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Original Research

Analysis of CCUS Challenges in the Yangtze River Delta Region, China

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Abstract

In the context of dual carbon goals, various regions in China are accelerating the development of CCUS technologies and projects. Researching the development status and paths of each region is conducive to promoting the scientific and rational layout of CCUS projects. It can promote efficient energy conservation and emission reduction so as to reduce the destruction of the ecological environment and promote China's dual carbon goals. In this paper, we take the Yangtze River Delta (YRD) region as an example to analyze the basic situation of CCUS technologies and projects from a macroscopic perspective. On this basis, we try to establish a CCUS project location model for the region. First, we focus on discussing the carbon emissions in the YRD over the past 20 years, analyzing the growth and fluctuation trends of carbon prices and trading volumes in domestic carbon exchanges over the past 10 years. Next, we identify the strengths and weaknesses of the existing CCUS projects in the YRD by comparing them with CCUS projects in other regions of China and some developed countries. We also demonstrate the necessity and feasibility of conducting CCUS projects in various areas of the YRD by analyzing the demand and potential for carbon storage in the region. Based on the above, we propose a macro-level CCUS project location model and discuss its rationality, feasibility, and potential improvement space. Research shows that YRD should focus on optimizing the planning and layout of CCUS projects through technological innovation, project tracking, carbon storage potential assessment, and comprehensive benefit research.

Keywords: CCUS, source-sink matching, industry cluster, project location model, Yangtze River Delta region

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Introduction

Research Background

Since the industrial revolution, the extensive extraction and utilization of fossil fuels by countries for industrial development and economic growth has led to a sharp increase in CO_2 concentration in the atmosphere, resulting in global warming and severe pollution of the atmospheric environment. These issues have had a detrimental impact on the ecological and environmental balance [1-4]. In response to the severe global ecological challenges, China announced in September 2020 at the 75th session of the United Nations General Assembly that it will continue to adhere to and deepen the realization of CO_2 emission reductions. China aims to reach peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060 [5]. Among the various scientific and technological solutions to achieve these dual carbon goals, the CCUS (carbon capture, utilization, and storage) technology is a crucial and comprehensive technology and engineering solution [5-9]. For detailed information about CCUS, please refer to Fig. 1.

As the final and crucial step in CCUS, Carbon storage can be categorized into onshore and offshore storage based on geographical location and into saline aquifer storage, depleted oil and gas reservoir storage and other types of storage based on the geological composition of the storage medium [8]. Regardless of the specific storage method, all methods contribute significantly to carbon reduction and emission mitigation. By 2030, the global reduction in emissions achieved through CCUS in different sectors is projected to be between 100 and 1,670 million tons per year, with an average of 490 million tons per year. These numbers are expected to reach 2,790 to 7,600 million tons per year, with an average of 4,660 million tons per year by 2050 [9]. The International Energy Agency (IEA) estimates that CCUS will be the fourth-largest contributing technology, accounting for 15% of cumulative emissions reductions by 2070. In fact, in the context of achieving dual carbon goals, CCUS is playing a crucial role in energy conservation and emission reduction across various regions and industries in China [10].

The Yangtze River Delta region (YRD) in China, consisting of Jiangsu, Zhejiang, Anhui provinces, and Shanghai, is not only the most economically developed area in China but also a crucial region for achieving the dual carbon goals. In 2022, the GDP of the YRD reached 29.03 trillion yuan, accounting for approximately 24% of the national GDP. With a strong industrial foundation and a complex and large-scale industrial layout, the region generates annual carbon emissions of approximately 1,614 million tons, accounting for approximately 20% of the national total. In consequence, it bears the important task of exploring a new development pattern for China's dual carbon strategy. In summary, the strategic significance of implementing CCUS projects in the YRD cannot be underestimated. The issues related to the layout of CCUS in this region hold significant research value [11]. Therefore, this article conducts an analysis and research on CCUS-related issues in the YRD.

Research Overview

Research on CCUS involves multiple disciplines and technical fields, such as environmental science, biochemistry, economic management, international relations and engineering technology. Scholars from different fields have conducted CCUS-related research from different perspectives and with different technical

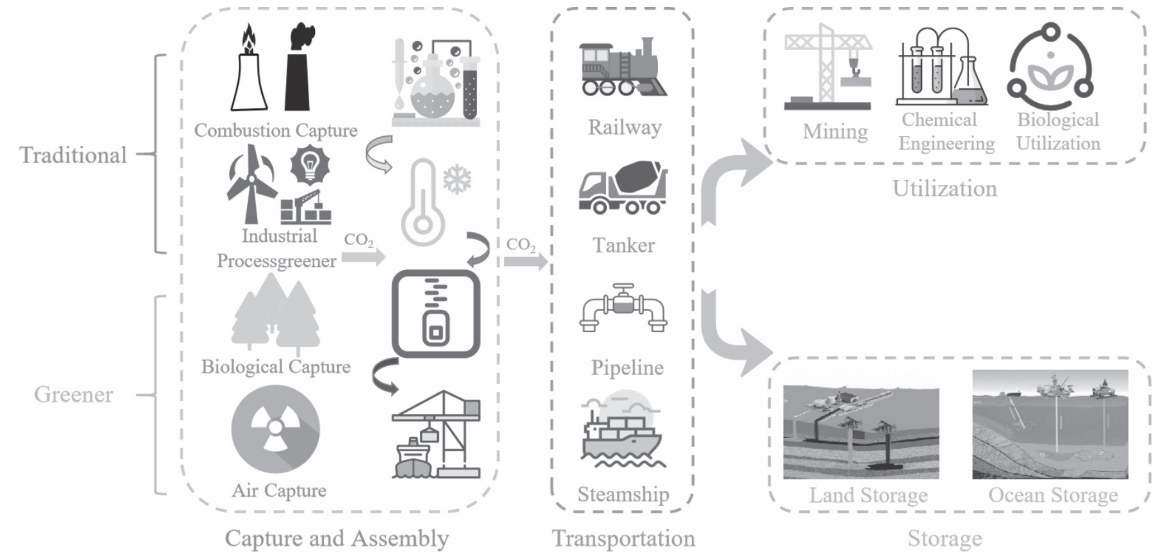

Fig. 1. The different stages of CCUS technology: CO_2 capture refers to the process of separating CO_2 from concentrated emission sources. CO_2 utilization involves the engineering techniques used to convert captured CO_2 into a valuable resource. Last, CO_2 storage entails injecting captured CO_2 into deep geological reservoirs, effectively isolating it from the atmosphere for an extended period.

