## ARTICLE

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# Dynamic simulation research on urban green transformation under the target of carbon emission reduction: the example of Shanghai

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This paper aimed to predict the trend of carbon emissions during the green transformation process in Shanghai, with a focus on the city's urban system structure. Green development has become an inevitable trend in urban progress, as traditional urban development has led to severe environmental problems caused by the emissions of a large amount of carbon dioxide. This study was motivated by the need for cities to actively pursue green transformation and achieve carbon peaking targets. Through a literature analysis, it was found that urban green transformation is influenced by various factors such as economy, energy, population, technology, and policy. Furthermore, carbon dioxide emissions primarily arise from fossil fuels and are regulated by carbon emission trading (CET) policies. With this knowledge, the urban system was divided, and the flow of carbon was analyzed. Using the general methodology of the IPCC, the carbon production resulting from energy consumption in Shanghai from 2014 to 2019 is calculated to construct an urban system dynamic (SD) model, which is used to predict the carbon emissions expected during the green transformation from 2020 to 2025. The key findings of the study are as follows: (1) The dynamic model of the urban green transformation system proved to be effective in predicting carbon emissions. (2) Based on the current status of green transformation in Shanghai, the city is capable of achieving its expected carbon emission peaking target by 2025. (3) The progress and timing of green transformation and carbon peaking in Shanghai vary across different scenarios, highlighting the importance of collective adjustments to identify the most appropriate path for urban green transformation. These findings provide valuable insights for cities seeking to adopt green development measures, facilitating the acceleration of their green transformation efforts and early attainment of carbon peaking targets.

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## Introduction

During the process of traditional urban development, the overuse of resources and the disregard for green development made it challenging to limit carbon emissions. This created a situation where the economy and resources were hindered by each other (Dong et al., 2020). To meet carbon reduction obligations, China introduced a plan at the 75th United Nations General Assembly to peak carbon dioxide emissions and achieve carbon neutrality (Lu et al., 2022). Subsequently, the *Opinions on Promoting Green Development of Urban and Rural Construction* proposed the establishment of a green development system for urban and rural construction in China by 2025 (General Office of the State Council, 2021). This policy aims to make significant advancements in green transformation, carbon reduction, and the alleviation of "urban diseases". In response to this policy, cities need to control $CO_2$ emissions and achieve coordinated improvements in economic restructuring and ecological quality (Guo et al., 2020). Therefore, developing a green transformation plan is of great importance as it can provide a theoretical and practical foundation for accelerating urban green development.

The concept of green transformation arose from the evolution of the green economy (Loiseau et al., 2016). In early developed countries, the focus of green transformation was on practicality (Table 1). Resource-based regions transformed and extended high-energy industries through green development planning and policy revisions (Labussière, 2021; Wang et al., 2022; Su et al., 2023; Herrador et al., 2023). In China, green transformation is guided by the concept of ecological civilization, which is based on a circular economy and supported by green management. The objective is to achieve resource conservation, environmental friendliness, ecological balance, and harmonious development of people, nature, and society (Feng et al., 2020). However, as scholars Wang et al. (2022) have noted, the level of urbanization has led to urban economic development playing an increasingly significant role in promoting carbon emissions. Moreover, the relationship between urban economic development and carbon emissions shows varying trends as urban income levels rise (Wang et al., 2023). This implies that China's urban green transformation faces the challenge of balancing economic growth and carbon emissions, with different cities at different stages of development requiring diverse approaches to green transformation. Therefore, accurately predicting carbon emission trends and identifying suitable green transformation strategies based on the specific stage of urban development is a worthwhile research question (Wei et al., 2022).

Scholars have devoted their efforts to aligning urban development with the requirements of green transformation, focusing on designing strategies and evaluating the effects of transformation plans. These research endeavors aim to provide guidance for cities to expedite their transformation towards green development. Guo and Ma (2023) utilized efficiency analysis and entropy value method to measure the efficiency of urban digital development and carbon emissions. They also analyzed the spatial and temporal evolution characteristics of these factors, providing valuable insights for urban development planning. Wang et al. (2022) constructed a conceptual framework to examine how regional integration affects the efficiency of green urban development. Their study investigated the facilitation of factor mobility and optimization of industrial layout through regional integration, offering development plan from the perspective of regional integration of city clusters. Evaluating the effects of green transformation, Su et al. (2023) constructed an evaluation index system for the synergistic governance of pollution reduction and carbon emission reduction in urban agglomerations. By applying this system, they evaluated the level of synergistic governance in seven urban agglomerations in the Yellow River Basin, providing empirical references for high-quality green development paths. Song et al. (2022) leveraged the Low Carbon City Pilot (LCCP) policy as a quasi-natural experiment to assess its emission reduction effect, providing an empirical basis for accelerating the realization of the "peak carbon emission" and "carbon neutral" targets. These studies collectively emphasize the need for future urban development to break free from resource constraints and environmental pollution, urging the adoption of a green development path. Therefore, researching and exploring urban green transformation pathways and assisting cities in formulating green development plans hold significant implications.

Peaking carbon dioxide emissions represents a historical turning point in which $CO_2$ emissions shift from increasing to decreasing (Chen et al. 2022). Traditional economic development heavily relies on massive energy consumption, and $CO_2$ emissions serve as a direct indicator of the degree of urban green transformation (Du et al. 2021). Existing studies on urban carbon emissions concentrates on energy consumption and carbon trading policies. Energy consumption refers to the process through which carbon dioxide is produced by consuming fossil and non-fossil energy, representing the main source of $CO_2$ production. Various methods, such as LMDI (Peng and Liu, 2022), remote sensing measurement (Wu et al., 2022), and structural equations (Xue and Yao, 2022), can be employed to decompose the factors influencing $CO_2$ production. Through these approaches, factors such as economic level (Jia et al., 2023), human capital (Wang et al., 2023), industrial structure (Fang, 2023), technological level (Wang et al. 2023), and energy intensity (Wang and Xue, 2023) have been identified as crucial determinants of $CO_2$ emissions. Among these factors, economic structure has been proven to be the most significant negative factor affecting carbon emissions (Li et al., 2021), while energy efficiency improvements effectively inhibits carbon emission growth (Li et al., 2022). In addition, $CO_2$ emissions can be affected by CET, which involves converting carbon emissions into cost constraints (Zhang et al., 2020). Some studies incorporate low-carbon policies

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**Table 1 Practice of early green transformation in foreign countries.**

| Region | Transformation approach |
|---|---|
| Ruhr, Germany | The region prepared master development plans, improved infrastructure, promoted industrial structure diversification, transformed traditional industries and developed new industries to get out of the dilemma of high resource dependence. |
| Kitakyushu, Japan | The region carried out nine coal policy revisions, adjusted the structure of the coal industry, and focused on infrastructure construction and employee training to create favorable conditions for the transformation and development of coal-producing regions. |
| Lorraine, France | The region undergoes industrial transformation, closing down high-cost, costly and polluting enterprises, transforming traditional industrial industries with high technology, and helping enterprises with low-energy and clean production. |
| Houston, USA | The region developed an industrial development path of developing leading industries, driving related industries, and improving basic industries to extend the oil industry chain while extracting oil, and timely cultivate and develop alternative industries. |

into urban construction evaluation (Ren and Liu, 2023) or employ simulation models to examine the impact of different carbon trading mechanisms (Yu et al., 2021). Zheng et al. (2023). explored whether and to what extent carbon markets function in developing countries. Their findings indicated that China's pilot carbon trading policy effectively reduced carbon emissions by about 38.61% Tang et al. (2021) investigated the effectiveness and heterogeneity of emission trading schemes from regional and industrial perspectives. It is important to note that all these factors exhibit spatial characteristics that can be used to forecast trends in urban carbon emissions.

Existing research primarily focuses on elucidating the concept of urban green transformation and devising strategies for its attainment. However, there are some limitations that necessitate attention. Firstly, the analysis of cities' dynamic development and intrinsic interconnectedness during the implementation process remains insufficient. While a few studies have undertaken phased transformation planning, it is imperative to consider cities as dynamic and complex systems that undergo economic and social evolution. Adopting a systemic perspective would furnish a more comprehensive understanding of the green transformation process. Secondly, the research on the factors that influence carbon emissions in cities often confines itself to energy consumption or CET at a singular level. This approach fails to adequately capture the interconnectedness of these factors. In addition, the prevalent reliance on empirical analysis using econometric models may not effectively depict long-term changes and nonlinear relationships in carbon emissions. Thirdly, while reducing carbon emissions is a crucial aspect of urban green transformation, many studies overlook the carbon flow underpinning it when examining economic, environmental, and resource systems. Consequently, the impact of carbon emissions on urban green transformation oftentimes goes unnoticed. In conclusion, further research should consider the dynamic nature of cities, delve into the interconnectedness of factors influencing carbon emissions, and pay attention to the role of carbon flow in the realization of urban green transformation.

In view of aforementioned research limitations, this study seeks to address these gaps through the following contributions: (1) Considering the developmental stage of Shanghai and taking into account factors that influence carbon emissions, such as energy consumption and carbon emission reduction policy, this study adopts a systemic perspective by dividing the urban system into sub-dimensions including industrial economy, environmental energy, social population, technological level, and carbon emission reduction policy. Through this analysis, the study aims to uncover the causal relationships and long-term dynamic changes in the process of urban green transformation within the context of carbon emission reduction targets. (2) This study also conducts a comprehensive assessment of carbon dioxide production from fossil energy sources in Shanghai, providing valuable insights into recent trends in the city. (3) To further examine the process of urban green transformation and carbon emissions reduction, this study develops a system dynamics model. Various scenarios are constructed based on different development objectives, allowing for a thorough exploration of the urban green transformation process and the achievement of carbon emissions peaks. The findings from these scenarios can serve as a scientific basis for future urban development planning. In summary, this study aims to overcome the limitations of previous research by providing a systemic and dynamic analysis of urban green transformation in Shanghai, with a particular focus on carbon emissions reduction. By utilizing a system dynamics model and conducting scenario analysis, this study intends to contribute to the field of urban planning and offer valuable insights for sustainable urban development.

