components of urban transportation infrastructure, underground parking facilities and tunnel systems play a pivotal role in alleviating surface traffic congestion and enhancing the efficiency of urban space utilization. From the perspective of CER, these facilities generate mitigation benefits primarily through the release of surface land for green spaces and the optimization of operational energy efficiency and management.

First, the CER benefits derived from the surface greening substitution mechanism. The construction of underground parking facilities and tunnel infrastructure enables the release of urban surface land previously occupied by parking and traffic, thereby providing spatial capacity for urban greening. According to a comprehensive survey of underground

parking facilities in Nanjing, the total number of underground parking spaces has reached approximately 1.0884 million, with a total building area of about 45.92 million m². In addition, the total length of urban road tunnels exceeds 55.5 km, forming an integrated underground traffic network of approximately 60 km. It is estimated that the construction of underground transport infrastructure has released around 46.52 million m² of potential green space. Based on Nanjing's average greening rate of 45.06%, the area actually available for greening is about 20.96 million m². Using a 6:4 configuration ratio of trees to shrubs and local carbon sink efficiency values (trees: 3.18 kg/m²·year, shrubs: 1.72 kg/m²·year), the annual CER benefit is estimated to be approximately 1.41×10^4 tCO₂e.

Second, carbon emissions during the operational phase of facilities. Unlike metro systems, underground parking facilities and tunnels exhibit higher energy consumption during operation, with ventilation and lighting systems serving as the primary sources of emissions. According to the Standards for Building Lighting Design and the General Code for Energy Conservation and Renewable Energy Use in Buildings, these facilities are required to maintain a high ventilation rate (5 times per hour) and lighting density (2.5–4 W/m²), with operational durations typically exceeding 12 h per day throughout the year. Based on Nanjing's annual average temperature (15 °C), the regional electricity emission factor (0.997 kg/kWh), and the energy consumption per unit area of the facilities, the annual carbon emissions from ventilation and lighting systems are estimated at approximately 1.52×10^4 tCO₂e.

4.2.2. Calculation of Underground Public and Commercial Infrastructure Systems CER Benefits

Nanjing has developed a multifunctional underground space system encompassing commercial, cultural, medical, and civil defense facilities, which not only reduces development intensity on the surface but also offers new pathways for carbon mitigation. According to the latest survey data, the city has constructed approximately 1.23 million m² of underground commercial facilities, along with around 657 thousand m² of underground medical, cultural, and civil defense spaces, resulting in a total of 1.89 million m² of underground public and commercial service space. This study systematically evaluates the CER benefits of these underground facilities from three perspectives: carbon sink gains through surface space release, energy-saving retrofits in buildings, and the substitution of conventional energy with renewable sources.

First, we will discuss the CER benefits of the surface greening substitution mechanism. The surface space released through underground development can be converted into green areas, thereby achieving CER benefits through urban vegetation systems. Based on the completed underground facility area of approximately 1.89 million m² and a local greening rate of 45.06%, the effective green space area is estimated at about 850.30 thousand m². Using a tree-to-shrub configuration ratio of 6:4 and local carbon sink efficiency values (trees: 3.18 kg/m²·year; shrubs: 1.72 kg/m²·year), the annual CER benefit is estimated to be approximately 571.82 tCO₂e. To avoid double counting, surface greening substitution and underground building energy savings are treated as mutually exclusive CER pathways. The greening substitution mechanism accounts only for carbon sequestration associated with newly released surface green space, whereas energy-saving benefits are calculated solely based on reductions in operational energy consumption of underground facilities, without attributing additional land-use-related carbon effects.