processes. Some scholars have attempted to study the mechanisms and effects of carbon storage in ecosystems such as tropical forests, subtropical jungles, grasslands, and farmland soils, as well as the potential for natural carbon storage in the geographical environment and ecosystems [12]. However, due to the constraints of the natural environment, relying solely on the natural environment for carbon emission reduction has limitations, not only the speed of carbon storage is slow but also the storage capacity is very limited. It is difficult to artificially control and faces challenges such as high costs, long investment cycles, slow effectiveness, and limited scale for carbon storage. Taking the YRD as an example, The total area of this region is 358,000 square kilometers, accounting for 2.19% of the national total, and it is estimated to have a population of 236.959 million permanent residents by 2023, accounting for approximately 16.7% of the mainland population. In the long run, it is difficult to change the pattern of human activities and rapid urban expansion in the YRD. As a result, the residential and industrial land area will continue to increase, while the agricultural land area will decrease, and the forest coverage rate will remain relatively stable. Therefore, there is limited room for optimizing carbon emissions reduction in the YRD solely by changing the natural ecosystem.

In order to scientifically develop feasible and more effective carbon reduction plans for the YRD, scholars have already conducted research and exploration from various aspects such as industrial structure, energy consumption structure, technology, and industrial level. They have also put forward numerous strategies and recommendations for optimizing carbon reduction plans for different regions and industries in the YRD [13-16]. Li proposed a coordinated mechanism for carbon emissions trading and carbon taxation for the governance of carbon emissions in the YRD and suggested that Jiangsu Province implement additional carbon taxation policies and tiered carbon taxation policies, while Anhui Province implement carbon emissions reward and punishment policies and effective industrial transformation policies [13]. Fang et al. used the Dynamic Spatial Durbin model to study the impact of the integration in the YRD on urban carbon emissions. They found that the implementation of regional integration in the YRD can optimize the industrial structure and urban governance level, which can significantly reduce carbon emissions and help the region achieve a carbon peak as soon as possible [14]. Fu et al. studied the efficiency and dynamic evolution characteristics of the integrated development of urban and rural areas in 27 central cities in the YRD from 2008 to 2017 based on the EBM super efficiency model, kernel density estimation, and GML index analysis and found that the redundancy of carbon emissions has a significant impact on the efficiency loss of urban–rural integration development [15]. Zhou et al. explored the mechanism of market integration development on carbon emissions benefits from a market perspective, used cross-sectional mean data from 2006 to 2015 in the YRD to construct a spatial econometric model, and then analyzed the impact of market integration on carbon emissions benefits [16].

Currently, professionals in the industry evaluate whether a certain location is suitable for CCUS projects based on the investigation of geological and geographical features. This means that the site selection decision is made based on the assessment of the carbon storage potential in that area. For example, Chen et al. used the single-level index evaluation method proposed by Bachu to evaluate and rank multiple regions in Shanxi Province based on geographical features, carbon storage potential, and economic and social factors [17, 18]. This work has limitations in terms of the geographical scope of its consideration and the project location recommendations provided. Qi et al. used AHP, factor analysis, and expert scoring methods to align the macro requirements and micro layout of China's dual carbon goals at the levels of project area selection and positioning selection, proposed a technical path for location decision-making based on project characteristics and selected a suitable location for a company's modern coal chemical engineering project [19]. However, this work specifically focuses on the site selection issue of individual coal chemical projects at the enterprise level in the context of the dual carbon goals. Concomitantly, the methods used in this work are relatively traditional. For complex CCUS project site selection issues that require a global perspective, the reference value of this work is relatively low.

Zhou et al. planned the whole process of the CCUS network layout from the perspective of the whole system. They elaborated on the creation mechanism and operation principle of the CCUS network, and described the dynamic characteristics of the CCUS network with mathematical expressions, so as to determine the configuration strategy of facilities and pipelines in each step of CCUS through mathematical methods. On this basis, they established a mixed integer nonlinear optimization mathematical model with the minimum annual total cost as the optimization objective [20]. This work has deep research on CCUS-related issues, comprehensively considers various influencing factors, and provides a scientific and reasonable optimization model. The theoretical basis is reliable and practical, but it may be difficult to implement.

This article builds on previous research and focuses on the carbon reduction and CCUS project development path in the YRD. Firstly, it outlines the current status of carbon emissions and carbon storage in the YRD. Secondly, it analyzes the key factors that impact the development of CCUS projects in the region. Then, based on the actual situation of CCUS in the YRD, the article establishes an evaluation model and optimization model for CCUS project site selection and layout from the perspective of CCUS project location and layout.

Basic Situation of Carbon Storage in the YRD

Carbon Emission Overview

As an important economic and social region in China, the YRD is characterized by its developed industries and significant carbon emissions resulting from various production and consumption activities. It is a key area for carbon storage projects and represents typical CCUS research compared to other regions in China. Fig. 2 shows the spatial geographic location of the YRD, indicating the relative geographic position of Zhejiang Province and the distribution of carbon emissions intensity.

To visually observe the carbon emissions of the YRD, we count and visualize the carbon emissions and GDP of the YRD in the past 20 years. The annual carbon emissions of a place in the year t are recorded as $CE(t)$, and to analyze the trend of carbon emissions, we define the growth rate of carbon emissions as $R_{CE}(t)$

$$RI_{CE}(t) = \frac{CE(t) - CE(t-1)}{CE(t-1)} \tag{1}$$

Let $CE_{PRP}(t)$ denote the annual per capita carbon emissions and $PRP(t)$ denote the annual permanent resident population of the region. then, $CE_{PRP}(t)$ is defined as $CE(t)$ divided by $PRP(t)$

$$CE_{PRP}(t) = \frac{CE(t)}{PRP(t)} \tag{2}$$

We divide the total regional carbon emissions of the year by the gross regional product of the current year to calculate the carbon emission intensity and record it as $CE(t)$, which is used to characterize the combination of carbon emissions and economic development. Its calculation formula and annual rate of change are

$$CEI(t) = \frac{CE(t)}{GDP(t)} \tag{3}$$

$$RI_{CEI}(t) = \frac{CEI(t) - CEI(t-1)}{CEI(t-1)} \tag{4}$$

Based on the results presented in Fig. 3, it is evident that the carbon emissions in the YRD have exhibited a consistent upward trajectory from 2000 to 2021. During this period, carbon emissions surged from 226.66 million tons in 2000 to 2760.54 million tons in 2021, representing an almost tenfold increase over two decades. Additionally, the annual growth rate of carbon emissions experienced significant fluctuations, oscillating by approximately 15%. Since 2013, Jiangsu Province has consistently had the highest carbon emissions among the four provinces, while Anhui Province has consistently had the lowest. This shows

