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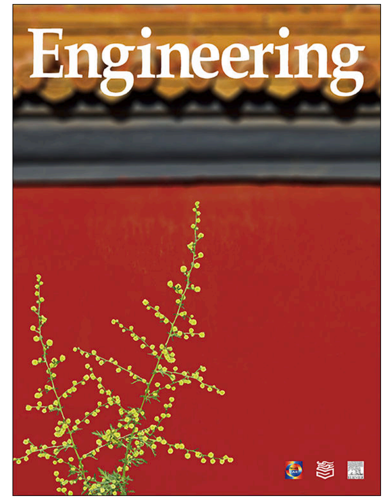

Article

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Research

Frontier Research on Carbon Neutrality—Article

Role of Urban Underground-Space Development in Achieving Carbon Neutrality: A National-Level Analysis in China

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Highlights

- Urban Underground Space (UUS) presents a strategic approach for sustainable urban development.
- A systematic framework is presented to assess UUS's carbon reduction potentials.
- UUS released approximately 547 Mt of carbon emissions during construction phase in 2020.
- Geothermal resources have significant potential for carbon sequestration in UUS sector.

Abstract

Surface space constraints and the associated massive carbon emissions present significant challenges to the sustainable development of megacities. Urban underground space (UUS) construction is expected to provide a practical approach for alleviating the space constraints of surface construction. However, in-depth examinations of the overall UUS system to reveal carbon emissions in the complex matrix are lacking. This study demonstrates the vital role of UUS development in achieving carbon neutrality using a streamlined life-cycle assessment method. Carbon emissions and the mitigation potential of building underground spaces, metro systems, and geothermal energy sources are analyzed. The construction of underground spaces in buildings is the largest carbon emitter within the entire UUS system, releasing a considerable 547.2 Mt in 2020. However, geothermal carbon sequestration, a significant element of the UUS system, provided an unexpected and impressive contribution, sequestering 170 Mt of carbon in 2020. This study shows that UUS addresses the lack of space for urban development and is a low-carbon method of urban construction. Therefore, developing low-carbon building technologies and improving the UUS development model is imperative to achieving better low-carbon balance. This helps to promote more coordinated and sustainable urban development.

Keywords: Urban underground space; Carbon emissions; Urban development; Construction sector

1. Introduction

The construction sector has always been a pivotal driver of economic development, fueling progress, prosperity, and modernization worldwide [1,2]. However, construction activities have been achieved at a cost; that is, the ever-increasing carbon footprint, which poses considerable challenges in achieving carbon-neutrality goals. In China, buildings and infrastructure are major energy consumers and significant carbon-dioxide (CO_2) emitters [3]. According to the China Building Energy Consumption Annual Report 2022 [4], emissions associated with building materials, construction, and building operations accounted for 28.2%, 1.0%, and 21.7% of China's total energy-related CO_2 emissions in 2020, respectively, equaling an accumulated emission quantity of 5.8 billion tonnes of CO_2 emissions. Despite the decrease in real estate development, infrastructure development still generates carbon emissions. Therefore, the construction industry plays a crucial role in achieving carbon-neutrality goals. Thus, low-carbon transformations in the construction industry are imperative [5]. In the context of national goals for achieving carbon neutrality, mitigation measures must be taken to help steer China's construction and building sectors towards low-carbon development modes.

Additional to the need for emission reduction, urban areas face another pressing concern: limited surface space for expansion [6]. As urban populations grow and urbanization rates increase, the conventional horizontal expansion of cities has become increasingly impractical and unsustainable [7,8]. The significance of urban underground space (UUS) development lies in its ability to provide broad opportunities to address various urban challenges and meet the growing demands of urban development. UUS is the primary underground space for human development and utilization, and refers to the space below the surface developed within the scope of an urban-planning area [9,10]. It provides sustainable and efficient use of underground areas for various purposes such as transportation, commercial activities, storage, utilities, and even clean-energy production. Effective exploitation and utilization of UUS can relieve the environmental pressure derived from traditional surface buildings and provide a new way of thinking for densely populated areas to overcome space constraints. The use of underground-space energy sources can help reduce carbon emissions. For example, geothermal energy is a renewable energy source that can heat and cool buildings and reduce their reliance on fossil fuels.

In a rapidly developing country such as China, economic development is an essential goal that has led to the rapid growth of UUSs [10,11]. As of the end of 2020, China has been actively promoting and making significant strides in the development of UUSs [12–15]. The cumulative construction of UUSs in the Mainland of China has reached a remarkable 2.4×10^9 m^2 [16]. In 2020, the country witnessed the addition of approximately 2.59×10^8 m^2 of new UUS, exhibiting an annual growth rate of 0.78% [16]. Newly added underground spaces accounted for approximately 22% of the total completed construction area in urban regions during the same period [16]. As China continues to face rapid urbanization and population growth, promoting UUS development is expected to remain a key priority for the future [17–19]. Globally, cities use underground space as an essential solution to meet the challenges of urbanization and optimize land use. For example, Helsinki, Finland, has more than 1.0×10^7 m^3 of underground space for parking, sports facilities, storage, and metro systems [20,21]. Helsinki uses UUS for transportation purposes in conjunction with the existing transportation infrastructure. For example, an underground metro system can be seamlessly connected to underground pedestrian tunnels, making moving around the city easy and efficient. Singapore is committed to doubling its metro network from 180 km by 2030, a global model for promoting underground-transport systems [22–25]. In Paris, France, where the population density is as high as 927 people per square kilometer owing to good ground conditions, a large amount of underground infrastructure is used for transportation networks, public utilities, and multiple functions [26]. These quantifiable examples highlight the fact that UUS forms an integral part of modern urban planning, enabling cities to maximize land use.