The focus of this paper is to understand the causal relationships and dynamic changes in the process of urban green transformation, provide insights into carbon dioxide emissions in Shanghai, and provide a framework for exploring different scenarios of urban green transformation and carbon peak. The study is divided into the following sections: "Research method and system analysis" section presents the research design process including research framework and systemic factors analysis. "Model construction" section describes the process of constructing the system dynamics model. "Analysis and result" section provides the scenario design and results of simulation. Finally, in "Conclusion and implication" section, the conclusions and implications of the study are given.

## Research method and system analysis

To comprehensively comprehend the intricacies of urban green transformation, adopting a systemic perspective to observe the holistic changes in the city is crucial. This entails considering the transformation of economic industries and energy utilization, as well as analyzing the nonlinear relationships and causal feedback between them using a systems thinking approach. One effective method for capturing the dynamic changes and nonlinear structural characteristics of systems is the system dynamics (SD) method. Specifically, urban carbon dioxide emissions, which are influenced by industrial energy consumption, are regulated by urban CET policies. Given the involvement of multiple urban subsystems, the application of system dynamics becomes a valuable tool for studying the process of urban green transformation. Scholars have begun to use SD model to predict the impact of different transformation conditions on future development. For instance, Lee et al. (2021) developed a SD model that considers the relationships between variables such as population, building area, industry, and the environment. Similarly, Wang et al. (2023) proposed a SD model of urban transportation system to examine the impacts of different strategies on $CO_2$ emission reduction as well as the economic benefits to the environment. By analyzing the feedback characteristics of causal relationships within the system, the evolution of carbon emissions in the context of urban green transformation can be effectively observed.

Professor Forrester (1961) laid the scientific foundations for SD in his seminal work, *Industrial Dynamics*, published in 1957, where he elucidated its principles and typical applications. This study follows the general steps of SD method, which involve determining the system boundary, delineating the internal structure and drawing a causal diagram, identifying system factors and their relationships, establishing a model in the form of a system flow chart, and conducting simulation analysis of future urban green transformation with respect to carbon emissions through parameter control (Bao et al. 2023).

**System boundary determination of research areas**. China's vast territory encompasses cities with diverse resource endowments and levels of economic development. Green transformation must be tailored to local conditions. This study examines the process of urban green transformation under carbon emission reduction goals, using Shanghai as a case (Fig. 1). Shanghai is a core city in the Yangtze River Economic Belt and one of China's national central cities. It has been continuously building an ecological civilization in recent years. The city's 14th Five-Year Plan outlines its goal to reach carbon peaking five years ahead of the national target (Niu et al. 2022). To this end, Shanghai launched a pilot carbon emissions trading program in 2013 (Li and Wang, 2021). As a pioneer in urban green development in China, Shanghai's early achievement of green development will position it as a
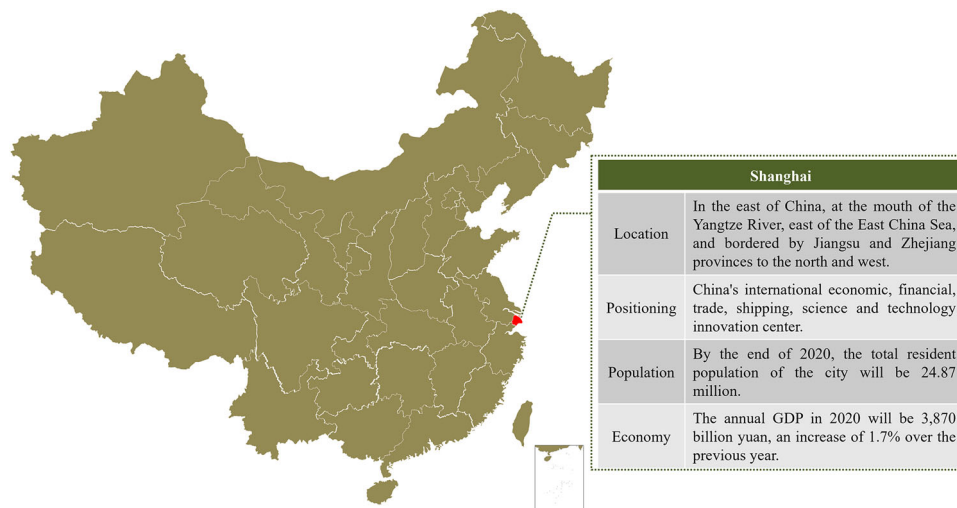
**Fig. 1 Overview of Shanghai.** It provides the geographical location and economic population situation.

trailblazing city that inspires and propels other cities towards green transformation.

Clarifying the urban system boundary excludes unrelated content. In terms of spatial boundaries, this study defines the urban system based on administrative divisions. By the end of 2022, Shanghai comprises 107 streets, 106 towns, and 2 townships, totaling 215 township-level divisions. In terms of temporal boundaries, this study focuses on key time points related to carbon emission reduction and green transformation in Shanghai. Since the study involves the participation of the CET policy subsystem, it is important to note that Shanghai became one of the pilot cities for urban CET in 2013, with steady development since the establishment of the carbon quota system in 2014. Therefore, the starting point of the study is set as 2014 and analyzes existing data from 2014 to 2019. Furthermore, one of the research objectives is to assess Shanghai's achievement of the carbon peak target before 2025, as proposed in the 14th Five-Year Plan. To ensure the reliability of the predictive results, a large time span is avoided. Hence, the study sets 2025 as the end point and uses a yearly time step to observe the dynamic changes in Shanghai's green transformation development from 2020 to 2025.

**Research framework analysis**. The literature on urban green transformation highlights the influence of the urban industrial economy, environmental energy, technological level, social population, and policy support. The industrial economy reflects the basic structure of urban economic development, while the environmental energy reflects the natural reserves and utilization in the city. Technological level acts as a means and tool, either promoting or inhibiting system development, while social population provides necessary support (Zheng et al. 2023). Policy support, on the other hand, provides external impetus (Luo et al. 2023). Meanwhile, the study of urban carbon reduction mainly focuses on energy consumption and carbon trading policies. Fossil energy consumption is the direct sources of carbon dioxide production, while CET policies establish carbon markets and facilitate the trading of carbon emission rights, providing important constraints to reduce actual carbon dioxide emissions. As shown in Fig. 2, carbon reduction is a development requirement for urban green transformation, and green transformation is a vital approach to achieving carbon reduction. The two are connected through the carbon flow, promoting coordinated

development and achieving the target of green development with carbon peaking.

The causal diagram is a qualitative analysis tool for describing the causal relationship between factors. This study divides the urban system into the industrial economy, environmental energy, technological level, social population, and carbon trading policy. To capture the flow of factors in the process of carbon generation to emission as factors flow, we construct the system causal diagram and distinguish subsystems by color (Fig. 3). The causal diagram can be further categorized into positive and negative feedback loops based on the loops present. The curves in the diagram represent the interconnections between factors within each subsystem. "+" represents a positive correlation, while "-" represents a negative correlation. In this paper, the constructed causal diagram consists of a total of fifteen feedback loops that constitute the urban green transformation system. The major feedback loops are as follows.

(1) GDP → (+) Secondary industry output value → (+) Industrial energy consumption → (+) Production energy consumption → (+) Total energy consumption → (+) Carbon emissions → (+) Carbon emission cost → (-) Enterprise profit → (+) GDP

(2) GDP → (+) Primary and tertiary industry output value → (+) Non-industrial energy consumption → (+) Production energy consumption → (+) Total energy consumption → (+) Carbon emissions → (+) Carbon emission cost → (-) Enterprise profit → (+) GDP

Loops (1)–(2) highlight the impact of industrial structure on the system. GDP growth is linked to an increase in output values. The output value of primary and tertiary industries mainly depends on non-industrial energy consumption. The output value of the secondary industry mainly depends on industrial energy consumption. Under the common influence of domestic energy consumption, the total amount of energy consumption continues to increase. The enterprises' cost of controlling carbon dioxide also increases accordingly, which has a negative impact on GDP.

(3) Total energy consumption → (+) Fossil fuel carbon emissions → (+) Carbon emissions → (+) Carbon emission cost → (-) GDP → (+) Industrial output value → (+) Total energy consumption