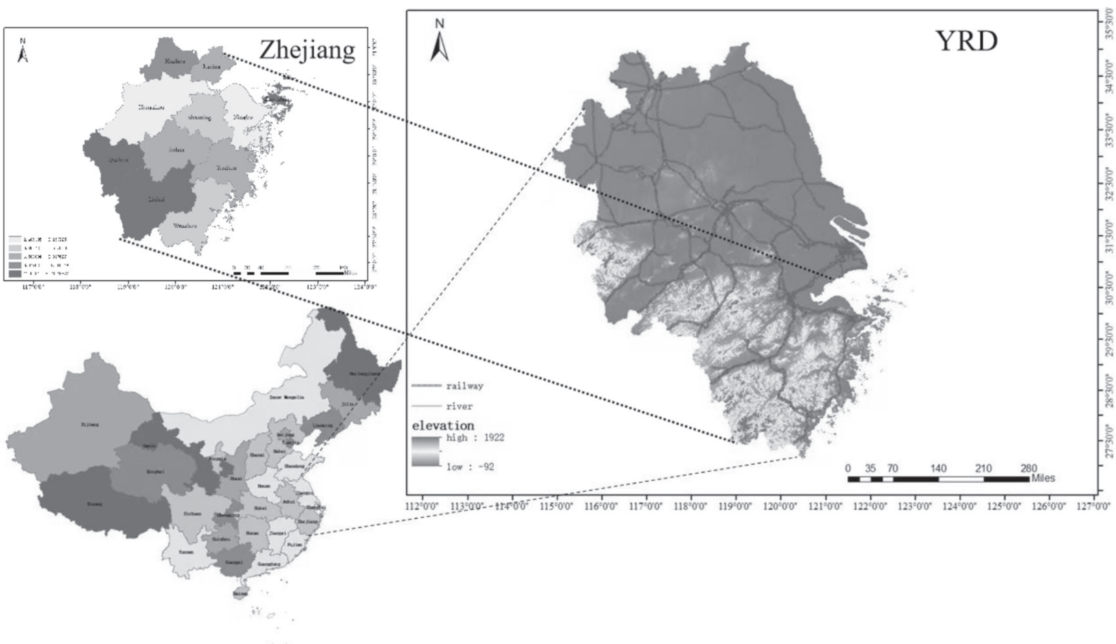

Fig. 2. The relative geographical location of the YRD in China and the basic situation of carbon emissions in the region: The carbon emission intensity depends on the level of economic development and carbon emissions of the region. The carbon emission intensity in the YRD, with a more developed economy and large carbon emissions, is significantly lower than that of Tibet, Gansu, Heilongjiang, and other regions and higher than that of Yunnan, Inner Mongolia and other places with low carbon emissions and a less developed economy. Taking Zhejiang Province in the Yangtze River Delta as an example, there is a strong correlation between local carbon emission intensity and the local economy and natural environment.

that carbon emissions and economic development have a significant relationship with industrial structure, and due to the implementation of relevant energy-saving and emission-reduction measures, the annual growth rate of carbon emissions decreased, basically dropping below 10%.

According to the results shown in Fig. 4, it is evident that over the past two decades, the provinces and cities in the YRD have been dedicated to reducing carbon emissions intensity. In comparison to the year 2000, by 2021, Jiangsu Province has successfully reduced its carbon emissions intensity by 77%, Zhejiang Province by 85%, Anhui Province by 86%, and Shanghai by 83%. In fact, over the recent twenty years, the YRD has exceeded the national targets for carbon emissions reduction.

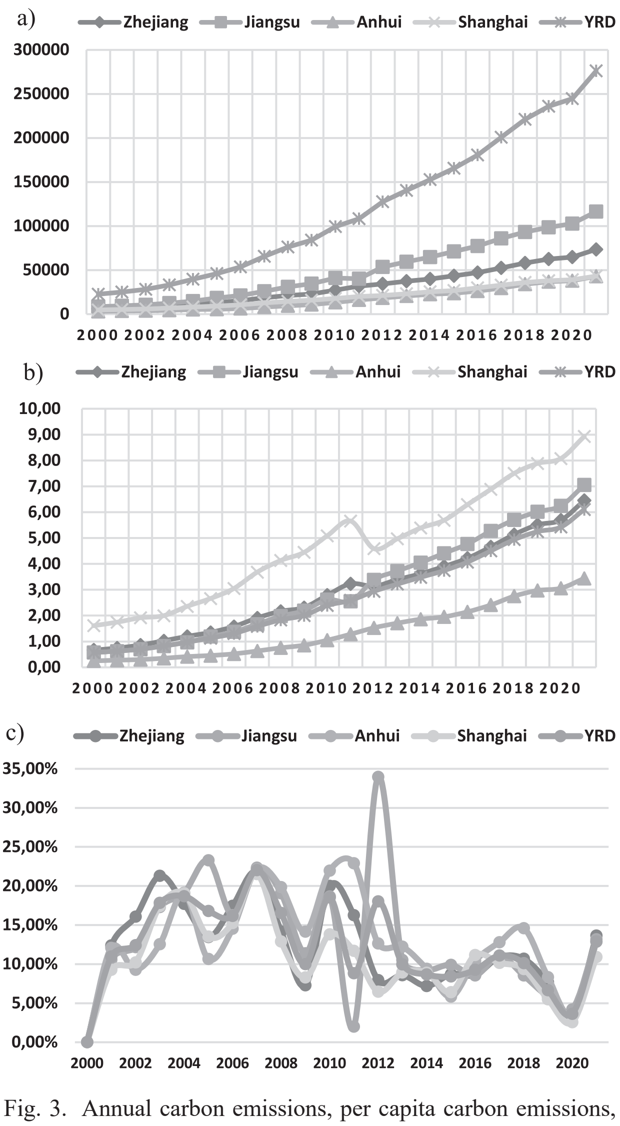

Fig. 3. Annual carbon emissions, per capita carbon emissions, and annual growth rate of carbon emissions in the YRD from 2000 to 2021 : a) Annual carbon emissions (in million tons), b) Per capita carbon emissions (in million tons per person), c) Annual growth rate of carbon emissions (%).