Considering the Sustainable Development Goals of the United Nations, the question of whether the intensive development of UUS is a low-carbon activity must be addressed, particularly in many megacities in China. Notably, the development of UUS involves a large amount of resources and energy inputs, and is likely to incur indirect carbon emissions [27–30]. This apparent negative effect deserves further investigation. For example, the energy-saving performance of metros during operation has replaced part of the ground automotive transportation as a low-carbon mode of transportation [31–35]. However, the considerable carbon emissions during the construction of underground metro tunnels contradicts the carbon-emission reduction potential that occurs during metro operation. With the common goal of carbon neutrality, the consideration of UUS as a low-carbon development approach at the national level must be properly justified. However, existing studies have mainly focused on quantifying carbon emissions from specific UUS projects [36–38]. Insufficient analysis can be attributed to various factors, including complex system boundaries, limited data availability, and the evolving characteristics of UUS development.

Therefore, this study conducts a comprehensive assessment of China's UUS development and embodied carbon impact over the past two decades using a top-down approach at the national level. Unlike previous studies that focused on specific UUS types, such as underground rail transit, this study takes a holistic approach to evaluate the overall carbon impact of multiple UUS types at a national scale. By examining the cumulative effects of UUS development and operation over nearly two decades, this study aims to elucidate the role of sustainable construction in reducing carbon emissions. Overall, this study aims to ① quantitatively analyze the performance of UUS in low-carbon sustainable development through statistical data and calculations of typical UUS applications in China from 2001 to 2020; ② examine the factors related to the performance of various typical urban underground spaces in terms of carbon emissions; ③ draw conclusions regarding the positive outcomes of China's UUS development in effectively reducing carbon emissions; and ④ suggest a low-carbon path for UUS development in China and beyond.

2. Methods

2.1 Research boundary

The primary assessment method used in this study was life-cycle assessment (LCA), which is a method for assessing the environmental impact of a product over its entire life cycle. It is suitable for sustainability assessments at regional, national, and global scales (details in Note S1 in Appendix A). In terms of an intensive literature review, the LCA method is more appropriate for calculating UUS carbon emissions at the national level.

UUS comprises a variety of categories, including buildings, tunnels, basements, underground parking lots, and other subterranean infrastructure [39,40]. The major categories of underground spaces related to carbon emissions, which are the focus of this study, can be summarized into three typical types: construction of commercial and residential underground spaces, development of underground metro systems, and utilization of geothermal energy [41–43]. These UUS types involve the intensive consumption of building materials, energy, or renewable-energy resources. Further details on the relationships between these three categories and their specific definitions are presented in Note S2 in Appendix A. In this study, we focus on a quantitative analysis of the carbon-emission mitigation associated with UUS development in these three specific aspects (Fig. 1). UUS contributes significantly to mitigating carbon emissions in the context of urbanization; however, considering the complexity of each aspect, a comprehensive examination of their effects presents considerable challenges. Therefore, to streamline this research and gain a deeper understanding of the impact of USS on carbon reduction, we focused on these three key areas.

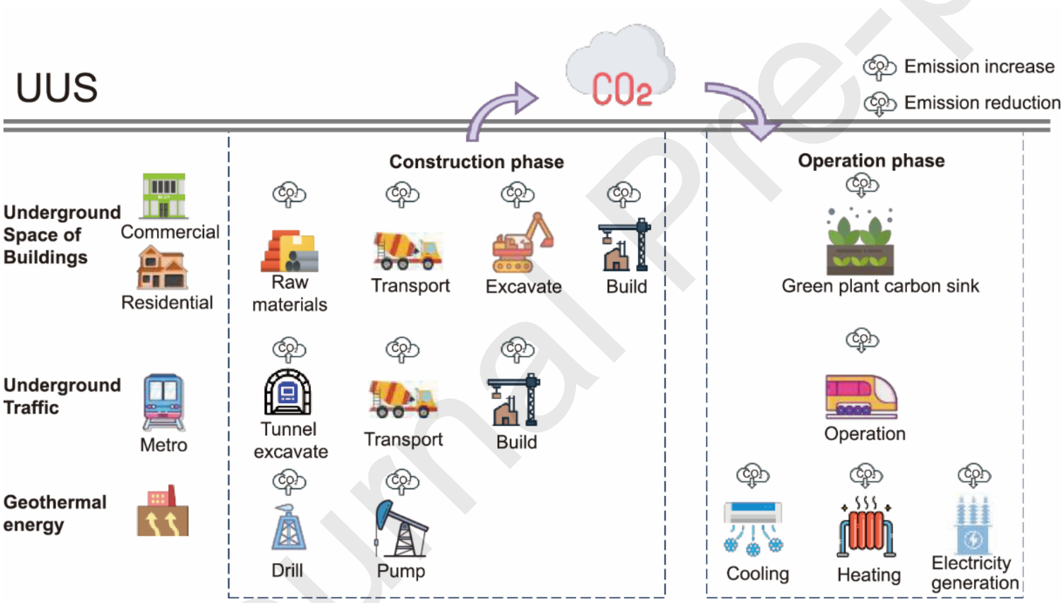

Fig. 1 Quantification boundary of the carbon mitigation of UUS.