Second, we will discuss the CER benefits from improved energy efficiency in green buildings and the substitution of conventional energy with ground source heat pump systems. According to the Design Standard for Energy Efficiency of Public Buildings, the annual average energy consumption intensity of underground buildings such as shopping malls, hospitals, and cultural or sports facilities is approximately 1.76 GJ/m²·year. If green

retrofitting is implemented with an energy-saving rate of 30%, and based on a total underground building area of 1.89 million m², significant energy savings can be achieved. According to a specialized survey conducted in Nanjing, 21 underground public service facilities have already adopted ground source heat pump systems, with a total energy supply area of 1.58 million m², representing a substitution rate of approximately 18.7%. Based on an energy supply intensity of 75 kWh/m², a coefficient of performance (COP) of 3.8, and an electricity emission factor of 0.997 kg/kWh, the combined CER benefit from green building energy efficiency improvements and geothermal energy substitution in underground public and commercial service facilities in Nanjing is estimated at 5.33×10^5 tCO₂e.

Finally, we will discuss carbon emissions resulting from operational energy consumption. Underground commercial and public service spaces are typically characterized by high foot traffic and extended operating hours, leading to relatively high energy consumption from lighting systems. Based on a lighting power density of no less than 9 W/m² and an average operating duration of 12 h per day, total annual carbon emissions are estimated at approximately 202.98 tCO₂e. Although the annual CER magnitude of municipal utilities is smaller in absolute terms, its practical significance lies in the long-term mitigation potential provided by carbon capture and storage, which supports sustained emission reduction beyond short-term energy-saving measures.

4.2.3. Calculation of Underground Municipal Utility Infrastructure Systems CER Benefits

To promote the intensive and efficient use of urban underground space, Nanjing has actively advanced the construction of underground utility tunnel systems in recent years. The city has explored integrated models of “multi-pipe consolidation” and “smart utility networks,” providing a new pathway for the low-carbon transition of urban infrastructure operations.

Based on the latest survey data, Nanjing has constructed a total of 81 km of underground utility tunnels, with approximately 28 km currently in operation, primarily located in the main urban area and the core functional zones of newly developed districts. The utility tunnel system reduces carbon emissions during the construction phase by minimizing land disturbance through centralized installation and unified maintenance, and further lowers operational energy consumption by reducing the need for repeated excavation and repair. In addition to the optimization of utility tunnels, urban underground space also serves as a strategic platform for deploying carbon capture, utilization, and storage technologies, thereby expanding the functional scope of underground systems in carbon mitigation. In 2022, Sinopec launched the construction of the largest flue gas CO₂ capture project from a coal-fired power plant in China, located in Nanjing. The project has an annual capture capacity of 150 thousand t CO₂, with a capture efficiency exceeding 90 percent and a purity level of 99.5%. CO₂ is transported and injected efficiently through underground pipeline systems, forming an integrated “source-network-storage” chain that provides technical support for large-scale point-source carbon reduction in urban areas. Based on carbon trading market data and estimates of operational energy consumption, the project is expected to achieve an annual carbon reduction benefit of approximately 9.76×10^4 tCO₂e.

A cross-system comparison further reveals clear differences among the three underground infrastructure systems. The underground transportation system exhibits the largest CER magnitude, primarily driven by energy-saving effects associated with travel mode substitution and operational efficiency improvements. In contrast, underground public and commercial service facilities generate moderate CER benefits, with a balanced contribution from energy substitution and building-related efficiency gains. Municipal utility systems contribute to a relatively smaller CER magnitude; however, their benefits are dominated by sequestration-oriented pathways, particularly carbon capture and storage, rather than

direct energy savings. This comparison highlights that energy-saving-driven mechanisms dominate in transportation and public/commercial systems, whereas sequestration-driven mechanisms play a more prominent role in municipal utilities.

Taken together, the reported CER values provide complementary contributions at different temporal scales. Transportation and public/commercial systems mainly deliver short- to medium-term emission reductions driven by energy efficiency and substitution effects, whereas municipal utility systems play a strategic role in long-term carbon mitigation through sequestration-oriented pathways. This temporal differentiation helps explain the practical relevance of large CER magnitudes reported in this study from a city-wide decarbonization perspective.