Carbon Storage Industry Demand

Despite occupying a mere 2.19% of the country's land area, YRD contributes 20 % of the country's carbon emissions and 24 % of the country's GDP. Due to the urgent need to achieve the dual carbon goals and the huge carbon emissions in the YRD, a large CCUS market has emerged. According to statistics released by the Shanghai Environment and Energy Exchange (SEEE), the total trading volume of carbon emission allowances in the national carbon market reached 50.89 million tons in 2022, with a total transaction value of 2.8 billion yuan. In the YRD, the carbon price fluctuated between 50.54 yuan/ton and 61.60 yuan/ton in 2022, with a carbon emission trading volume of about 27.3 million tons.

Even if carbon prices decrease significantly due to technological advancements in carbon storage, the total industry scale could still reach 8 billion yuan. However, the current scale of carbon storage projects in the YRD is only about 700,000 tons/year, with an annual industry scale of only 400 million yuan. Compared to the potential scale of the carbon storage industry that may be generated before reaching the carbon emissions peak, there is a significant gap in the existing industry. This indicates that the YRD has great market potential to promote the development of the carbon storage industry.

By conducting statistical analysis and comparison of the trading data in various carbon trading markets in China, we can obtain more conclusions about the carbon storage demand in the YRD. For more detailed information, please refer to Fig. 5 and 6.

Potential of the Carbon Storage Industry

The Subei Basin is the main onshore distribution area of deep saline aquifers suitable for carbon storage in the YRD. It is located in the boundary zone between the Pacific Plate and the Eurasian Plate, with a total area of approximately 305,000 square kilometers. Its carbon storage potential is estimated to be around 432.7 billion tons [21]. Although the land area suitable for carbon storage in the YRD is relatively small, the carbon storage potential of the Subei Basin is enormous [22]. Just in terms of quantity, the carbon storage capacity of the Subei Basin alone is more than enough to meet the carbon storage needs of the YRD. At present, many CCUS projects have been deployed in the Subei Basin. For example, the Jiangsu Oilfield exploited the advantages of carbon flooding and carbon storage technology and built the first CCUS_EOR carbon-neutral oil production demonstration area, which utilized 38 fault blocks of the Union Oilfield in the Gaoyou Sag in the Subei Basin.

Since the Subei Basin is mainly located in the northern part of the YRD, far away from areas like southern Zhejiang and southern Anhui, concentrating CCUS projects in the Subei Basin would result in higher transportation costs for carbon storage in these regions.

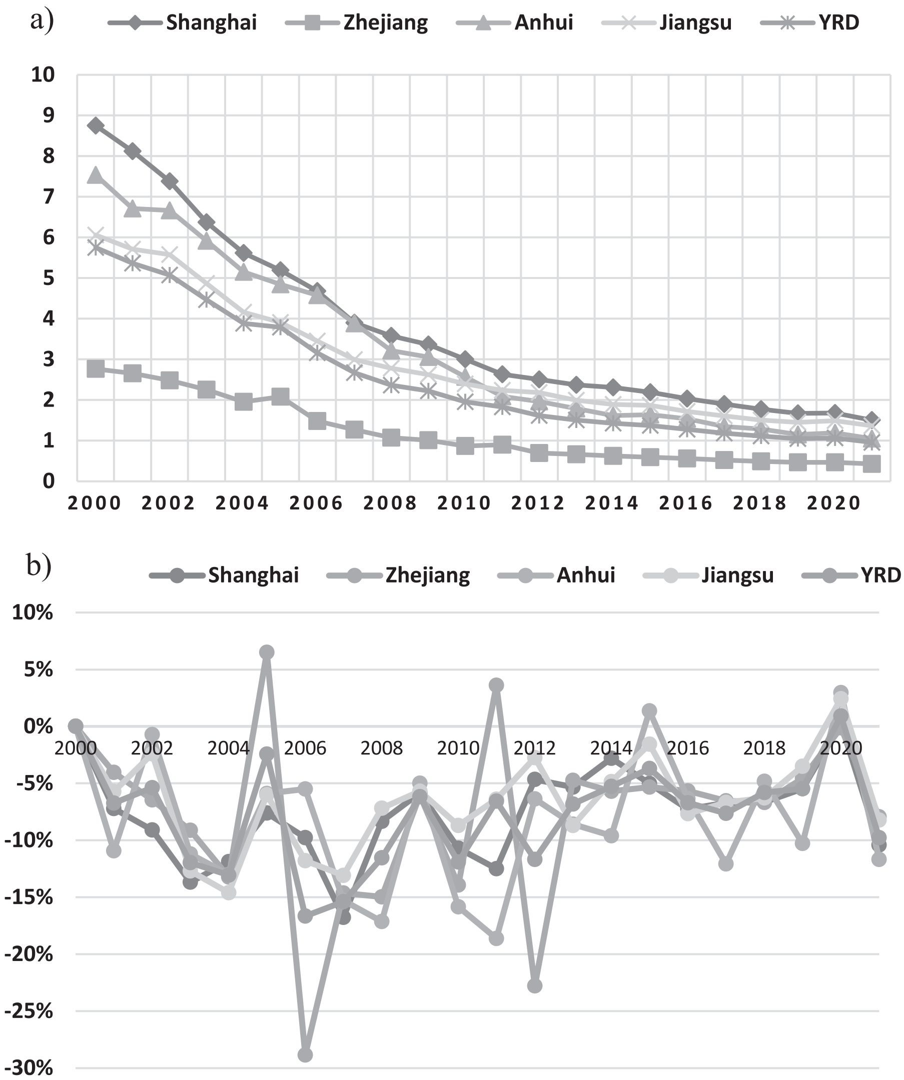

Fig. 4. Annual carbon emission intensity and annual change trend in the YRD from 2000 to 2021: a) Annual carbon emission intensity (10,000 tons/100 million RMB), b) Annual rate of change in carbon emission intensity (%).