(4) Total energy consumption → (+) Non-fossil fuel carbon emissions → (+) Carbon emissions → (+) Carbon emission cost → (-) GDP → (+) Industrial output value → (+) Total energy consumption
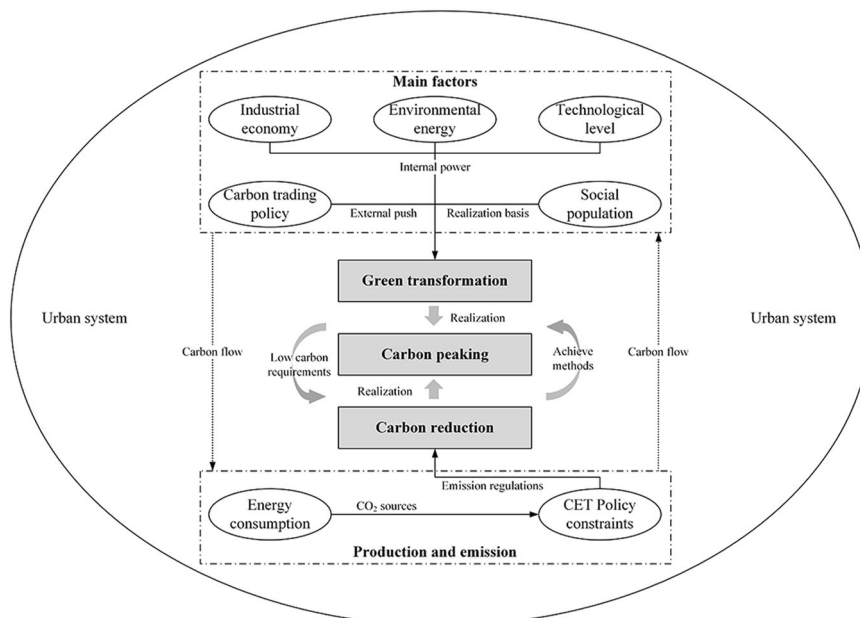
**Fig. 2 The relationship between urban green transformation and carbon emissions.** It illustrates the relationship between green transformation influenced by factors such as industrial economy, environmental energy, technological level, social population, and policy support in the urban system, and carbon emissions reduction related to energy consumption and carbon trading policies. This relationship is achieved through carbon flow to attain carbon peak.
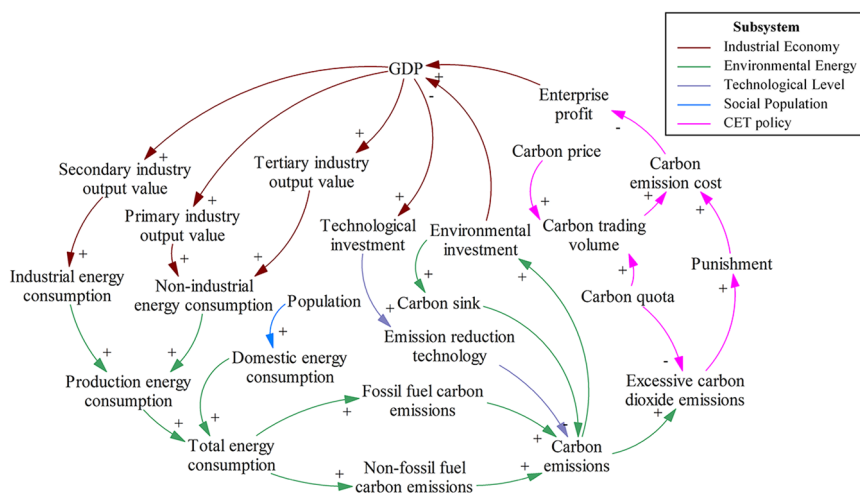


**Fig. 3 System causal loop diagram.** It depicts the causal relationships between various factors influencing urban green transformation. Brown represents the industrial economy subsystem, green represents the environmental energy subsystem, purple represents the technological level subsystem, blue represents the social population subsystem, and pink represents the carbon trading policies subsystem.

Loops (3)–(4) highlight the impact of energy structure on the system. Total energy consumption is composed of fossil and non-fossil fuel consumption. Fossil fuels have strong pollution and high carbon emission coefficients. Clean energy such as natural gas and other renewable energies have smaller carbon emission coefficients and produce less carbon dioxide accordingly. Carbon dioxide of both types determine the level of carbon emission costs and extends to influencing urban GDP growth, acting on industrial output values and cycling back to energy consumption.

(5) Carbon emissions → (+) Environmental investment → (-) GDP → (+) Technological investment → (+) Emission reduction technology → (-) Carbon emissions

Loop (5) highlights the impact of carbon reduction technology on the system. In the face of increasing $CO_2$ emissions, the government invests more in environmental governance, leading

to an increase cost and a negative impact on economic growth, while the cities' scientific and technological level is closely related to GDP. Although enterprises produce a large volume of $CO_2$ during energy consumption, through the application of emission reduction technology, actual emissions are effectively reduced.

(6) Carbon emissions → (+) Excessive carbon dioxide emissions → (+) Punishment → (+) Carbon emission cost → (-) Enterprise profit → (+) GDP → (+) Industrial output value → (+) Total energy consumption → (+) Carbon emissions

Loop (6) highlights the impact of CET policies on the system. An important content of policies is to punish enterprises for excessive carbon dioxide emissions based on their carbon dioxide quota. The fines paid by enterprises can be regarded as part of their carbon emission costs. Increased costs reduce enterprise profits and affect regional economic growth, which in turn affects

**Table 2 Variables and equations of Shanghai green transformation system.**

| Variables | Unit | Properties | Equations |
|---|---|---|---|
| GDP | billion | $L$ | = INTEG(Incremental GDP,25269.8) |
| Forestry areas | km$^2$ | $L$ | = INTEG(Incremental forestry areas,1033.6) |
| Total carbon trading quota | billion tons | $R$ | = INTEG(The change in carbon trading quota, 1.6) |
| Technology investment ratio | % | $A$ | = (((Time-2013)*0.1048 + 3.1802)*0.01)*100 |
| Emission efficiency | % | $A$ | = Technology Investment*0.009 + 52.1023 |
| Excessive carbon dioxide emissions | million tons | $A$ | = Carbon emissions - Total carbon trading quota*10000 |
| Carbon sink | million tons | $A$ | = Forestry areas * Forestry carbon sink coefficient/10000 |
| Punishment price | RMB/ton | $A$ | = Carbon trading price *3 |
| Maximum fine | billion | $A$ | = Total carbon trading quota * Punishment price |
| Industrial energy consumption | million tons of standard coal | $A$ | = Secondary industry output value*(−0.1883) + 7346.71 |
| Non-industrial energy consumption | million tons of standard coal | $A$ | = Tertiary industry output value *0.133908–2.67798* Primary industry output value + 3012.24 |
| Total energy consumption | million tons of standard coal | $A$ | = Production energy consumption + Domestic energy consumption |
| Production energy consumption | million tons of standard coal | $A$ | = Non-industrial energy consumption + Industrial energy consumption |
| Domestic energy consumption | million tons of standard coal | $A$ | = Per capita domestic energy consumption * Total population*0.001 |
| Fines | billion | $A$ | = IFTHENELSE (Excessive carbon dioxide emissions <0, 0, IFTHENELSE (Excessive carbon dioxide emissions < (Maximum fine/Punishment price*10000), Punishment price* Excessive carbon dioxide emissions *0.0001, Maximum fine)) |
| Birth rate | ‰ | $A$ | = WITHLOOKUP (Time, ([(2014,0) -(2025,0.01)], (2014,0.00835), (2015,0.00752), (2016,0.009), (2017,0.0081), (2018,0.0072), (2019,0.007), (2022,0.008), (2025,0.0068))) |
| In-migration population | million people | $A$ | = WITHLOOKUP (Time, ([(2014,0) -(2025,15)], (2014,11.55), (2015,11.61), (2016,11.25), (2017,11.85), (2018,13.75), (2019,13.69),(2025,15))) |
| The proportion of secondary industry output value in GDP | – | $A$ | = WITHLOOKUP (Time, ([(2014,0) -(2025,0.5)], (2014,0.330), (2015,0.317), (2016,0.304), (2017,0.292), (2018,0.280), (2019,0.276), (2020,0.270), (2021,0.266), (2022,0.262), (2023,0.258), (2025,0.252))) |
| The proportion of non-fossil fuel energy consumption | – | $A$ | = WITHLOOKUP (Time, ([(0,0) -(3000,10)], (2014,0.11), (2015,0.12), (2016,0.13), (2017,0.14), (2018,0.15), (2019,0.16), (2025,0.18))) |
| Per capita domestic energy consumption | tons of standard coal/person | $A$ | = WITHLOOKUP (Time, ([(2014,0) -(2025,600)], (2014,474.16), (2015,505.7), (2016,489.27), (2017,500.54), (2018,529.65), (2019,528.92), (2025,524.2))) |
| Carbon trading price | RMB/ton | exogenous | = WITHLOOKUP (Time, ([(2014,0) -(2025,60)], (2014,39.9997), (2015,20.7483), (2016,5.2343), (2017,23.2841), (2018,28.9083), (2019,41.4464), (2025,87))) |

urban total carbon emissions through factors such as energy consumption and technological investment.

**Research subjects and main factors**. As shown in Fig. 3, the causal relationships among industrial economy, environmental energy, social population, technological level, and CET policy constitute the urban green transformation system under carbon emission reduction goals. Drawing on the research by Du et al. (2018), the variable selection starts with urban GDP, which can be divided into primary, secondary, and tertiary industries based on the industrial structure. Each industry is then categorized into industrial and non-industrial energy consumption types, collectively constituting productive energy consumption. Combining with domestic energy consumption, the total urban energy consumption is obtained. The energy consumption is then subdivided according to the energy structure to calculate the carbon dioxide emissions for each fossil energy source. Taking into account technology utilization efficiency and forestry carbon sinks, the actual carbon emissions are derived. Moreover, the carbon emission quotas imposed by urban CET policies are applied to production enterprises. Measures are taken based on the quota ratio and excess carbon emissions to ensure

compliance. Ultimately, these actions have feedback impacts on urban GDP. These variables have been discussed in the research by Ye et al. (2021). The system model depicts the interrelationships and causal feedback between different variables, thereby reflecting the influences on urban green transformation from carbon generation to emission. This model serves as a basis for the design of scenario plans in subsequent sections.

Table 2 presents the variables and equations of the Shanghai low-carbon green transformation system dynamics model. It provides a comprehensive overview of the units of the variables and categorizes them as $L$-state factors, $R$-rate factors, $A$-auxiliary factors, and exogenous factors. Regression analysis is employed to examine variables exhibiting significant linear correlations, such as industrial energy consumption and the technology investment ratio. For variables without significant linear correlation, a table function is used for analysis, such as birth rate and carbon trading price.