2.1.1 Underground building

The term "underground building" explicitly pertains to the subterranean levels of both commercial and residential buildings. A comprehensive top-down methodology was employed to determine the cumulative area of the constructed underground spaces in China between 2001 and 2020. The annual aggregated floor areas of completed buildings from 2001 to 2020 were sourced from the *Statistical Yearbooks of China 2020* (covering the years 2002–2019) [44]. According to "The 13th Five-Year Plan for the Development and Utilization of Urban Underground Space" [45] and *The Blue Book on the Development of Urban Underground Space in China 2021* [16], the annual proportion of underground area in completed building floor areas increased from 10% to 19% during the past two decades. This proportion involves the annual completed metro area. Hence, the annual completed metro areas were calculated using Eq. (1) and then deducted using Eq. (2). Annual statistics on the metro operating mileage and in-use stations from 2001 to 2020 were obtained from the *China Urban Construction Statistical Yearbook* (2002–2020) [46] as well as the China Urban Rail Transit Association (2020).

$$S_{\text{sub}(i)} = L_{\text{tunnel}(i)} \times w_{\text{tunnel}} + \sum_{t=1}^{n(i)} h_t \times w_t, (1)$$

where $S_{\mathrm{sub}(i)}$ refers to the area newly occupied by metro in the year i (m^2); $L_{\mathrm{tunnel}(i)}$ denotes the newly added metro operating mileage in the year i (m); w_{tunnel} is the width of the metro tunnel, which is equivalent to the diameter of shield segments, that is, 6.98 m; n refers to the number of newly opened metro stations in the year i; h_t and w_t are the length and width of the tth newly opened metro station, and for this study, these values are 240 and 24 m, respectively [47].

The CO_2 emissions of an underground building during the construction phase can be calculated as follows:

$$E_{\mathrm{c-ug}(i)} = \left(S_{\mathrm{com}(i)} \times d_{\mathrm{com}(i)} - S_{\mathrm{sub}(i)}\right) \times e_{\mathrm{c-ug}}, (2)$$

where $E_{\mathrm{c-ug}(i)}$ is the CO_2 emission of building underground space in the construction phase in the year i (tonnes of CO_2, tCO_2); $S_{\mathrm{com}(i)}$ refers to the newly completed floor area of buildings in the year i ($\times 10^4$ m^2), and the full set of data are provided in Note S2; $d_{\mathrm{com}(i)}$ is the ratio of the underground area to the total annual completed building floor area in the year i; $e_{\mathrm{c-ug}}$ refers to the carbon-emissions factor of underground building in the construction phase, that is, 0.72 $tCO_2 \cdot m^{-2}$ [48].

Greenery and vegetation also contribute to carbon sequestration. Assuming that the areal equivalent of the building underground space had all been developed into greenery and vegetation on the ground, the quantity of the resulting fixed CO_2 in a certain year can be estimated as follows:

$$E_{\mathrm{cs-ug}(i)} = (S_{\mathrm{com}(i)} \times d_{\mathrm{com}(i)} - S_{\mathrm{sub}(i)}) \times e_{\mathrm{g}} \times 3.67, (3)$$

where $E_{\mathrm{cs-ug}(i)}$ is the amount of fixed CO_2 in the year i (tCO_2), and e_{g} refers to the average carbon-sequestration factor of urban greenery, that is, 2.16 tonnes of carbon per hectare per year ($tC \cdot hm^{-2} \cdot a^{-1}$) [49].

2.1.2 Metro

CO_2 emissions associated with the construction phase are non-negligible when the low-carbon effect of the metro is considered. Metro construction can be divided into two distinct categories: tunnels and stations. In the construction phase, the total CO_2 emissions are the sum of the emissions from both parts, as reflected in Eq. (4):

$$E_{\mathrm{c-sub}(i)} = L_{\mathrm{tunnel}(i)} \times e_{\mathrm{tunnel}} + \sum_{t=1}^{n(i)} h_t \times w_t \times e_{\mathrm{station}}, (4)$$

where $E_{\mathrm{c-sub}(i)}$ denotes the CO_2 emissions associated with the construction phase of metro in the year i (tCO_2); e_{tunnel} and e_{station} refer to the carbon-emissions factors associated with the construction of metro tunnels and stations, that is, 10.192 $tCO_2 \cdot m^{-1}$ and 3.924 $tCO_2 \cdot m^{-2}$, respectively [50].

In addition to the metro, public buses and taxis are the major types of urban public-transport vehicles in China. This is reflected by the annual total ridership data for each type of vehicle from 2001 to 2020, which can be found in the *China Urban Construction Statistical Yearbook* (2002–2020) [46] and the *Statistical Bulletin on the Development of the Transportation Industry* (2009–2020) [51]. The three types of vehicles were compared on a macro scale in terms of operation-induced CO_2 emissions, which were acquired using Eq. (5):

$$E^t_{\mathrm{o-trans}(i)} = N^t_i \times M^t_i, (5)$$

where t refers to the type of vehicles, namely metro, public bus, or taxi; $E^t_{\mathrm{o-trans}(i)}$ denotes the CO_2 emissions of the type t vehicle in the year i ($kgCO_2$); N^t_i is the total ridership of the type t vehicle in the year i (passenger-ride); M^t_i represents the CO_2 emissions per passenger-ride of the type t vehicle in the year i, that is, 0.7 $kgCO_2$ per passenger per ride for metro [52], 0.68 $kgCO_2$ per passenger per ride for public bus [53], and 1.72 $kgCO_2$ per passenger per ride for taxi [53]. The emission factors of public buses and taxis consider the combined emission indicators of both petrol-powered and electric vehicles.

2.1.3 Geothermal energy

The utilization of hot, dry rock geothermal resources remains limited worldwide. Thus, for simplicity, this section is concerned only with shallow and hydro-geothermal energy. The carbon-mitigation effect of shallow geothermal energy can be quantitatively determined using heat-pump data [54], as follows:

$$E_{\mathrm{geoth-s}(i)} = N_{\mathrm{pump}(i)} \times J_{\mathrm{ave}} \times e_{\mathrm{tr}}, (6)$$

where $E_{\text{geoth-s}(i)}$ refers to the amount of CO_2 reduced by utilizing shallow geothermal energy in the year i (tCO_2); $N_{\text{pump}(i)}$ is the number of heat pumps in the year i (pumps); J_{ave} is the average amount of energy of each pump for building heating and air-conditioning ($J \cdot pump^{-1}$); e_{tr} is the carbon-emissions factor of electricity ($tCO_2 \cdot J^{-1}$).