Therefore, in order to effectively utilize the carbon storage resources in various regions and reduce the cost of carbon transportation as much as possible, CCUS industrial clusters should be formed not only in northern Jiangsu, which has great potential for carbon storage but also for rational arranging of CCUS projects of appropriate scale in other places far away from the industrial cluster. However, in areas like Anhui and Zhejiang, which are mostly characterized by plains and hills, there are few large-scale basins suitable for carbon storage. Therefore, it is essential to explore suitable sites for carbon storage and estimate the corresponding storage potential and benefits in these areas. This work is necessary to achieve a rational layout and optimized path for CCUS in the YRD.

In terms of the potential for ocean carbon storage, the YRD mainly relies on the East China Sea Shelf Basin. It has a large area and relatively high tectonic stability. It is a sub-cold to sub-hot basin with favorable geological conditions for saline aquifer carbon storage. Preliminary estimates suggest that the theoretical capacity for carbon storage in the East China Sea Shelf Basin is 185,652 billion tons [23]. For the YRD, the conditions for implementing CO2 saline aquifer geological storage are mature. When considering the development of offshore CCUS projects, the main factors to be considered are the construction difficulty and operational stability of the project site, as well as the distance to carbon emission sources and shipping conditions [24].

CCUS Demonstration Projects

In the economically developed YRD, CCUS projects are being promoted as a priority. Many government departments are actively promoting the development of CCUS-related technologies and projects. Currently, China has the engineering capacity to capture, utilize, and store CO_2 at a million-ton scale [25]. For example, out of 21 large-scale CCUS projects in operation in China, the PetroChina Jilin Oilfield EOR Project

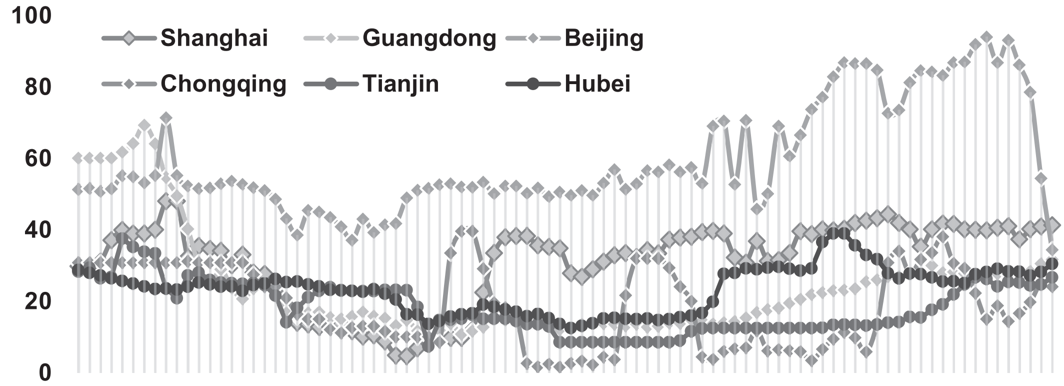

Fig. 5. Average monthly carbon trading price curves of China's carbon exchanges between 2013 and 2021 (RMB/ton).

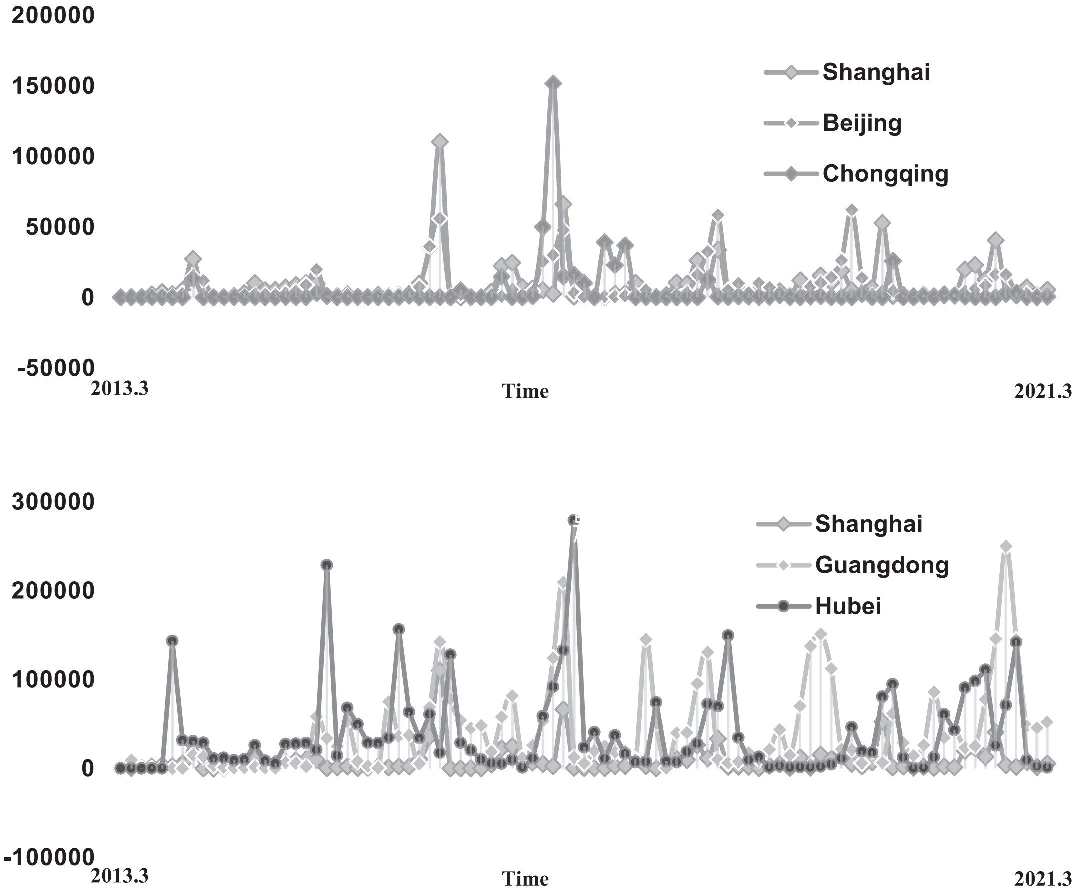

Fig. 6. Monthly carbon trading volume curves of China's carbon exchanges from 2013 to 2021 (in million tons).

is the only one with an annual oil production capacity of 100,000 tons and an annual storage capacity of 250,000 tons. The CO_2 capture energy storage demonstration project of China Energy Group Guohua Jinjie Power Plant started construction in 2019. With a capacity of 150,000 tons/year, it will become China's largest coal-fired power plant CCUS demonstration project.