In order to know exactly the level of $CO_2$ production, a common accounting method is to use the carbon coefficients of energy sources in the IPCC National Greenhouse Gas Emissions Inventory Guidelines. According to the *China Energy Statistical Yearbook*, regional terminal energy consumption is classified into eight categories: coal, crude oil, coke, gasoline, kerosene, fuel oil,

**Table 3 CO$_2$ emission coefficients of energy.**

| CO$_2$ emission coefficients | Coal | Coke | Crude oil | Fuel oil | Gasoline | Kerosene | Diesel | Natural gas |
|---|---|---|---|---|---|---|---|---|
| kgCO$_2$/kg | 1.9003 | 2.8604 | 3.0202 | 3.1705 | 2.9251 | 3.0179 | 3.0959 | 2.1622 |

**Table 4 CO$_2$ production from energy consumption in Shanghai Unit: million tons.**

| Time (Year) | Coal | Coke | Crude oil | Fuel oil | Gasoline | Kerosene | Diesel | Natural gas | Total |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | 9303 | 1873 | 9674 | 1688 | 1360 | 1698 | 1763 | 1123 | 28483 |
| 2015 | 8985 | 1804 | 10899 | 1778 | 1544 | 1739 | 1713 | 1201 | 29662 |
| 2016 | 8790 | 1708 | 10675 | 1866 | 1768 | 1741 | 1844 | 1226 | 29617 |
| 2017 | 8699 | 1694 | 10755 | 1938 | 1969 | 1704 | 2132 | 1291 | 30183 |
| 2018 | 8301 | 1778 | 10787 | 1967 | 2112 | 1690 | 2086 | 1403 | 30123 |
| 2019 | 7903 | 1820 | 10873 | 1967 | 2266 | 1732 | 2086 | 1516 | 30162 |

diesel, and natural gas. The amount of CO$_2$ produced by fossil energy in Shanghai is calculated as follows(Guo et al. 2012).

$$Q = \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} \alpha_i \beta_i$$

Where $Q$ represents the total volume of CO$_2$ produced by energy consumption in Shanghai. The production of the $i$-th fossil energy is denoted by $\alpha_i$, the carbon emission coefficient of the $i$-th fossil energy is denoted by $\beta_i$, and the consumption of the $i$-th fossil energy is denoted by $C_i$. Table 3 displays the CO$_2$ emission coefficients for various types of energy.

Without taking into account the impact of technology and other factors on carbon emissions, Table 4 shows the CO$_2$ produced by energy consumption in Shanghai from 2014 to 2019.

### Model construction
**Data collection**. In this study, the data on economics, population, and energy are sourced from the *China Urban Statistical Yearbook*, *China Energy Statistical Yearbook*, and *Shanghai Statistical Yearbook* for the years 2015 to 2020. The environmental data, such as forestry area, are obtained from the *Shanghai Municipal National Economic and Social Development Statistical Bulletin* for each year. The data on total carbon trading quotas and free quota are obtained from the *China Carbon Emissions Trading Network*. The data on carbon trading amount, carbon trading price, and auction price are sourced from the *Shanghai Environment and Energy Exchange*. Variables that are not directly available in the statistical yearbooks are calculated indirectly. Furthermore, for variables with missing or abnormal original data, appropriate data processing techniques such as mean or regression methods are employed.

**Flow chart drawing**. The system flow chart is derived by analyzing the relationships between factors in the causality loop diagram, as described by Crielaard et al. (2022). As shown in Fig. 4, the variables of industrial economy, environmental energy, social population, technological level, and CET policy together comprise the system. By incorporating the equations presented in Table 1 into the system flow chart and using VENSIM to run the urban system, we have constructed a SD model. This model forms the basis for designing scenarios in subsequent sections.

**Validity test**. The validity test of the SD model is assessed through a structure test and a historical test. The structure test verifies the reasonableness of the variables and equations in the model, and the VENSIM software has confirmed that the structure of the model is effective. The historical test involves comparing the simulation results with historical data and assessing

the accuracy of the model based on the error range. Generally, if the absolute value of the error falls within 20%, the model is considered to be highly credible (Qian et al. 2023).

In this study, the selection of GDP, total energy consumption, technology investment, carbon emissions, and total population as observed variables within each subsystem reflects their fundamental importance. These variables have a significant influence on the accuracy of other variables within their respective subsystems. For example, the value added of each industry is derived by multiplying the GDP by a pre-determined industry proportion coefficient. Energy consumption in different sectors is determined by multiplying the total energy consumption by the energy proportion structure. The efficiency of emissions reduction and absorption is dependent on technological investment. Policies addressing excessive carbon dioxide emissions are constrained by regional carbon emission levels. The level of energy consumption in daily life is influenced by the total population. By ensuring the high accuracy of these observed variables, the potential errors of other variables in the subsystems can be, to some extent, controlled. The test results are shown in Table 5.

The absolute errors for these five variables over the past six years are all below 5%, indicating that they fall within the acceptable error threshold. This demonstrates that the model is highly accurate and capable of effectively representing the actual system dynamics.

### Analysis and result
**Scenario design**. To assess changes in the system, it is necessary to identify the parameters from various variables that largely determine the operational state of Shanghai's SD system and then make appropriate adjustments. Parameters are usually human-adjusted variables. In this study, parameters are identified through sensitivity analysis. We set the selected variable according to its value range while other variable values remained unchanged. If the simulated results varied greatly, then it indicates that the variable is sensitive and can be treated as a parameter for designed scenarios, calculated as follows.

$$S = \left| \frac{\Delta y}{y} \cdot \frac{x}{\Delta x} \right|$$

Where $S$ represents the sensitivity of factor $y$ to $x$, $\Delta x$ and $\Delta y$ represent the changes in the variables. Then $S$ can be expressed as the change magnitude of $y$ when $x$ changes by 1%, and a larger $S$ indicating the higher sensitivity. Since more than one $y$ is selected, the mean value of $S$ is calculated for each $x$ to make the sensitivity
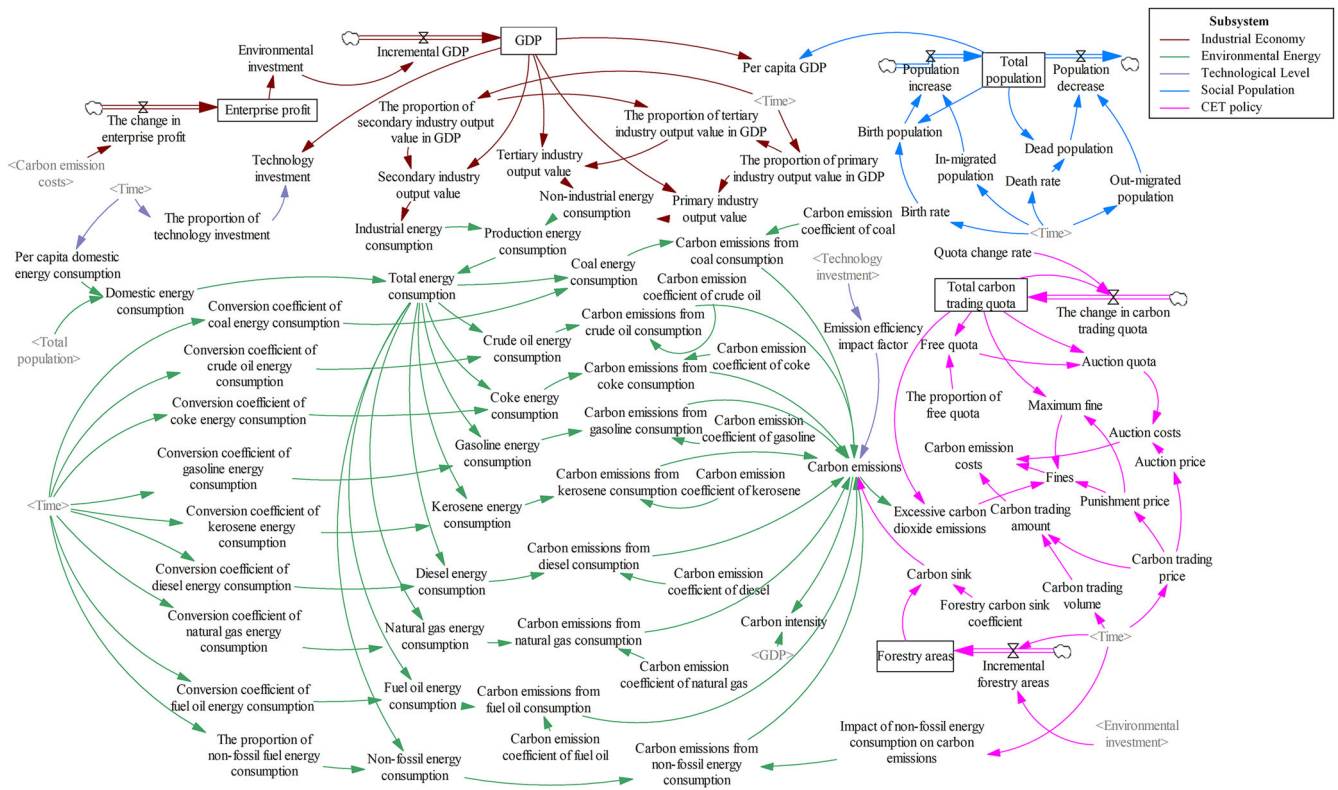
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**Fig. 4 System flowchart for urban low-carbon green transformation.** It illustrates the relationships between different types of variables. Brown represents the industrial economy subsystem, green represents the environmental energy subsystem, purple represents the technological level subsystem, blue represents the social population subsystem, and pink represents the carbon trading policies subsystem.

**Table 5 Validity test results of SD model.**

| Time (Year) | | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | Averages |
|---|---|---|---|---|---|---|---|---|
| GDP (billion) | Simulated | 25270 | 28093 | 30809 | 33466 | 35998 | 38339 | |
| | Real | 25270 | 26887 | 29887 | 32925 | 36012 | 38155 | |
| | Error | 0.00% | 4.49% | 3.09% | 1.64% | −0.04% | 0.48% | 1.62% |
| Technology Investment (billion) | Simulated | 830 | 952 | 1077 | 1205 | 1333 | 1460 | |
| | Real | 862 | 936 | 1049 | 1205 | 1358 | 1526 | |
| | Error | −3.70% | 1.74% | 2.64% | −0.03% | −1.81% | −4.30% | 2.37% |
| Total energy consumption (million tons of standard coal) | Simulated | 10658 | 10959 | 11101 | 11326 | 11716 | 11952 | |
| | Real | 10640 | 10931 | 11242 | 11382 | 11454 | 11696 | |
| | Error | 0.17% | 0.26% | −1.26% | −0.49% | 2.29% | 2.19% | 1.11% |
| Carbon emissions (million tons) | Simulated | 20241 | 21323 | 21537 | 22197 | 22266 | 22750 | |
| | Real | 20770 | 20856 | 20940 | 20148 | 21318 | 22214 | |
| | Error | −2.55% | 2.24% | 2.85% | 10.17% | 4.45% | 2.41% | 4.11% |
| Total population (million people) | Simulated | 2426 | 2439 | 2453 | 2469 | 2483 | 2497 | |
| | Real | 2426 | 2415 | 2420 | 2418 | 2424 | 2428 | |
| | Error | 0.00% | 0.99% | 1.37% | 2.10% | 2.44% | 2.85% | 1.62% |

results more stable.

$$\overline{S} = \frac{S}{n}$$

Where $n$ is the number of $y$, the mean sensitivity $\overline{S}$ of all selected $y$ to a certain $x$ is calculated. When $\overline{S}$ is lower than 5%, the system is considered to be insufficiently sensitive to $x$. When $\overline{S}$ is higher than 5%, $x$ is considered to be a parameter affecting the system.