4.3. Discussion

4.3.1. Comparative Analysis of CER Benefits in Urban Underground Space

Understanding the carbon reduction contribution of urban underground space at the regional scale is of great significance for identifying areas with high mitigation potential, optimizing low-carbon spatial structures, and formulating targeted spatial strategies. As a representative city that has systematically promoted underground space development, Nanjing represents a large Chinese metropolitan city with a relatively mature and diversified urban underground space system, and exhibits notable differences across administrative districts in terms of construction intensity, functional configurations, and energy system deployment related to underground transportation, public services, and municipal infrastructure. Therefore, it is necessary to conduct a comparative analysis of carbon reduction benefits across different regions, based on the previously calculated results, from the dual perspectives of system category and spatial distribution. This approach helps reveal the spatial structure of carbon mitigation across different types of underground infrastructure and provides a regional basis for subsequent policy formulation.

Tables 4 and 5 show that among the underground transportation infrastructure systems in Nanjing, Jiangning district demonstrates the most significant CER benefit, with an annual reduction of 1.62×10^5 tCO₂e. This is primarily attributed to the extensive metro line coverage (total length of 85.5 km) and large station building area, which contribute substantially to both travel substitution and building energy savings. Jianye district and Jiangbei New Area follow, with annual reductions of 1.02×10^5 tCO₂e and 1.02×10^5 tCO₂e, respectively, where travel substitution and geothermal energy substitution represent key advantages. Although central districts such as Gulou and Xuanwu exhibit high metro network density, their carbon reduction benefits remain at a moderate level due to spatial constraints. Peripheral districts such as Lishui and Gaochun show relatively limited benefits, owing to low coverage of underground transportation facilities. Overall, the structure of emission reduction in the rail transit system is shaped by factors including line density, building form, and functional integration, reflecting a spatial pattern jointly dominated by central functional zones and newly developed urban areas.

Table 4. Scale characteristics of underground transportation infrastructure systems.

Administrative District	Metro Line Length ($\times 10^2$ km)	Underground Parking Spaces ($\times 10^2$ unit)	Underground Parking Area ($\times 10^2$ m ²)	Underground Tunnel Length ($\times 10^2$ km)
Gulou	0.42	0.091	4.05	0.088
Xuanwu	0.35	0.046	2.35	0.095
Qinhuai	0.265	0.059	2.80	0.032
Jianye	0.385	0.132	6.30	0.072
Jiangbei new area	0.305	0.081	2.95	0.18
Pu kou	0.32	0.053	2.05	0.145

Table 4. Cont.

Administrative District	Metro Line Length ($\times 10^2$ km)	Underground Parking Spaces ($\times 10^2$ unit)	Underground Parking Area ($\times 10^2$ m ²)	Underground Tunnel Length ($\times 10^2$ km)
Yuhuatai	0.22	0.1	4.50	0.02
Qixia	0.28	0.147	6.35	0.065
Lishui	0.103	0.049	2.20	0.005
Jiangning	0.855	0.245	9.80	0.045
Gaochun	0.36	0.029	0.80	0
Luhe	0	0.051	1.60	0
Total	3.539	1.083	45.75	0.747

Table 5. CER benefits of underground transportation infrastructure systems.

Administrative District	Travel Substitution ($\times 10^2$ tCO ₂ e/year)	Green Space Replacement Sink ($\times 10^2$ tCO ₂ e/year)	Building Energy Savings ($\times 10^2$ tCO ₂ e/year)	Geothermal Substitution ($\times 10^2$ tCO ₂ e/year)	Ventilation and Lighting Emissions ($\times 10^2$ tCO ₂ e/year)	Total ($\times 10^2$ tCO ₂ e/year)
Gulou	845	14.5	32.3	2.48	15.5	894.10
Xuanwu	661	11.3	25.3	1.94	12.2	699.30
Qinhuai	482	8.3	18.4	1.42	8.9	510.18
Jianye	960	16.4	36.7	2.82	17.7	1015.92
Jiangbei new area	963	16.5	36.8	2.83	17.7	1019.54
Pu kou	781	13.4	29.9	2.30	14.4	826.87
Yuhuatai	578	9.9	22.1	1.70	10.6	611.25
Qixia	910	15.6	34.8	2.68	16.7	963.25
Lishui	267	4.6	10.2	0.78	4.9	282.26
Jiangning	1533	26.2	58.6	4.51	28.2	1622.51
Gaochun	112	1.9	4.3	0.33	2.1	118.99
Luhe	170	2.9	6.5	0.50	3.1	179.38
Total	8272	141.4	316	24.29	152	8601.7