Table 1 presents a statistical analysis of the current typical CCUS projects in the YRD. The existing CCUS projects in the YRD are mainly distributed in Jiangsu because it has vast carbon storage potential in the Subei Basin, with a strong industrial foundation, and can undertake multiple large-scale CCUS projects. The layout of CCUS projects in Jiangsu can meet the carbon capture and storage needs of many enterprises and departments in Jiangsu Province and Shanghai. There are substantial differences in the scale of CCUS projects in the YRD. The scale of projects that have been put into operation is generally small, and larger

Table 1. Some representative CCUS projects in the YRD. Unit of project scale: ten thousand tons per year.

Project name	Landing Address	Project type	Operating state	Scale
Lianyungang Clean Energy Power Force Systems Research Facility	Lianyungang (Jiangsu Province)	Capture	in service	3
Huaneng Shkou Power Plant	Shanghai	Capture	in service	12
Conch Group, Wuhu, White HorseMountain Cement plant 50,000-ton carbon dioxide capture and purification demonstration project	Wuhu (Anhui Province)	Capture	in service	5
Sinopec East China Oil and Gas Field CCUS full process demonstration project	Dongtai (Jiangsu Province)	Capture	in service	10
CO_2 separation project of Lishui 36-1 gas field, CNOOC	Wenzhou (Zhejiang Province)	Capture	in service	5
300 N m3/h flue gas CO_2 Chemical absorption pilot test platform	Hangzhou (Zhejiang Province)	Capture	in service	0.05
East China Oil and Gas Field, Haian Block	Nantong (Jiangsu Province)	Utilization and Storage	in service	10
Zhejiang Energy Lanxi carbon capture and mineralization utilization integration demonstration project	Lanxi (Zhejiang Province)	Capture	in construction	1.5
CO_2 Catch and resource recovery of energy utilization technology research and demonstration project	Taizhou (Zhejiang Province)	Comprehensive	in construction	50
Jiangsu Huadian Jurong Phase II (2x1000MW) expansion project flue gas carbon capture EPC project	Yangzhou (Jiangsu Province)	Capture	in construction	1
CCUS cooperation project between East China Petroleum and Nanhua Company	Fengxian (Shanghai)	Comprehensive	in service	20
Ningbo Iron and Steel Company 20,000 tons/year CCUS capture and resource utilization project	Ning Po (Zhejiang Province)	Capture and Utilization	in construction	2
A project of CO_2 mineralization to produce fully solid waste carbon building materials	Hefei (Anhui Province)	Utilization and Storage	in construction	-
Jinling Petrochemical CCUS project supporting engineering	Nanjing (Jiangsu Province)	Comprehensive	in service	10
Anhui Huainan Pingwei power Plant	Huainan (Anhui Province)	Capture	in construction	-

and ultra-large-scale projects are still in the stage of project approval and construction. According to incomplete statistics, in the operation of the project, the smallest is only 0.05 million tons/year, and the largest is 200,000 tons/year, with an average of 80,000 tons/year. Among the projects under construction, the smallest one is 10,000 tons/year, and the largest one is 500,000 tons/year.

Compared with other regions in China, the YRD is leading in carbon storage technology, the associated industrial base and capital chain are relatively strong, the number of carbon storage projects is large (in operation and under construction), and the overall scale of these projects is also large. However, the rapid development stage started late, and the scale of a single project was small. There are no large-scale CCUS projects, such as the Qilu Petrochemical Shengli Oilfield CO_2-EOR project (Shandong, 1 million tons/year) and the EOR project of the CNPC Jilin Oilfield (Jilin, 250,000 tons/year). Similar to other regions, the YRD has high carbon capture and storage costs and low commercial utilization rates. It is worth emphasizing that CCUS projects in YRD are relatively dispersed, and carbon capture and storage industry clusters need to be developed.

Compared with other developed countries and regions, YRD has obvious shortcomings in its CCUS project. Specifically, the CCUS-related technology in the YRD region is relatively backward, the scale of a single project is small, and the project development time is late. In the United States, CCUS projects with a scale of more than 1 million tons/year have reached 50. For example, the Century plant project (Texas, 4.32 million tons/year) and the Petra Nova project (Texas, 1.4 million tons/year) became operational in 2010 and 2016, respectively, while most other projects will be operational by 2025, and the rest will be operational by 2030 at the latest.

In general, the development of CCUS projects in the YRD remains in the experimental and demonstration stages. Although this region is at the forefront in China, it has obvious gaps compared with other developed countries and still faces many challenges.

Location Programming of CCUS Projects in the YRD

Foreword

In terms of carbon storage site selection, Bachu first established CO_2 geological storage evaluation criteria in 2003 [18]. Building on this foundation, Bachu et al. further established the CO_2 geological storage potential pyramid model [19, 26, 27]. After that, organizations such as the Carbon Storage Leadership Forum (CLSF), the European Union (EU), and the IEA developed standards and processes for carbon storage site selection. Qi Shengwen et al. have established a detailed evaluation system for land-based carbon storage site selection and ocean-based carbon storage site selection based on existing research results and engineering practices both domestically and internationally [19]. This system provides a reference for CO_2 geological storage site selection at different levels, scales, and reservoir types. It also lays the foundation for future exploration of key indicators, optimization of indicator systems, and practical applications.