GDP, carbon emissions, total energy consumption, and carbon emission cost were chosen as $y$. The sensitivity results in Fig. 5 were obtained by calculating the independent parameters, except for the joint parameters such as industrial structure and energy

structure, which have high sensitivities. It can be seen that $\overline{S}$ is greater than 5%, and the parameters that have a greater impact on Shanghai's green transformation system are, in order of importance: the proportion of technology investment, the carbon trading price, the punishment price, the proportion of free quota, and per capita domestic energy consumption.

Under the 14th Five-Year Plan for Comprehensive Energy Conservation and Emission Reduction planning in Shanghai, we have developed six scenarios to compare the impact on urban green transformation. A natural development scenario is set based on the city's current state. An industrial structure adjustment scenario is set to reduce the proportion of traditional

high-energy-consuming industries, and increase the proportion of tertiary industries. An energy structure adjustment scenario is set to promote the transformation of fossil energy consumption to non-fossil energy consumption. An environmental technology advances scenario is set to accelerate technological innovation by increasing investment, and improve domestic energy efficiency. A CET policy adjustment scenario is set to reasonably regulate carbon quotas, and incentivize and constrain enterprise carbon dioxide emissions. Without considering the priority of each scenario, a coordinated development scenario is set by comprehensively considering the impact of industrial structure, energy structure, environmental technology and CET policy on Shanghai's green transformation process.

Based on historical data from 2014 to 2019, this study conducted Logistic analysis to estimate the values of various
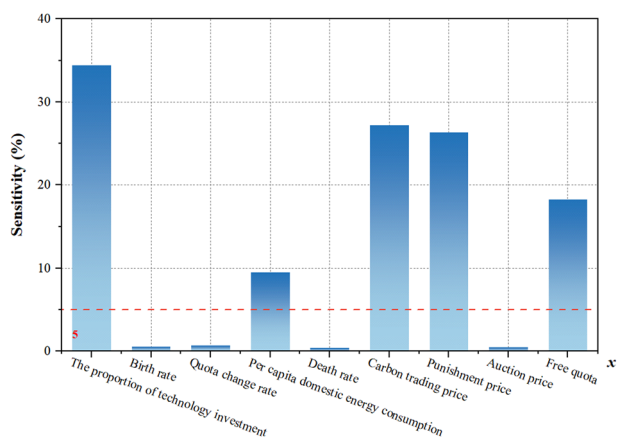


**Fig. 5 Sensitivity analysis results.** It shows the impact of each parameter on Shanghai's green transformation. Parameters with values higher than 5% have a significant impact, while those below 5% have a minor impact.

parameters for the year 2025. However, it was observed that the linear trends of certain parameters, such as the proportion of tertiary industry and the proportion of coal energy consumption, did not align with the actual situation in Shanghai. Therefore, these parameters were treated as idealized states in Scenario II and Scenario III. To improve the realism of the results, a trend analysis of the industrial and energy structures was conducted after applying logarithmic transformations to the time variable. This analysis was combined with information from the Shanghai Clean Air Action Plan (2023–2025), the Shanghai Carbon Market Report, the Residential Energy Consumption Index (RECI), and predictions from domestic experts regarding the remaining parameters. These inputs were used to obtain adjusted values for the year 2025. Furthermore, the punishment price was determined based on relevant carbon trading policies in China and is simulated to be 3 or 4 times the carbon trading price. To facilitate a comparison within a reasonable range, this study used three times the carbon trading price as the predicted price under natural conditions, and four times as the adjusted price. The predicted and adjusted values for each parameter in 2025 are presented in Table 6.

**Simulation analysis**. Based on the above scenarios, all parameters in the system change accordingly by adjusting the values of a specific scenario. The simulation results are shown in Fig. 6. As GDP reflects the city's overall economic development, carbon emission cost represents the economic impact on enterprises under carbon trading policy, total energy consumption corresponds to energy conservation, carbon emissions correspond to emission reduction, and carbon intensity is a critical indicator of the degree of balance, GDP, total energy consumption, carbon emissions, carbon intensity, and carbon emission cost are selected as the five variables for result analysis. The simulation results are summarized in Table 7.

**Table 6 Adjustment values of parameters in scenarios design.**

| Scenarios | I<br>Natural Development | II<br>Adjustment of industrial structure | III<br>Adjustment of energy structure | IV<br>Advances of environmental technology | V<br>Adjustment of CET policy | VI<br>Coordinated Development |
|---|---|---|---|---|---|---|
| The proportion of secondary industry output value in GDP | 25.2% | **19.3%** | 25.2% | 25.2% | 25.2% | **19.3%** |
| The proportion of tertiary industry output value in GDP | 74.6% | **80.5%** | 74.6% | 74.6% | 74.6% | **80.5%** |
| The proportion of coal energy consumption | 35.3% | 35.3% | **30.0%** | 35.3% | 35.3% | **30%** |
| The proportion of natural gas energy consumption | 14.5% | 14.5% | **21.2%** | 14.5% | 14.5% | **21.2%** |
| The proportion of non-fossil energy consumption | 18.0% | 18.0% | **20.0%** | 18.0% | 18.0% | **20.0%** |
| The proportion of technological investment | 4% | 4% | 4% | **4.5%** | 4% | **4.5%** |
| Per capita domestic energy consumption | 524.2 | 524.2 | 524.2 | **500** | 524.2 | **500** |
| The proportion of free quota | 97% | 97% | 97% | 97% | **90.0%** | **90.0%** |
| Carbon trading price | 66 | 66 | 66 | 66 | **87** | **87** |
| Punishment price | 198 | 198 | 198 | 198 | **348** | **348** |

The bold values represent the adjusted parameter values specific to each scenario.
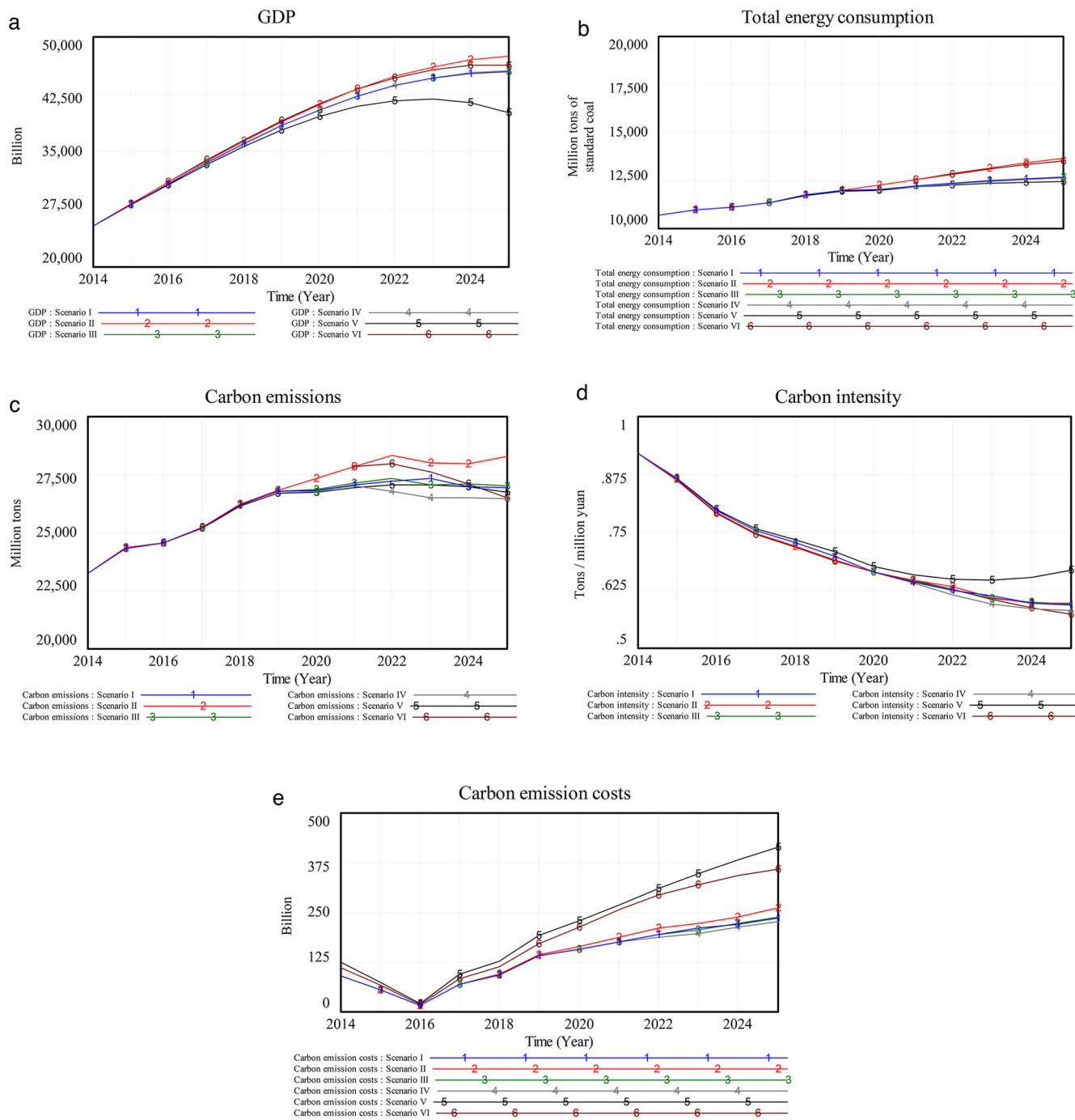
**Fig. 6 Simulation results of Shanghai. a** Simulation results of GDP in Shanghai. **b** Simulation results of total energy consumption in Shanghai. **c** Simulation results of carbon emission in Shanghai. **d** Simulation results of carbon intensity in Shanghai. **e** Simulation results of carbon emission cost in Shanghai.