As the embodied energy of one tonne of standard coal is well known, amounts of geothermal energy are typically expressed as a particular quantity of standard coal. Thus, the carbon-mitigation effect of geothermal energy can be calculated as follows:

$$E_{\text{geoth}(i)} = N_{\text{coal}(i)} \times e_{\text{coal}}, \quad (7)$$

where $E_{\text{geoth}(i)}$ refers to the amount of CO_2 reduced by utilizing geothermal energy in the year i (tCO_2); $N_{coal(i)}$ is the equivalent quantity of standard coal in the year i (t); e_{coal} is the carbon-emissions factor of standard coal ($tCO_2 \cdot t^{-1}$).

2.2 Data collection

Conducting a systematic and long-term analysis at the national level presents significant challenges for data acquisition. The primary data sources for this study were government documents, such as the *China Statistical Yearbook*, and industry reports, such as the *13th Five-Year Plan for the Development of Urban Underground Space in China* and the *Blue Book for the Development of Urban Underground Space in China 2021* [16]. Government and industry data are relatively reliable and extensive, covering 20 years (2001–2020). For example, the China Statistical Yearbook provides the annual gross floor area of completed buildings. Other professional reports and yearbooks also provide valuable data on metro operations and other types of public transportation such as buses and taxis. Some parameters or data were assumed if they were difficult to gather; however, uncertainties were captured. The error values of the results were obtained using a Monte Carlo simulation.

3. Results and discussion

3.1 Total carbon emission and mitigation of UUS

The comprehensive analysis presented in this study sheds light on the pivotal role of UUS as a significant contributor to sustainable urban development and carbon-emissions reduction. Urban and national development is intrinsically tied to construction activities, which inevitably lead to carbon emissions [55]. Therefore, the pursuit of low-carbon development approaches has become critical. In this context, the development of underground spaces has emerged as an effective means of mitigating the constraints of the limited availability of surface land while minimising carbon emissions.

The results of this study show that the construction process is the main source of carbon emissions during the entire life cycle of the UUS. Production and transportation of construction materials are the primary sources of carbon emissions [56]. In addition, emissions showed a continuous upward trend over time. Although emissions are generated during the construction phase, carbon-sink offsets during operation make UUS a sustainable construction model that complements urban development. From a life-cycle perspective, UUS does not lead to higher carbon-emission outcomes. Simultaneously, UUS can be used for transportation and commercial facilities through proper planning, thereby reducing the pressure on surface space development and promoting sustainable urban development. The space saved on the surface provides opportunities for green plants, and plant carbon sequestration is useful for reducing carbon emissions.

Geothermal energy plays a vital role in carbon reduction in UUS. The use of geothermal resources provides UUSs with a considerable capacity for carbon sequestration. China has a large land area and abundant natural resources, and the rational utilization of geothermal resources provides powerful assistance for the low-carbon development of UUS. Economic growth must be connected to infrastructure, and UUS offers new ideas for developing countries such as China. Moreover, the combination of geothermal-energy utilization and underground-space development offers an innovative and sustainable model. This synergy provides a new direction for low-carbon urban developments. The results of this study also confirm that UUS can be used as a low-carbon construction method, which has been validated in other developing countries. In addition to analyzing historical data on UUS emissions, this study projected future trends under different scenarios. The results illustrate the potential paths for carbon emissions and sequestration from 2021 to 2035 under various scenarios. These scenarios are critical for understanding the impact of current measures.

Overall, the carbon-reduction potential of UUS is clear. Although underground buildings still produce emissions during construction, UUS is a low-carbon system based on the overall evaluation of the system. Urban-planning authorities can use UUSs to enhance planning and design to further reduce emissions. Rationally planning the distribution of UUS and seizing low-carbon construction opportunities derived from it are essential. These findings demonstrate the urgent need to implement low-carbon strategies and take proactive measures in carbon strategies, particularly when considering the overall construction of cities. Future UUS development should explore advanced construction materials, improved energy-efficient systems, and innovative carbon-capture and -storage techniques. Carbon negativity can be achieved more efficiently through synergy with geothermal-energy utilization. Moreover, sustainable design principles, such as maximizing green spaces and employing smart ventilation systems, can further contribute to carbon negativity. These technologies and approaches are pertinent to the UUSs in China and have implications for urban development.

In addition, the assumptions made during the carbon-emission calculation process are limited. For example, the average carbon-sequestration factor may not accurately represent sequestration rates in different regions or ecosystems. Additionally, our data may not account for the potential impact of technological advances on emission factors, which may introduce uncertainties into the results. However, we captured these uncertainties in the modelling results. Most importantly, these assumptions and limitations did not significantly alter the overall trend of carbon calculations in the macro-level analysis. In fact, in some extreme hypothetical scenarios, the use of assumed parameters can provide a more intuitive understanding of the analytical results. Future research should aim to refine these assumptions and incorporate more precise data to further enhance the accuracy of carbon calculations.