Tables 6 and 7 indicate that among underground public and commercial service facilities, Gulou district achieves the highest annual carbon reduction benefit, reaching 1.54×10^5 tCO₂e. This district hosts a high concentration of intensive functional facilities, including commercial, medical, and civil defense spaces, and exhibits a relatively high integration rate of geothermal systems. As a result, building energy savings and energy substitution serve as the dominant mitigation pathways. Jianye district and Xuanwu district follow, with annual reductions of 0.91×10^5 tCO₂e and 0.92×10^5 tCO₂e, respectively, showing strong contributions from green building energy efficiency. In particular, the concentrated layout of underground commercial and cultural spaces in the Xinjiekou area significantly enhances large-scale emission reduction. Although districts such as Pukou, Qixia, and Lishui contain relatively fewer public facilities, they still demonstrate notable potential when considering carbon reduction efficiency per unit area. It is also worth noting that in certain areas such as Yuhuatai district, high lighting energy consumption caused by specific operational characteristics imposes a slight carbon burden, though its overall impact on total carbon reduction remains limited.

Table 6. Development scale of underground public and commercial facilities in Nanjing.

Administrative District	Underground Commercial Development Area ($\times 10^2$ m ²)	Underground Cultural and Sports Development Area ($\times 10^2$ m ²)	Underground Medical Development Area ($\times 10^2$ m ²)	Civil Air Defense Construction Area ($\times 10^2$ m ²)
Gulou	2650	190	560	650
Xuanwu	1080	240	130	950
Qinhuai	2250	68	210	720
Jianye	3900	72	15	1260
Pukou	/	/	/	150
Yuhuatai	1500	92	20	570
Qixia	920	148	50	/
Lishui	/	/	/	80
Jiangning	/	/	/	420
Gaochun	/	/	/	/
Luhe	/	/	/	/
Total	12,300	810	985	7800

Table 7. CER benefits of underground public and commercial facilities in Nanjing.

Administrative District	Carbon Sink from Green Space Replacement ($\times 10^2$ tCO ₂ e/year)	Green Building Energy Savings and Geothermal Substitution ($\times 10^2$ tCO ₂ e/year)	Lighting Carbon Emissions ($\times 10^2$ tCO ₂ e/year)	Total ($\times 10^2$ tCO ₂ e/year)
Gulou	1.6496	1538	0.5856	1539.06
Xuanwu	1.0207	915	0.3623	915.66
Qinhuai	0.9007	84	0.3197	840.58
Jianye	0.9774	911	0.3469	911.63
Pukou	0.1787	167	0.0634	167.12
Yuhuatai	0.5355	499	0.1901	499.35
Qixia	0.4407	411	0.1564	411.28
Lishui	0.0953	888	0.0338	888.06
Jiangning	0.5003	466	0.1776	466.32
Gaochun	/	/	/	/
Luhe	/	/	/	/
Total	6.299	6635	2.236	6639

As shown in Table 8, the overall scale of CER in the underground municipal utility system is relatively limited. However, in regions where Carbon Capture, Utilization, and Storage projects are deployed, the reduction benefits are significantly enhanced. For instance, the annual emission reduction in Pukou District reaches as high as 1.87×10^4 tCO₂e, making it the area with the most prominent CCUS reduction benefits in the city. This is followed by Qinhuai District, Qixia District, Jianye District, and Jiangning District, where annual emission reductions range from 1.0 to 1.6×10^4 tCO₂e, mainly driven by demonstration projects. Underground utility tunnels generate certain carbon reduction benefits through reduced construction disturbance and enhanced maintenance efficiency; however, compared with transportation and public systems, their scale and structural advantages remain limited. This system exhibits a differentiation characteristic where traditional pathways are weak while frontier pathways are strong.

Table 8. CER benefits of underground municipal utility facilities in Nanjing.