*Scenario I: Natural development.* Under Scenario I, the parameters maintain their current growth trends. From 2014 to 2025, Shanghai's GDP is expected to increase from 2.527 trillion yuan to 4.5418 trillion yuan. Total energy consumption is projected to rise from 106.58 million tons of standard coal to 126.61 million tons of standard coal. Carbon emissions are estimated to reach their peak in 2023 at 27.31 million tons and gradually decline thereafter. This indicates a decoupling of economic development and carbon emissions, with carbon intensity decreasing from 0.6977 to 0.5928, aligning with Shanghai's goal of peaking carbon emissions by 2025. In addition, the implementation of CET mechanism incurs corresponding emission costs. Since the reform of carbon trading products in 2016, the market has

stabilized, with annual trading volume increasing and emission costs rising year after year.

*Scenario II: Adjustment of industrial structure.* Under Scenario II, the objective is to impact carbon dioxide emissions by altering the proportion of industries in Shanghai. Traditionally, resource-intensive heavy chemical industries have been the dominant drivers of economic growth and major energy consumers. As the share of the secondary industry increases, the energy consumption also rises. Following the adjustment, Shanghai's GDP experiences a notable increase of 203.3 billion yuan compared to Scenario I. However, this economic growth is accompanied by a substantial rise in energy consumption, which is projected to

**Table 7 Summary of simulation results for Shanghai under each scenario.**

| Time (Year) | | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
|---|---|---|---|---|---|---|---|---|
| GDP (billion) | I | 38,339 | 40,411 | 42,171 | 43,585 | 44,616 | 45,235 | 45,418 |
| | II | 38,886 | 41,138 | 43,110 | 44,762 | 46,054 | 46,954 | 47,451 |
| | III | 38,339 | 40,411 | 42,170 | 43,580 | 44,609 | 45,229 | 45,409 |
| | IV | 38,339 | 40,411 | 42,172 | 43,589 | 44,629 | 45,286 | 45,524 |
| | V | 37,807 | 39,573 | 40,885 | 41,666 | 41,835 | 41,316 | 40,039 |
| | VI | 38,978 | 41,203 | 43,099 | 44,604 | 45,665 | 46,234 | 46,276 |
| Total energy consumption (million tons of standard coal) | I | 11,952 | 12,022 | 12,186 | 12,334 | 12,465 | 12,572 | 12,661 |
| | II | 11,974 | 12,247 | 12,539 | 12,833 | 13,122 | 13,398 | 13,655 |
| | III | 11,952 | 12,022 | 12,186 | 12,334 | 12,465 | 12,572 | 12,660 |
| | IV | 11,952 | 12,012 | 12,165 | 12,304 | 12,424 | 12,523 | 12,603 |
| | V | 11,931 | 11,990 | 12,133 | 12,253 | 12,342 | 12,393 | 12,407 |
| | VI | 11,978 | 12,239 | 12,518 | 12,794 | 13,058 | 13,301 | 13,514 |
| Carbon emissions (million tons) | I | 26,750 | 26,801 | 27,035 | 27,207 | 27,310 | 26,970 | 26,924 |
| | II | 26,798 | 27,302 | 27,820 | 28,309 | 27,984 | 27,965 | 28,256 |
| | III | 26,750 | 26,847 | 27,115 | 27,310 | 27,058 | 27,081 | 27,021 |
| | IV | 26,750 | 26,778 | 26,989 | 26,776 | 26,493 | 26,499 | 26,438 |
| | V | 26,703 | 26,728 | 26,918 | 27,026 | 27,041 | 26,945 | 26,741 |
| | VI | 26,806 | 27,332 | 27,856 | 27,952 | 27,582 | 27,103 | 26,503 |
| Carbon intensity (Tons / million yuan) | I | 0.6977 | 0.6632 | 0.6411 | 0.6242 | 0.6121 | 0.5962 | 0.5928 |
| | II | 0.6891 | 0.6637 | 0.6453 | 0.6324 | 0.6076 | 0.5956 | 0.5955 |
| | III | 0.6977 | 0.6644 | 0.6430 | 0.6267 | 0.6066 | 0.5988 | 0.5951 |
| | IV | 0.6977 | 0.6627 | 0.6400 | 0.6143 | 0.5936 | 0.5851 | 0.5807 |
| | V | 0.7063 | 0.6754 | 0.6584 | 0.6486 | 0.6464 | 0.6522 | 0.6679 |
| | VI | 0.6877 | 0.6634 | 0.6463 | 0.6267 | 0.6040 | 0.5862 | 0.5727 |
| Carbon emissions costs (billion) | I | 141 | 156 | 175 | 193 | 210 | 220 | 234 |
| | II | 141 | 163 | 186 | 210 | 222 | 238 | 261 |
| | III | 141 | 157 | 176 | 194 | 206 | 222 | 236 |
| | IV | 141 | 156 | 174 | 186 | 196 | 211 | 225 |
| | V | 191 | 227 | 268 | 308 | 346 | 381 | 413 |
| | VI | 170 | 211 | 255 | 292 | 319 | 341 | 357 |

reach 136.55 million tons of standard coal by 2025. Consequently, the carbon intensity, measured as the amount of carbon dioxide emitted per unit of GDP, remains similar to Scenario I at 0.5955 tons per 10,000 yuan. In this scenario, carbon emissions are expected to fluctuate rather than reach a peak during the forecast period. After reaching the first peak in 2022, carbon emissions initially decrease but then start to rise again. By 2025, carbon emissions will surpass the level of natural development by 13.32 million tons, resulting in carbon emission costs of 26.1 billion yuan. This situation occurs because the tertiary industry dominates Shanghai's economy, and the rapid expansion of emerging industries has led to a swift increase in energy consumption. The shift towards the tertiary sector has also driven led to substantial growth in electricity and refined oil consumption, further contributing to higher carbon emissions. As shown in Fig. 7, despite the industrial structure adjustment, total energy consumption for production actually increases, with non-industrial energy consumption rising more noticeably than industrial energy consumption. This becomes the primary driver of the increase in carbon emissions.

*Scenario III: Adjustment of energy structure.* Scenario III impacts carbon emissions by altering the proportion of energy sources in Shanghai. Coal consumption is a major contributor to carbon emissions in the city's urban development, while the consumption of natural gas and non-fossil energy is relatively low. After adjustment are made, it is projected that by 2025, Shanghai's GDP will increase to 4.5409 trillion yuan, with a total energy consumption of 126.6 million tons of standard coal and a carbon intensity of 0.5951 tons/10,000 yuan. In 2022, carbon emissions are expected to reach a peak of 27.31 million tons, achieving an early peak in carbon emissions. This demonstrates that

optimizing the energy structure can effectively reduce carbon emissions and expedite the attainment of the carbon emission peak. As depicted in Fig. 8, increasing the proportion of clean energy has a noticeable substitution effect in reducing carbon dioxide emissions from coal use. The increase in the share of non-fossil energy does not lead to significant additional carbon emissions. Therefore, efforts should be made to promote the transition from fossil energy to non-fossil energy use, advocate for clean energy utilization, and effectively control the growth of carbon emissions.