3.1.1 Underground building

Fig. 2 shows the carbon emissions associated with various stages of underground space for building construction, juxtaposed with the carbon-sequestration potential attributed to urban greenery and vegetation in equivalent surface areas. CO_2 emissions associated with the construction of underground buildings have increased continuously from 70.2 Mt in 2001 to 547.2 Mt in 2020. The average annual growth rate was calculated as 11.4% over the entire two-decade period. As shown in Fig. 2, the annual increments in emissions appeared relatively stable and modest during the first decade. However, the annual emissions growth became more significant thereafter. Between 2011 and 2013, emissions increased noticeably, the momentum of which prompted annual emissions to exceed 400 Mt in 2015. During the 13th Five-Year Plan period, annual emissions increased to over 500 Mt for the first time in 2018, and peaked at 547.2 Mt in 2020. Notably, the increase from 2019 to 2020 was small and even negligible, which can be attributed to the coronavirus disease 2019 (COVID-19) pandemic in 2020.

Notably, the figure reveals a steady increase in CO_2 emissions during the construction phase of underground buildings, primarily driven by the stages of building-material production and transportation, particularly cement production. The production of cement involves numerous chemical reactions. Therefore, the carbon emission from cement production during the construction process is a topic that requires attention. Transportation consumes a considerable amount of energy, and the estimated results verify that energy savings in transportation require special attention. Notably, while this carbon-emissions segment is linked to underground-space construction, equivalent surface building construction similarly necessitates building-material production and transportation, including cement production. Consequently, this fraction of carbon emissions is not exclusively associated with underground-space development, but constitutes an inherent aspect of the holistic building process. This awareness helps to mitigate the misattribution of increased carbon emissions solely to the construction of underground spaces.

The results showed that plant carbon sequestration in cities did not result in considerable carbon reduction. As assumed in this study, ① the development of underground space for buildings has released the same size as the surface space, and ② all this surface space is used for carbon sequestration in the form of green plants and vegetation. The purpose of these two assumptions is to estimate the role of plant carbon sinks in urban areas. Using these assumptions, we calculated the trends and significance of plant carbon sinks in cities. Simultaneously, we assumed that the carbon-sequestration capacity of urban greening remains constant, that is, 2.16 $tC\cdot hm^{-2}\cdot a^{-1}$. Even under extreme conditions, plant carbon sinks in cities do not result in an order-of-magnitude reduction of carbon. However, UUS solves part of the surface-land problem and provides opportunities for the development of urban plant carbon sinks. This study evaluated the development trends of urban carbon sinks using the limiting condition hypothesis. **Fig. 2** illustrates the amount of CO_2 compensated by these means during a 20-year period. The amount of fixed CO_2 increased continuously and rapidly over the two-decade period, reaching a total of 6 Mt in 2020, and annual growth appeared to accelerate. The gradual increase in carbon sequestration observed over the years suggests that urban greening plays an auxiliary role in the sustainable development of UUS.

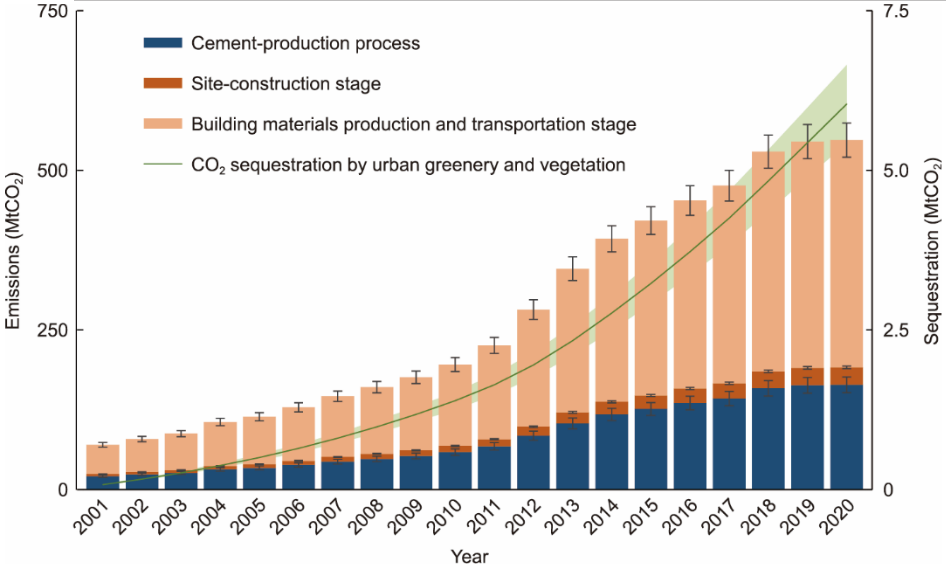

Fig. 2 Carbon emissions and sequestration in construction of underground building.

3.1.2 Metro

Fig. 3 summarizes the CO_2 emissions attributed to the different stages of metro development over the past two decades (2001–2020). The figure visually represents these emissions, highlighting distinct metro construction and operation trends. Carbon emissions linked to metro construction, including stations and tunnels, exhibited a significant shift in 2010, increasing sharply from 2.8 Mt in 2009 to 12.5 Mt. This indicates a notable division between the pre-2010 period and subsequent years. This is because of increased government investment in urban-infrastructure development, with metro construction being an important aspect. Policy support facilitated the development of metro-construction projects. With the acceleration of urbanization, the urban population is proliferating and the pressure on urban transportation is increasing. As an efficient and fast mode of transportation, the metro can effectively alleviate the problem of urban traffic congestion. Therefore, metro construction has grown rapidly during the process of urbanization. Regarding metro operations, emissions exhibited steady growth from 2001 to 2009. Subsequently, a noticeable acceleration in emission was observed until 2019, peaking at 14.3 Mt. Notably, in 2020, the COVID-19 pandemic led to a considerable decline in the total ridership, which, in turn, had a discernible impact on the operational carbon emissions of the metro.