Administrative District	Construction Scale of Underground Utility Tunnels (km)			Carbon Capture and Storage ($\times 10^2$ tCO ₂ e/year)
	Completed	Under Construction	Planned	
Gulou	19.5	3.5	9.0	103.93
Xuanwu	/	/	/	/
Qinhuai	31.0	5.5	15.0	167.26
Jianye	18.5	11.0	4.5	110.43
Jiangbei new area	/	/	/	/
Pukou	38.0	0.0	19.5	186.76
Yuhuatai	1.5	5.5	19.0	84.44
Qixia	4.0	0.0	40.0	142.91
Lishui	0.0	4.0	0.0	12.99
Jiangning	4.0	4.0	34.5	138.04
Gaochun	3.0	0.0	6.0	29.23
Luhe	/	/	/	/
Total	119.5	33.5	147.5	976

Figure 8 presents the total annual CER of the three types of underground infrastructure systems across different administrative districts. The results indicate that Jiangning district achieves the highest overall CER benefit, reaching 2.09×10^5 tCO₂e, serving as a representative example of green development in urban underground space. Gulou district, benefiting from the balanced development and high-intensity deployment of all three systems, reaches a total reduction of 2.44×10^5 tCO₂e. Jianye district and Jiangbei New Area have established strong regional CER capacities through the coordination of transportation and public service systems. In contrast, peripheral districts such as Gaochun and Lishui have not yet formed an effective CER system for underground space and should enhance the development of green infrastructure and the integration of low-carbon pathways in the future.

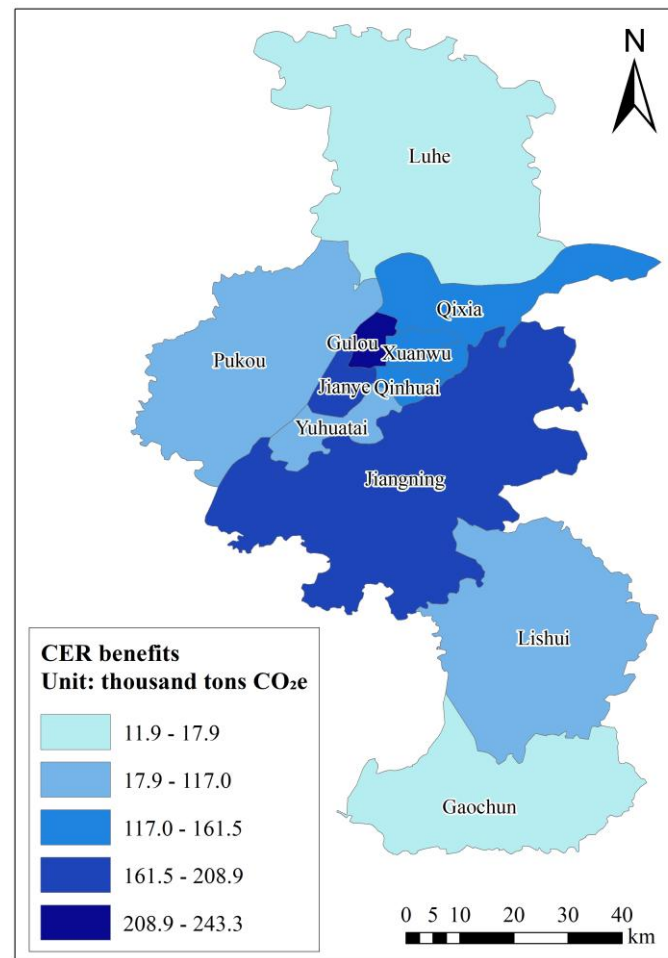


Figure 8. Spatial distribution of total CER benefits from urban underground space across administrative districts in Nanjing.

To improve the comparability of CER performance across different underground infrastructure systems, normalized indicators on a per-capita and per-unit-area basis are introduced in addition to absolute CER values. The results indicate that the per capita CER of the underground transportation system is approximately 0.083 tCO₂e/(person·year), compared with 0.064 tCO₂e/(person·year) for the underground public and commercial system, suggesting a relatively higher mitigation contribution of underground transportation at the individual scale. From a per-unit-area perspective, the CER intensities of the underground transportation system and the underground public and commercial system are approximately 1.08×10^{-2} and 8.30×10^{-3} tCO₂e/(m²·year), respectively. Overall, the normalized indicators further clarify differences in mitigation efficiency and associated pathways among underground infrastructure systems, while the resulting conclusions remain consistent with those derived from the analysis based on absolute CER values.