In recent years, scholars have proposed the concepts of "source-sink matching" and "CCUS cluster" as development paths for CCUS projects [28-30]. Source-sink matching refers to the mutual matching of CO_2 emission sources and carbon storage sites based on factors such as emission sources, transportation conditions, and storage sites. It also involves comprehensive management and optimization of factors such as economics, energy consumption, and operational risks to establish the optimal matching relationship between emission sources and storage sites. CCUS clustering refers to an industry cluster composed of multiple CCUS projects, where CO_2 captured from different emission sources is transported in an orderly manner to be centrally and uniformly treated within the cluster. Source-sink matching and CCUS clustering have advantages such as infrastructure sharing, strong project systematic, high inter-generational technical relevance, energy resource interchange, and close integration of industrial demonstration and commercial applications. They represent a low-cost, efficient, widely covered, and systematic development approach for CCUS projects.

However, these theoretical paths are constrained by certain objective conditions in practice. For example, when the length of CO_2 transportation pipelines is less than 250 kilometers, the construction and transportation costs of pipelines are lower compared to roads and railways. Therefore, from a cost-saving perspective, the distance for source-sink matching in CCUS projects generally does not exceed 250 kilometers [30]. Additionally, some geological structures and geographical environments in certain areas may not meet the basic criteria for carbon storage sites, or they may not have the necessary infrastructure and sufficient available area to meet the implementation conditions of CCUS projects [28, 29, 31]. Taking these objective factors into consideration, this paper improves the development ideas of source-sink matching and CCUS clustering, and adopts an optimization modeling approach to formulate specific CCUS development plans.

Description of the Problem

In the carbon storage site selection problem, each location in the YRD is associated with two key indicators: carbon storage potential and carbon storage demand. From a regional perspective, taking into account the rational utilization of carbon storage resources and meeting the carbon storage demands of different locations, how can the layout of carbon storage projects be adjusted or planned to minimize the costs or maximize the comprehensive benefits of carbon storage in the YRD? It is important to emphasize that rational utilization here must comply with the objective laws of carbon storage project development and be subject to objective conditions constraints. For example, the distance between a carbon storage project site and the service site should not be too long. Additionally, a carbon storage site can serve multiple carbon emission sites, but each carbon emission site corresponds to only one carbon storage site. Moreover, it is evident but not to be overlooked that the carbon storage industry scale of a carbon storage site must be larger than the total carbon storage demand it serves.

Assumptions and Parameter Definitions

1. Due to the need to achieve the dual carbon goal, each location has a carbon emission reduction target, which corresponds to a carbon storage demand. The carbon storage capacity or project scale of each carbon storage site must meet the total carbon storage demand of its service locations, but should not exceed its carbon storage potential. If the carbon storage potential of a location does not meet the evaluation criteria, the placement of carbon storage projects in that location will not be considered.
2. The YRD is considered as a whole, and the overall cost is the sum of partial costs. The layout of partial carbon emission projects needs to be considered from the perspective of the whole. In other words, the whole area incurs costs for the construction of carbon storage projects, including carbon capture, carbon transportation, and carbon storage. When a location is used as a carbon storage site, it mainly consumes initial development costs and ongoing operation costs for carbon storage. When a location is used as a carbon emission site, it mainly incurs carbon capture costs and carbon transportation costs.
3. The transportation methods in CCUS projects mainly include pipeline transportation and road transportation. The distance for pipeline transportation should not exceed 250 kilometers, which means that the total distance between a carbon storage site and its service locations should

not exceed 250 kilometers. For simplicity, the transportation of carbon from a carbon emission site to a carbon storage site can only be done through either pipeline transportation or road transportation.

4. To accurately calculate costs, it is necessary to know the total operating time of the carbon storage project, the carbon storage market price at each moment during operation, and the unit prices of various costs. However, these data are highly uncertain, and the cost of data collection is expensive, making it difficult to accurately estimate these data and information through predictive methods. At the same time, conducting data collection and prediction deviates from the core of site selection for projects. Therefore, it is assumed that cost calculation is based on a fixed unit of time (or a carbon storage cycle), with constant unit prices for all costs within that cycle.
5. The construction and solution of the optimal location model are based on reliable carbon storage potential assessment and related data and information. It is also assumed that each location in the Yangtze River Delta has the necessary infrastructure conditions for carbon storage project placement. The definitions of relevant indicators and parameters are shown in Table 2.

Optimal Model

The total cost of carbon storage includes initial development cost, daily maintenance cost, carbon capture cost, labor cost, and transportation cost.

Table 2. Parameter definitions and symbol descriptions.

Symbol	Specification
N	A collection of optional carbon storage project addresses
M	A collection of emission sources with carbon storage needs
D_r	Road transport distance from emission sources to project site (km)
D_p	Distance from the source of the pipeline to the project site (km)
W_p	Emission source: carbon production in a treatment cycle (10,000 tons)
W_e	Emission sources: carbon emissions in a treatment cycle (10,000 tons)
W_d	Emission source: carbon reduction demand in one treatment cycle (10,000 tons)
K	Alternative address: carbon storage capacity in one treatment cycle (10,000 tons)
x	Whether the alternative address is selected for the 0-1 decision variable for the layout of the carbon storage project
m_r	Highway matching factor for emission sources and project sites
m_p	Pipe matching factor for emission sources and project sites
c_d	The development cost of unit-scale projects with alternative addresses (RMB/10,000 tons)
c_m	Maintenance cost of one treatment cycle of carbon storage project (RMB/10,000 tons)
c_{cc}	Unit capture cost of carbon storage (RMB/10,000 tons)
c_h	Unit labor cost of carbon storage (RMB/10,000 tons)
c_{up}	Unit cost of carbon storage (RMB/10,000 tons)
c_{rt}	Unit road transportation cost (RMB/km/10,000 tons)
c_{pt}	Unit transportation cost of pipelines (RMB/km/10,000 tons)

$$C_{total} = C_d + C_m + C_h + C_{cc} + C_{up} + C_{tr} + C_{tp} \tag{5}$$

The development cost and daily maintenance cost are the costs incurred by a certain location as a carbon storage project site. The carbon capture cost, labor cost, transportation cost, and storage cost are the costs incurred by a certain location for carbon storage. Under assumptions (1) and (4), if the unit capture cost, unit labor cost, and unit storage cost are the same for each location in the YRD, then we have

$$\begin{aligned} C_{up} &= \sum_{j=1}^{m}\sum_{i=1}^{n} x(i)m_r(i,j)c_{rt}(i,j)c_{up}(i)W_d(j) \\ &= \left(\sum_{i=1}^{n} x(i)m_r(i,j)c_{rt}(i,j)c_{up}\right)\sum_{j=1}^{n} W_d(j) = \sum_{j=1}^{n} c_{up}W_d(j) \end{aligned} \tag{6}$$

$$C_{cc} + C_h + C_{up} = \sum_{j=1}^{m} c_{cc}W_d(j) + \sum_{j=1}^{m} c_h W_d(j) + \sum_{j=1}^{n} c_{up}W_d(j) \triangleq C_f \tag{7}$$