*Scenario IV: Advances of environmental technology.* Scenario IV impacts carbon emissions by promoting emission reduction efficiency and domestic energy consumption. Following the adjustments, Shanghai's GDP growth will not be hindered by increased costs and is projected to increase to 4.5524 trillion yuan by 2025. The total energy consumption will reach 126.03 million tons of standard coal, and carbon emissions will peak in 2021 at 26.989 million tons. The carbon intensity will decrease annually to 0.5807 tons/10,000 yuan. Technological advancements also reduce the burden of carbon emission on enterprises, and by 2025, carbon emission costs will be reduced to 22.5 billion yuan. As shown in Fig. 9, the energy consumption and $CO_2$ directly generated by economic production activities will exceed 300 million tons. However, through the utilization of emission reduction technologies, the actual carbon emissions are reduced by almost one-fifth. Compared to natural development, the actual carbon emissions further decrease, highlighting the importance of investing in environmental technologies to reduce urban carbon dioxide. In this scenario, enterprises improve their carbon emission efficiency, reduce excess carbon emissions, increase profits, and offset the expenditure of environmental technology investment in GDP.
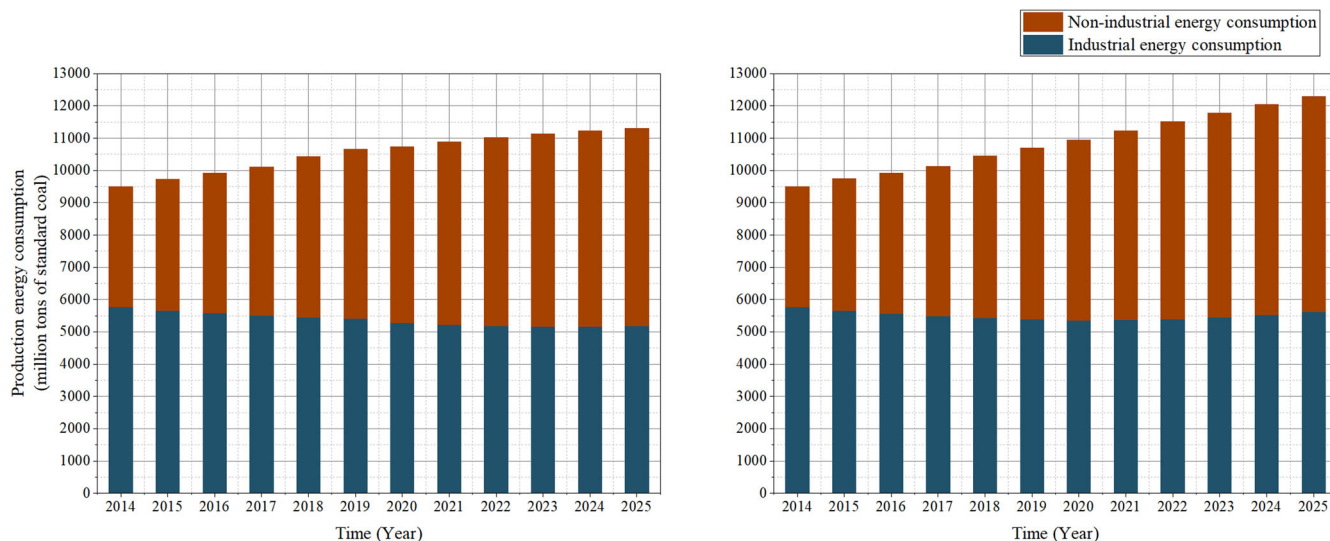
**Fig. 7 The changes in production energy consumption in Shanghai under Scenario II.** Production energy consumption before (left) and after (right) industrial structure adjustment.
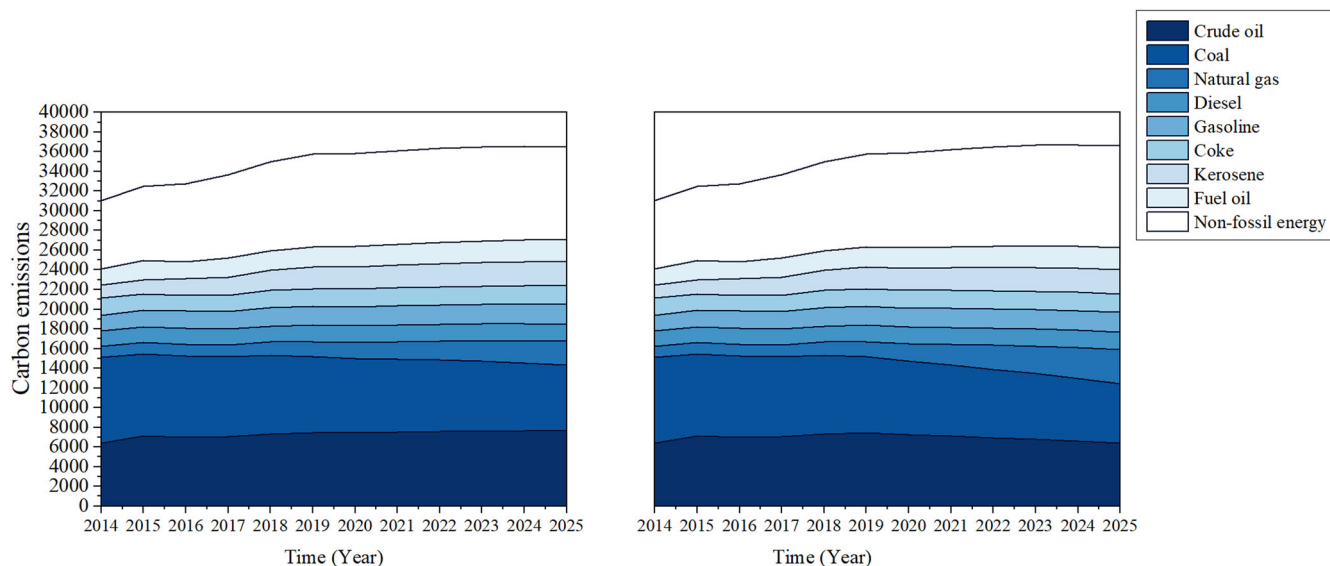


**Fig. 8 The changes in carbon emissions from energy consumption in Shanghai under Scenario III.** Carbon emissions from energy consumption before (left) and after (right) energy structure adjustment.

*Scenario V: Adjustment of CET policy*. Scenario V impacts carbon emissions by adjusting carbon trading costs, punishment, and carbon trading quotas. Following the adjustment, it is projected that Shanghai's GDP will be 4.0039 trillion yuan by 2025, with a total energy consumption of 124.07 million tons of standard coal, and a carbon emissions peak in 2023 at 27.041 million tons. Similar to Scenario II, although the total energy consumption and carbon emissions are restricted, the policy imposes a heavier burden on enterprises. Figure 10 shows that Shanghai's excess carbon emissions still reach ~100 million tons, and the decrease in excess emissions is not significant after the reduction in quota ratio. Compared to natural development, the increase in punishment price results in a significant increase in fines imposed on enterprises. The cost burden slows down the decoupling between the economy and energy consumption, resulting in a carbon intensity of 0.66 tons/10,000 yuan. In this scenario, the decrease in total energy consumption is partly due to the increase in carbon emission costs and the decline in production capacity,

rather than an improvement in energy-saving and emission reduction capabilities.

*Scenario VI: Coordinated development*. Scenario VI focuses on energy conservation and emission reduction while maintaining stable economic development. Through coordinated adjustments, Shanghai's GDP will reach 4.6276 trillion yuan by 2025, with a total energy consumption of 135.14 million tons of standard coal and a carbon intensity decrease to 0.5727 tons/10,000 yuan. The carbon emission costs will be 35.7 billion yuan. In this Scenario, Shanghai's carbon emissions will peak in 2022 at 27.952 million tons and then decline. Under the coordinated development plan, although the adjustment of industrial structure and the implementation of the Carbon Emission Trading (CET) policy may increase carbon dioxide emissions and the cost of emissions, technological progress will also enable enterprises to improve energy efficiency and reduce emission costs. Due to the high degree of optimization of Shanghai's industrial structure, the
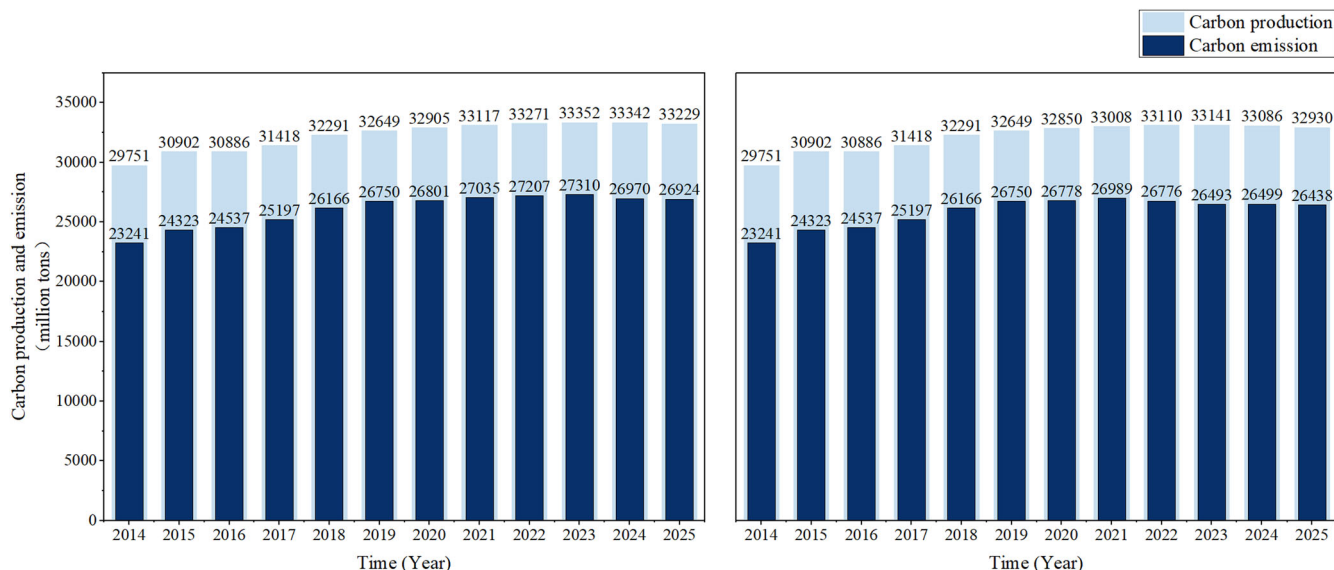
**Fig. 9 The changes in CO$_2$ production and emissions in Shanghai under Scenario IV.** CO$_2$ production and emissions before (left) and after (right) technology investment adjustment.
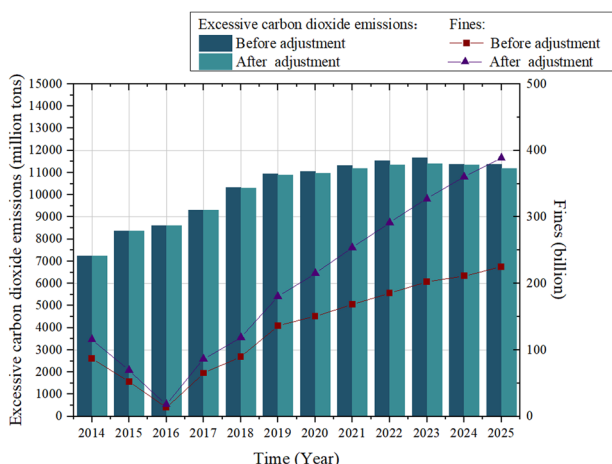


**Fig. 10 The changes in excess carbon emissions and fines in Shanghai under Scenario V.** Excess carbon emissions and fines before and after policy adjustment.

increasing proportion of the tertiary industry, such as the service industry, will lead to higher energy consumption compared to the reduced energy consumption in the secondary industry. Therefore, in the short term, the total energy consumption and carbon emissions required for Shanghai's coordinated development show an increasing trend, which needs to be balanced by long-term technical support provided by energy-saving and emission reduction measures in high-tech industries within the tertiary sector.