4.3.2. Sensitivity Analysis

To assess the robustness of the CER assessment with respect to key parameter assumptions, sensitivity analyses were performed for operational energy parameters, the COP, and the electricity emission factor. With the spatial configuration, service scale, and other parameters held constant, perturbation scenarios of $\pm 10\%$ and $\pm 20\%$ were specified for each parameter relative to the baseline scenario (S0), referred to as S1 to S4. Changes in operational energy parameters primarily affect building energy savings and ventilation and lighting emissions in underground facilities, variations in COP influence only the

geothermal substitution pathway, and adjustments in the electricity emission factor impact all emission reduction and emission pathways associated with electricity consumption. Other mitigation pathways, including travel structure substitution, carbon sinks from green space replacement, and carbon capture and storage, remain unchanged across scenarios but are consistently incorporated into CER accounting at both the system and citywide levels.

The results show that the magnitude of impacts on CER varies across different parameters (see Tables 9–11). Under perturbations in operational energy parameters, the citywide CER changes marginally from 162.17×10^4 tCO₂e in the baseline scenario to 162.49×10^4 tCO₂e, corresponding to an overall variation of less than 0.5%. This indicates that variations in building energy savings and lighting energy use exert a limited marginal influence on the total mitigation scale. By contrast, changes in the COP produce a more substantial effect on CER, with the citywide total decreasing to 155.85×10^4 tCO₂e or increasing to 168.49×10^4 tCO₂e. Notably, geothermal substitution within underground public and commercial infrastructure increases to 37.62×10^4 tCO₂e, highlighting the high sensitivity of this pathway to COP variations. The electricity emission factor has the most pronounced impact on CER, as the citywide total varies from 131.98×10^4 tCO₂e to 192.35×10^4 tCO₂e, primarily due to the concurrent amplification of travel substitution, building energy savings, and ventilation and lighting emission pathways in the underground transportation system. Although absolute CER values vary with parameter changes, the relative contribution structure and dominant mitigation pathways across underground infrastructure systems remain consistent across all scenarios, indicating that the proposed assessment framework maintains structural robustness under parameter uncertainty.

Table 9. Impact of operational energy parameter on CER benefits of urban underground space.

Operational Energy Consumption Variation		S0	S1 = −20%	S2 = −10%	S3 = +10%	S4 = +20%
Underground transportation infrastructure	Building energy savings	3.16	2.53	2.84	3.47	3.79
	Ventilation and lighting emissions	1.52	1.22	1.37	1.67	1.82
	Total	86.02	85.69	85.85	86.18	86.34
Underground public and commercial infrastructure	Lighting carbon emissions	0.022	0.018	0.020	0.025	0.027
	Total	66.3906	66.3951	66.3929	66.3884	66.3862
Underground municipal utility infrastructure	Carbon capture and storage	9.76	9.76	9.76	9.76	9.76
Total		162.17	161.85	162.00	162.33	162.49

Note: Unit: $\times 10^4$ tCO₂e/year.

Table 10. Impact of COP parameter on CER benefits of urban underground space.

COP Variation		S0	S1 = −20%	S2 = −10%	S3 = +10%	S4 = +20%
Underground transportation infrastructure	Geothermal substitution	0.2429	0.1943	0.2186	0.2672	0.2915
	Total	86.02	85.97	86.00	86.04	86.07
	Geothermal substitution	31.35	25.08	28.215	34.485	37.62
Underground public and commercial infrastructure	Green building energy savings	35	35	35	35	35
	Total	66.39	60.12	63.26	69.53	72.66
Underground municipal utility infrastructure	Carbon capture and storage	9.76	9.76	9.76	9.76	9.76
Total		162.17	155.85	159.02	165.33	168.49

Note: Unit: $\times 10^4$ tCO₂e/year.