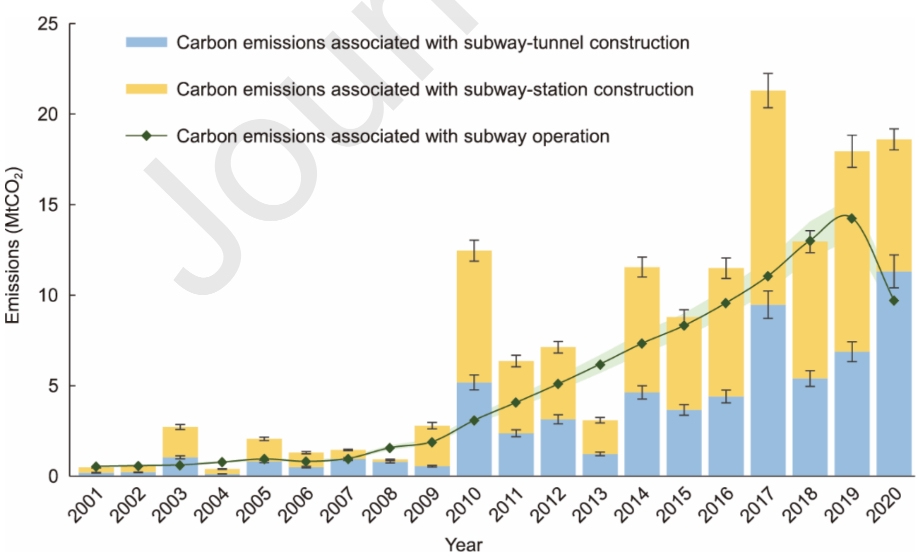

Fig. 3 Trends in carbon emissions at different stages of metro construction and operation.

Fig. 4(a) shows the operational CO_2 emissions associated with the three primary categories of public-transport vehicles from 2001 to 2020. A closer examination showed that public buses and taxis generated more CO_2 emissions in the latter ten-year period than in the first decade, a trend similar to that observed for the metro. Notably, the collective emissions of public transport, including the metro, public buses, and taxis, consistently exceeded 120 Mt between 2012 and 2019, peaking at 130 Mt in 2014. As the economy develops, people's willingness to travel increases and public transportation grows. Simultaneously, with the promotion of environmental protection, people are choosing a higher proportion of public-transportation trips. Fig. 4(a) shows the distinction in operational carbon emissions between the metro and other public-transportation options. Metro emissions were consistently lower than those of public buses and taxis. Quantitatively, the annual emission proportions attributed to the metro within the broader public-transport context ranged from 1.05% to 11.77%, with an average of 4.53% over the twenty-year period. Transportation modes are vulnerable to external factors, and the impact of the COVID-19 pandemic led to a significant reduction in carbon emissions from transportation after 2019. The development of the carbon-emission trend in the graph reveals a positive correlation with transportation development.

A scenario analysis was conducted under extreme conditions to delve deeper into the roles of major public-transport types in CO_2 emissions. This analysis involved allocating the genuine annual aggregate ridership to the three major vehicle categories. As shown in Fig. 4(b), the scenario analysis results align with those shown in Fig. 4(a). The scenario analysis highlighted that taxis provided significantly higher CO_2 emissions than in the actual situation. In contrast, metro and public buses exhibited emissions that were considerably lower than the actual data. Additionally, the metro and public buses appear to have reasonably comparable presumptive carbon emissions, with the metro maintaining only a modest lead over public buses. The metro continues to perform well in terms of low-carbon performance while significantly easing road traffic and effectively improving transportation efficiency.