Based on predictive results, Shanghai can achieve carbon emissions peaking in 2023 under the premise of sustained economic growth and stable energy consumption, with Scenario I as the benchmark and Scenario VI as the development trend. While previous studies have made predictions about carbon emissions in Shanghai (Zhou et al. 2023), this paper is more aligned with the actual policy requirements of Shanghai and provides a more focused predictive result compared to the conclusion that carbon peaking can be achieved before 2030. In contrast to the isolated adjustment of subsystems, scenario VI

emphasizes the joint action of different influencing factors. It is observed that under scenario VI, although Shanghai achieves carbon peaking one year earlier, GDP, energy consumption as well as carbon emissions all rise, which can be seen as a double-edged sword. The reasons for this can be identified in scenarios II–V. For instance, previous predictions showed a small fluctuation in Shanghai's decoupling index, indicating strong decoupling (Wu and Xu, 2022). However, this study found that adjusting the industrial structure alone seems to increase carbon emissions. Further investigation revealed that Shanghai's economic development highly relies on the tertiary industry, particularly finance and trade, and the actual improvement of emission reduction technology primarily relies on the support of high-tech industries. In addition, energy structure adjustment and environmental technology advances face challenges such as lengthy implementation cycles and high difficulty. In contrast, the implementation effect of policies is evident and can be seen immediately, albeit at a considerable cost. Therefore, considering the characteristics of various scenarios, the study suggests that Shanghai should focus on developing high-tech industries to enhance its economic strength; use technology to optimize carbon emission efficiency; employ energy transformation to optimize energy structure; and utilize policy guidance to constrain enterprise behaviors. Coordinated development in all aspects can accelerate the green transformation process as soon as possible.

## Conclusion and implication

**Conclusions**. This study simulates the green transformation process of Shanghai under the goal of carbon emission reduction using the methods of system dynamics. The process includes three main steps: Firstly, the IPCC general method is used to calculate the carbon dioxide production of Shanghai's main fossil energy from 2014 to 2019. Secondly, the urban system is divided into subsystems. Main factors of the system are identified and a SD model is constructed. Then, parameters are screened and combined through sensitivity analysis. Finally, through scenario simulation, the green transformation situation and carbon emission peaking time of Shanghai are explored. The results provide a reference for low-carbon green transformation in Shanghai. Specifically, the following conclusions can be drawn:

(1) The feasibility of conducting research on urban low-carbon green transformation based on system dynamics (SD) has been established. This study focuses on Shanghai as a case study and divides the urban system into various subsystems, including industrial economy, environmental energy, technology level, social population, carbon trading policy subsystems and uses SD methods to explore the urban green transformation process with the target of carbon emission reduction. The model's validity has been tested and confirmed, providing methodological support for the research.

(2) The main factors influencing the urban green transformation system under the target of carbon emission reduction have been identified. Sensitivity analysis results reveal that, in addition to industrial structure and energy structure, system control parameters include the proportion of technology investment, the carbon trading price, the punishment price, the proportion of free quota, and per capita domestic energy consumption. Therefore, when designing scenarios, emphasis should be placed on optimizing industrial structure, transforming energy sources, improving trading policies, and advancing environmental technologies to enhance the effectiveness of the transformation.

(3) Shanghai is expected to achieve its carbon emission peaking target under its current green transformation status. Assuming no sudden changes occur in the system, Shanghai's total carbon emissions during the green transformation process will peak at 27.31 million tons in 2023 and begin to decline in 2024, achieving its goal by 2025.

(4) Different scenarios have varying impacts on the urban green transformation process and carbon emission peaking. The industrial structure adjustment scenario exhibits a trend of expanding Shanghai's carbon emissions, necessitating continuous optimization to promote the development of high-tech industries. The energy structure adjustment scenario has the most obvious reduction in Shanghai's energy consumption and carbon emissions, emphasizing the promotion of the transformation from fossil energy to non-fossil energy and the adoption of clean energy. The environmental technology advances scenario has the most comprehensive impact on Shanghai, not only reducing emission costs but also lowering energy consumption levels. It serves as a major driver for urban green transformation. The improvement of the carbon trading polices directly affect enterprise behaviors and imposes cost burdens, providing certain auxiliary effect on low-carbon development.

(5) Through the joint adjustment of industrial structure, energy structure, technological level and policy guidance, cities can find suitable green transformation paths and strive to achieve carbon emission peaking as soon as possible. Shanghai should ta For Shanghai, it is crucial to prioritize the development of high-tech industries to enhance its economic strength; leverage environmental technology as a means to improve carbon emission efficiency; utilize energy transformation to optimize energy structure; and take policy guidance as an auxiliary to constrain enterprise behaviors. The results of Shanghai have practical implications for urban green transformation. Most cities in China still have heavily rely on the secondary industry and lack a sufficient level of greening. They should aim to achieve coordinated optimization across multiple aspects according to their development requirements and accelerate the process of urban green transformation.

**Policy implications**. The green transformation of cities is a crucial strategy for achieving carbon reduction targets. By promoting green transformation, carbon emissions can be effectively reduced, environmental quality can be improved, and urban sustainability can be enhanced. It is important to recognize that green transformation is not only an environmental protection action but also a new catalyst for economic development. Based on research findings from Shanghai, cities should prioritize the importance of green transformation and adopt appropriate policy measures to facilitate its comprehensive implementation.

First and foremost, promoting the development of high-tech industries in the context of green transformation is a key direction. The government should increase support for high-tech industries by providing financial assistance and tax incentives. This will encourage enterprises to innovate and develop in the field of green technology, thus accelerating the growth of high-tech industries. Simultaneously, it is crucial to strengthen the oversight of enterprises to ensure their compliance with environmental regulations and standards during green transformation. In addition, establishing a green technology innovation platform can facilitate technical exchange and collaborative research and development among high-tech enterprises. This will promote the innovation and application of green technology, as well as facilitate the integration of high-tech industries with traditional sectors. Furthermore, efforts should be made to enhance the cultivation of high-tech talent by establishing relevant training institutions and research centers. Attracting more talented individuals to engage in the development of green technology industries will contribute to reducing carbon emissions, enhancing resource utilization efficiency, and achieving sustainable urban development.

Secondly, proactive promotion of clean and renewable energy development is pivotal to achieving carbon peaking. In light of the carbon reduction targets, cities must urgently prioritize the development of clean energy. To achieve this objective, the government should increase financial support for clean energy projects and encourage enterprises and individuals to invest in this sector. A range of preferential policies, such as tax and fee reductions for clean energy enterprises, as well as land and electricity subsidies, can be implemented to attract more investment in clean energy.

Lastly, improving the CET mechanism is essential for achieving carbon reduction targets. Currently, carbon trading pilots are concentrated in a limited number of cities. Going forward, more cities should establish robust platforms that provide a fair and transparent trading environment for enterprises and institutions. Such platforms should have efficient trading systems and regulatory mechanisms to ensure fairness and compliance in transactions. Simultaneously, a carbon emission quota allocation mechanism should be established to equitably distribute carbon emission rights based on the production capacity and emission levels of enterprises, incentivizing them to reduce carbon emissions. The government can encourage enterprise participation in carbon trading by establishing incentive mechanisms and providing economic and policy support. For instance, rewards can be granted to enterprises that demonstrate advanced emission reduction practices in the form of carbon emission rights. In addition, tax incentives for carbon trading can be implemented. It is critical to strengthen the supervision and enforcement of the carbon trading market to address illegal trading and fraudulent activities related to carbon emission rights. Maintaining market order and stability is essential. By improving the carbon trading mechanism, cities can also identify new economic growth opportunities and stimulate green transformation.

To promote green transformation, it is imperative to emphasize coordinated progress within the urban system. Coordinated progress entails collaboration and coordination among various departments, industries, and sectors of society to achieve comprehensive advancement towards carbon reduction goals and green transformation. Government departments at all levels should enhance policy integration and coordination, while avoiding conflicts and duplications. In addition, close cooperation

with pertinent departments and industries should be pursued to jointly formulate and implement policies and measures for carbon reduction and green transformation. This collaborative approach will generate synergistic effects.

In summary, promoting green transformation necessitates government support and supervision, the promotion of high-tech industry development, the advancement of clean and renewable energy, enhancements to the carbon trading mechanism, and coordinated progress within the urban system. The recommendations provided in this paper aim to assist cities in formulating relevant policy measures that promote the achievement of green transformation, carbon reduction, and mutual benefits through sustainable development.

**Limitations and future recommendations**. This study presents a model construction and scenario simulation of urban green transformation systems, using Shanghai as a case study to explore carbon reduction targets. The research aims to provide a systemic perspective on the carbon flow in cities, considering the constraints of energy consumption and carbon emission trading (CET) policies. However, several limitations should be considered in the interpretation of these findings. Firstly, it should be noted that the green transformation strategies and implementation may vary among different cities. The focus of this study on Shanghai limits the generalizability of the findings to other cities at different stages of economic development. Therefore, future research should expand the scope of cities and categorize them based on their development stages to explore and compare the various green transformation paths. Secondly, the calculation of $CO_2$ production in this study only considers major types of fossil fuels, neglecting other sources of emissions. In addition, the selection of variables and their interrelationships in the construction of the system dynamics model might not be sufficiently comprehensive, thus limiting the universality of the model. Future research should incorporate additional factors and variables into the urban system to create a more comprehensive green transformation system dynamics model. Lastly, the scenario settings in this study are based on existing literature or historical data for predicting adjustable variables, which may fluctuate over time and affect the accuracy of future urban development predictions. Therefore, future research should consider employing other methods to design more reliable scenarios to enhance the accuracy of projections.

Therefore, while this study sheds light on the model construction and scenario simulation of urban green transformation systems, there are several limitations that need to be addressed in future research. Expanding the scope of cities, incorporating more factors and variables, and employing alternative scenario design methods are important directions for future investigation.

### Data availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request. The historical data and predicted results used for the study will be presented in the supplementary materials.

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## Informed consent

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