Table 11. Impact of electricity emission factor on CER benefits of urban underground space.

Electricity Emission Factor Variation		S0	S1 = −20%	S2 = −10%	S3 = +10%	S4 = +20%
Underground transportation infrastructure	Travel substitution	82.72	66.18	74.45	90.99	99.26
	Building energy savings	3.159	2.5272	2.8431	3.4749	3.7908
	Geothermal substitution	0.2429	0.1943	0.2186	0.2672	0.2915
	Ventilation and lighting emissions	1.52	1.216	1.368	1.672	1.824
	Total	86.02	69.10	77.56	94.48	102.94

Table 11. Cont.

Electricity Emission Factor Variation		S0	S1 = −20%	S2 = −10%	S3 = +10%	S4 = +20%
Underground public and commercial infrastructure	Carbon sink from green space replacement	66.35	53.08	59.715	72.985	79.62
	Lighting carbon emissions	0.0224	0.0179	0.0201	0.0246	0.0268
	Total	66.39	53.13	59.76	73.02	79.66
Underground municipal utility infrastructure	Carbon capture and storage	9.7600	9.7600	9.7600	9.7600	9.7600
Total		162.17	131.98	147.07	177.26	192.35

Note: Unit: $\times 10^4$ tCO₂e/year.

4.3.3. Implications

This study, through a comparative analysis of the CER benefits of different types of underground infrastructure systems across various regions in Nanjing, reveals multiple implications into the role of urban underground space in promoting low-carbon transition.

- (1) Different types of systems should be matched with differentiated carbon reduction strategies. The study finds that the CER benefits of underground transportation systems mainly stem from travel substitution and building energy savings, indicating that the layout of metro stations should coordinate the efficiency of commuting substitution with the optimization of green building standards. Underground public and commercial service facilities exhibit high carbon reduction efficiency per unit area, supported by green building design and the integration of shallow geothermal energy, suggesting that in high-density urban areas, priority should be given to energy system retrofitting and the integration of green infrastructure. The CER benefits of municipal utility systems rely primarily on advanced technologies such as carbon capture, utilization, and storage, highlighting the practical necessity of utilizing underground space to support industrial carbon mitigation demonstration projects.
- (2) The spatial differences in CER benefits across regions highlight the practical need to establish targeted mitigation pilot projects. Districts such as Gulou, Jianye, and Jiangning have already developed relatively comprehensive underground space systems, characterized by a high degree of infrastructure integration and strong functional complementarity. These areas represent priority locations for initiating pilot projects that integrate multiple carbon reduction mechanisms. Promoting a coordinated model of underground green development that links transportation, energy, and building systems in such regions can help explore synergistic pathways between policy mechanisms and engineering solutions.
- (3) The linkage between facility layout and carbon reduction potential reinforces the importance of integrated spatial planning. The results indicate that CER benefits are not only determined by the technical configuration of individual facilities but are also influenced by the coordination among facility types, spatial locations, and functional combinations. Therefore, it is necessary to strengthen the integration of underground development and carbon emission indicators within the overall urban land use planning. By optimizing site selection, functional zoning, and temporal sequencing, the systematic contribution of underground space to the urban carbon neutrality framework can be enhanced.
- (4) Despite the robustness of the reported results, several limitations should be acknowledged. First, construction-phase carbon emissions associated with underground infrastructure development are not fully captured, which may lead to an underestimation of lifecycle emissions. Second, the feasibility of underground space utilization and carbon capture and storage deployment depends on site-specific geological conditions, which may limit the transferability of results across cities. Third, the large-scale

implementation of CCS in dense urban areas may be influenced by policy, regulatory, and economic factors in addition to technical feasibility.