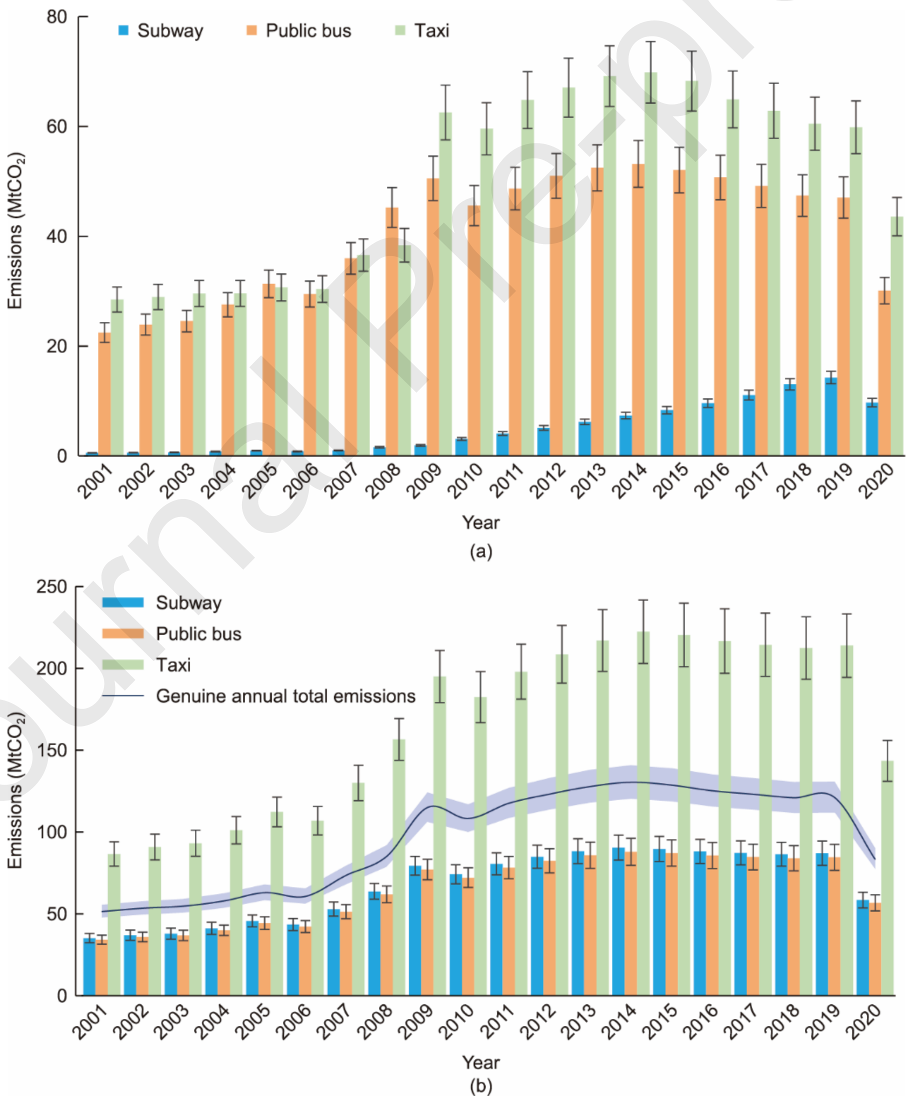

Fig. 4 Comparison of carbon-emission trends in (a) the operation of different public-transportation options for actual passenger flow and (b) after average passenger distribution (blue belt represents the range of the uncertainty analysis).

As urban populations grow and cities become more congested, the expansion of surface-level transportation infrastructure encounters challenges owing to limited physical space. Thus, the significance of the metro as a pivotal player in the transportation landscape has become even more pronounced. The metro, an underground transport mode, operates independently of surface constraints and effectively utilizes the underutilized space beneath the city. Beyond its capacity to alleviate urban congestion, the metro's inherent attributes align with low-carbon urban-development goals. The results show that the metro system generates emissions that are no higher than those of other public-transportation options. Thus, the metro system can address the twin challenges of urban congestion and carbon emissions. Its ability to provide a reliable, efficient, and low-carbon transportation option, while bypassing the limitations posed by surface-level transport, underscores its importance in achieving sustainable urban mobility.

3.1.3 Geothermal energy

Table 1 presents a comprehensive overview of the present state and potential carbon-reduction impact achievable by utilizing geothermal resources. This data-driven analysis underscores the pivotal role of geothermal energy in UUS development. A notable trend is the steady expansion of geothermal-energy applications, particularly for shallow heating/cooling and hydro-geothermal heating. This not only aids in mitigating reliance on conventional fossil fuels, but also empowers cities with sustainable alternatives for heating, cooling, and electricity generation. The use of underground space for the development of UUS may destroy the structure of the underground strata and impact the utilization of geothermal resources, such as the conduction and extraction of geothermal energy. However, these effects are typically local and controllable and can be reduced with appropriate design and management. Therefore, the temperature loss of geothermal resources was not considered in this study. Geothermal energy, similar to solar, wind, and other clean-energy sources, is an essential approach for carbon reduction that cannot be ignored. China's abundance of natural geothermal-energy resources holds promise for low-carbon development or even the carbon neutrality of the UUS system. This expansion signifies the growing recognition of the versatility of geothermal energy across diverse sectors, which considerably supports urban carbon-reduction aspirations.

Furthermore, the data highlighted the substantial potential of geothermal resources to replace fossil fuels. As geothermal-energy applications continue to expand, the corresponding displacement of fossil fuels increases annually. Projections suggest that geothermal resources may replace an energy equivalent of 280 Mt of standard coal by 2035. This projection promises a significant reduction in fossil-fuel consumption, which is vital for catalyzing efforts to reduce urban carbon emissions. From a research perspective, the significance of the 2025 and 2035 data points lies in their foundation for the existing national planning. These projections are not arbitrary. Instead, they are rooted in well-established strategies and policies. Incorporating this contextual information enriches the analysis, highlighting the harmonization of these projections with the country's long-term sustainability objectives. Geothermal energy plays an irreplaceable and vital role as a clean energy source in UUS development.

Table 1 Current Status and potential for carbon reduction through the application of geothermal resources.

Year	Shallow geothermal heating/cooling area ($\times 10^6$ m^2)	Hydro-geothermal heating area ($\times 10^6$ m^2)	Installed power-generation capacity (MW)	Substitution of fossil energy (million tce)	Reduction in CO_2 emissions (Mt)
2015	392.0	102.1	27.28	20	48.6
2020	1118.5	502.1	527.28	70	170.0
2025	2237.0	1004.2	1054.60	140	340.0
2035	4474.0	2008.4	2109.20	280	680.0

Data were cited from the "13th Five-Year Plan" for developing and utilizing geothermal energy [42], and the future-development target data were derived from the National Energy Administration. tce: tonnes of coal equivalent.

3.2 Scenarios of future carbon emissions in UUS

The carbon-emission results show that UUS is currently in line with the concept of low-carbon sustainability; however, more strategies are still needed to improve low-carbon efficiency. Scenario projections can provide decision support and a better understanding of possible future scenarios. Based on the results of this study, these three types of emissions are summarized as historical data to predict future emission trends. Therefore, this study provides nine different scenarios for a comprehensive projection of the potential trajectory of carbon emissions and sequestration in the UUS from 2021 to 2035, based on economic development goals and policy development (shown in Fig. 5). This predictive illustration is instrumental in comprehending the ramifications of contemporary actions on the future environmental tableau. Central to the figure is the depiction of three principal trajectories concerning carbon emissions and sequestration: planned, increased, and decreased, each symbolizing either a continuation of present trends, an activity escalation, or a decline, respectively. These pathways are juxtaposed to formulate nine amalgamated scenarios, each pinpointing a unique confluence of emission and sequestration prospects (the scenario set can be found in Note S3 and Table S1 in Appendix A).