- (5) The CCUS-related carbon emission reduction quantified in this study is based on a large-scale industrial project with stable operating conditions and concentrated emission sources. The resulting CER value therefore reflects the mitigation performance achievable under such representative project conditions, providing a concrete reference for the potential role of CCUS within urban underground space systems. Within the broader context of municipal utility infrastructures, differences in facility type, operational scale, and spatial setting influence the extent to which similar CCUS-based mitigation pathways can be applied. Facilities with continuous operation and relatively concentrated emissions are generally more compatible with CCUS integration, whereas other municipal systems may exhibit different technical suitability. At the city scale, these characteristics suggest that CCUS contributes to urban carbon mitigation through selected projects and locations, complementing other energy-saving- and substitution-based pathways. In this sense, CCUS represents an important component of the underground infrastructure mitigation portfolio, particularly for applications where site conditions and emission characteristics are favorable.
- (6) The proposed assessment framework is structured around mitigation pathways rather than city-specific configurations, which enables its application to other urban contexts. By adjusting baseline scenarios, local emission factors, and infrastructure characteristics, the framework can be adapted to cities with different stages of underground space development. Moreover, additional underground facility types, such as logistics systems, utility corridors, or mixed-use underground complexes, can be incorporated by mapping their functions to the same set of mitigation pathways, ensuring analytical consistency across cases.

5. Conclusions

Focusing on the carbon reduction potential of underground space within the context of urban carbon neutrality strategies, this study constructs an analytical framework covering mechanism identification, pathway analysis, and benefit accounting. It explicitly categorizes three reduction pathways, including biological carbon sequestration, carbon capture and storage, and energy substitution, and establishes CER benefit assessment models for three typical infrastructure types: underground transportation, public and commercial services, and municipal utilities. On this basis, by taking Nanjing as a case study, this paper quantifies the CER benefits of different infrastructure systems under multi-pathway synergy and conducts a difference analysis at the regional scale to verify the applicability and urban practicality of the models.

The results indicate that urban underground infrastructure possesses significant and structured CER capacity, with notable differences across systems in terms of dominant mitigation mechanisms and spatial distribution. Specifically, underground transportation infrastructure achieves the highest annual CER benefit, reaching 8.74×10^5 tCO₂e, primarily driven by travel substitution and building energy savings. Jiangning district and Jianye District are representative high-contribution areas. Underground public and commercial service facilities exhibit outstanding carbon reduction efficiency per unit area, supported by green building integration and geothermal energy utilization. Core urban districts such as Gulou (1.54×10^5 tCO₂e) and Xuanwu (9.16×10^4 tCO₂e) demonstrate strong synergistic advantages. Although the overall CER benefit of underground municipal utility systems is limited, their mitigation capacity is significantly enhanced in areas where carbon capture and storage projects have been implemented, such as Pukou (1.87×10^4 tCO₂e) and Qinhuai (1.67×10^4 tCO₂e). The comparative analysis shows that different types of

underground infrastructure, through pathway coordination and spatial integration, play an important supplementary role in advancing urban carbon neutrality, particularly by providing considerable marginal mitigation potential in high-density built-up areas.

Although this study has preliminarily established a CER assessment system for multi-type infrastructure in urban underground space, certain limitations remain. On the one hand, when constrained by data availability, some parameters, such as the thermal performance of underground buildings and operational energy efficiency, still rely on estimation, which may affect the accuracy of carbon reduction accounting. On the other hand, emerging space types such as underground industrial facilities and underground logistics systems have not yet been incorporated into the assessment, and their carbon reduction potential and mechanisms have yet to be explored in depth. Future research can be expanded in the following directions. First, data collection on micro-scale facility operations and dynamic model updating should be strengthened to improve the accuracy and adaptability of calculations. Second, the scope of carbon reduction mechanism identification should be expanded to cover complex processes such as underground industrial facilities and cryogenic energy storage. Third, a multi-level optimization model oriented towards the overall urban carbon neutrality goal should be constructed by integrating the perspective of synergy between above-ground and underground systems.

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Abbreviations

The following abbreviations are used in this manuscript:

CER	Carbon emission reduction
UUS	Urban underground space
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalent
COP	Coefficient of performance
LCA	Life cycle assessment
DAC	Direct air capture
GHG	Greenhouse gas
GSHP	Ground source heat pump
HVAC	Heating, ventilation, and air conditioning
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency

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