Notably, the most optimistic scenario (S1) involves strong environmental stewardship, leading to reduced emissions and enhanced sequestration. Similarly, the most pessimistic trajectory, S6, is worth observing and is characterized by rampant industrial activities paired with insufficient carbon-capture initiatives. These extremes encapsulate a spectrum of possibilities, starkly admonishing the divergent outcomes that have emerged from our current choices. This scenario shows that even a UUS currently assessed as low-carbon cannot be developed and built indiscriminately or without restraint. In baseline Scenario S1, geothermal-energy development alone is insufficient to offset the carbon emissions generated by UUS construction under the state's current planning. Therefore, additional measures and innovative techniques for carbon sequestration must be implemented to reduce the carbon footprint. Scenario S7 is predicated on escalated UUS construction aligned with urban-development demands coupled with enhanced policy-driven geothermal carbon sequestration, and it presents a future in which carbon sequestration potentially neutralizes emission impacts, manifesting a steady decline in overall carbon discharge.

Specifically, Fig. 5 underscores the need for assertive interventions in carbon strategies and the pivotal role of foresight in sculpting sustainable environmental outcomes. By orchestrating a suite of scenarios, the illustration provides a nuanced perspective on conceivable futures, enlightening policymakers, scholars, and environmental proponents on critical junctures in decision-making.

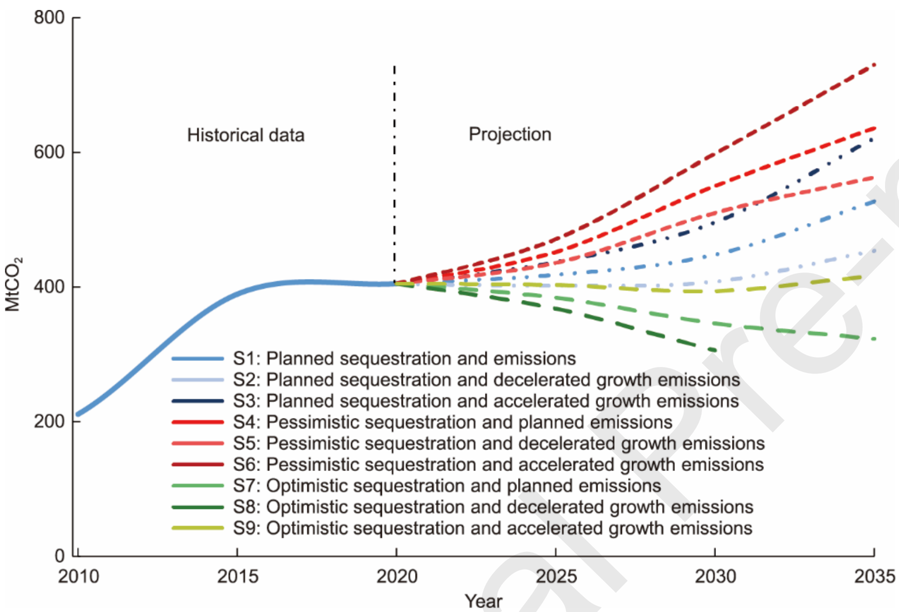

Fig. 5 Projections of carbon emissions and sequestration of UUS by scenario over time.

4. **Conclusions**

The construction sector has long been a driver of economic growth. However, the surge in carbon emissions has called for urgent action to reduce and mitigate carbon emissions. The development of UUS presents an innovative solution that relieves pressure on surface space and presents a low-carbon construction model. This study comprehensively analyzed the interactions between various aspects of UUS, such as urban development, energy consumption, and carbon reduction. This study focused on the vital role of the operational phase in UUS systems, particularly in metro networks. Metros provide low-carbon transportation options while reducing roadway congestion.

Moreover, this study quantified the capacity for geothermal energy to displace considerable fossil energy, thereby aligning with China's sustainability objectives and contributes globally to climate change mitigation. Similarly, future trends and possibilities of the carbon impact of UUS were analyzed. The potential trajectories of carbon emissions and sequestration from 2021 to 2035 were presented through a scenario analysis. In essence, UUS development has become a strategic approach to achieving sustainable urban growth while minimizing carbon footprints. For developing countries, the development of UUS presents a positive solution for land-resource constraints. UUS offers a new solution for the conflict between economic growth and environmental protection. From the perspective of environmental benefits, the carbon-emission reduction advantages of the UUS construction phase may not be significant in the short-term. However, both the operation of the metro system and utilization of geothermal resources can offer significant carbon-sequestration potential in the long-term, which can help meet the overall carbon-emission reduction goal. Long-term thinking is essential for regional and national development. Therefore, policymakers should focus on new technologies and materials for the development of UUS to further expand low-carbon construction.

This study has certain limitations, such as limited attention given to geothermal energy. The primary focus of this study was on shallow and hydraulic geothermal energy. By contrast, other forms of geothermal resources, such as hot, dry rock geothermal resources, were not considered. Because of the macroscale calculations involved, this study made assumptions about the setting of some coefficients, such as the average carbon-sequestration coefficient. Technological advances in emission factors were not included in the data. As mentioned above, UUS can be developed for purposes other than building underground spaces, metros, and geothermal energy. Future research can extend the scope of this study to cover other types of UUS developments. Additionally, private motorized vehicles can be incorporated into ridership allocation.

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Compliance with ethics guidelines

Jiajia Wang, Huabo Duan, Kunyang Chen, Isabelle Y. S. Chan, Fan Xue, Ning Zhang, Xiangsheng Chen, and Jian Zuo declare that they have no conflicts of interest or financial conflicts to disclose.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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