The above equation shows that in the overall carbon storage project in the YRD, there is a portion of costs that are fixed. The optimization and control of these fixed costs are limited, so it is necessary to focus on the non-fixed and more optimal portion of costs.

$$C^*_{total} = C_d + C_m + C_{tr} + C_{tp} \tag{8}$$

The initial development cost and daily maintenance cost are primarily influenced by factors such as the land price, labor price, infrastructure, and carbon storage potential of the carbon storage site. The differences in these factors determine that carbon storage projects in different locations will have different development and maintenance costs. The cost is calculated by multiplying the unit price by the quantity.

$$\begin{aligned} C_d &= \sum_{i=1}^{n} x(i)c_d(i)K(i) \\ C_m &= \sum_{i=1}^{n} x(i)c_m(i)K(i) \end{aligned} \tag{9}$$

According to the principle of source-sink matching, if there is a matching relationship between the carbon emission source j and the carbon storage site i, and if road transportation is used, we have $x(i) = 1$, $m_r(i,j) = 1$. The calculation formulas for road transportation cost and pipeline transportation cost are as follows

$$\begin{aligned} C_{tr} &= \sum_{j=1}^{m}\sum_{i=1}^{n} x(i)m_r(i,j)c_{rt}(i,j)D_r(i,j)W_d(j) \\ C_{tp} &= \sum_{j=1}^{m}\sum_{i=1}^{n} x(i)m_p(i,j)c_{pt}(i,j)D_p(i,j)W_d(j) \end{aligned} \tag{10}$$

The optimization model for carbon storage project site selection can be constructed by taking the total variable cost C^*_{total} for carbon storage as the optimization objective and using $x(i)$, $K(i)$, $m_r(i,j)$ and $m_p(i,j)$ as decision variables.

$$\min Z = C^*_{total} = C_d + C_m + C_{tr} + C_{tp} = \sum_{i=1}^{n} x(i)K(i)\left(c_d(i) + c_m(i)\right) + \sum_{j=1}^{m}\sum_{i=1}^{n} x(i)W_d(j)\left(m_r(i,j)c_{rt}(i,j)D_r(i,j) + m_p(i,j)c_{pt}(i,j)D_p(i,j)\right)$$

$$s.t.\begin{cases} x(i) = \begin{cases} 1, i \text{ is selected} \\ 0, i \text{ is not selected} \end{cases} \\ m_r(i,j) = \begin{cases} 1, \text{Road transport between i and j} \,\&\, D_r(i,j) \le \delta_r \\ 0, \text{others} \end{cases} \\ m_p(i,j) = \begin{cases} 1, \text{Pipeline transport between i and j} \,\&\, D_r(i,j) \le \delta_p \\ 0, \text{others} \end{cases} \\ 0 \le K(i) \le Q(i) \\ \sum_{i=1}^{n} x(i)\left(m_r(i,j) + m_p(i,j)\right) \ge 1; j = 1,2,\cdots,m \end{cases}$$

Discussion of the Model

Disadvantages and Limitations

The project location model considers the YRD as a whole and treats the overall cost as the sum of individual costs. However, different locations within the YRD may have different geographical, economic, and social conditions, resulting in significant cost differences among them. The model overlooks these differences, which may lead to solutions that are difficult to align with the real situation or are not accurate enough. Additionally, the model assumes that the transportation methods for carbon storage projects are mainly pipeline and road transportation, with a maximum distance of 250 kilometers for pipeline transportation. However, in practical applications, there may be other transportation options to consider, such as shipping or railway transportation. The model does not incorporate these transportation modes into the alternatives. Although it reduces the complexity of the model, it may make the optimization results deviate from the actual situation.

The project location model proposed in this article is built and analyzed based on a fixed spatial and temporal scale of the YRD. However, in reality, there may be differences in geographical, economic, and social conditions at different scales, which may cause applicability issues for the model at different temporal and spatial scales. Additionally, the model primarily focuses on economic factors, such as costs and benefits. There are also many non-economic factors, such as environmental impacts and social acceptance, which may have significant effects on project location decisions.

Further Work

The incomplete statistics of data and information pose significant challenges to the solution and application of models. Therefore, future research will focus on the application and improvement of the model. Here are some specific work ideas:

1. Design algorithms for the constructed project location model. Take the YRD as an example, gather the data and information required for solving the model, and provide an optimal plan for the development of CCUS projects in the region based on the solution results.
2. Further improve the project location model from aspects such as parameter selection, model assumptions, optimization objectives, and influencing factors. For example, consider the role of non-economic factors such as the environmental impact of carbon storage and social recognition in the decision-making process of CCUS project siting. Revise and supplement the model accordingly. While ensuring a high solvable of the model, strive to enhance its accuracy and make both the model itself and the solution results more realistic.
3. Reconstruct and solve the model from different spatial and temporal scales to compare the differences in model performance under different scales.
4. Apply the model to other regions to provide references for the siting of CCUS projects in those areas.

Recommendations and Summary

Recommendations

The construction of CCUS projects in the YRD is still in the trial and demonstration stage, and there are still many prominent problems restricting the development of CCUS-related industries. For example, compared with developed countries, the carbon storage technology in the YRD is lagging behind and the assessment of carbon storage potential is not comprehensive and accurate [32, 33]. Meanwhile, the safety and reliability of long-term carbon storage for the natural environment and society needs to be tested. As a key part of CCUS technology, carbon storage also has many challenges in the layout of project sites, sizes of project scales, and matching of service areas [34, 35]. This analysis of the current CCUS situation and the modeling process for CCUS project site selection and planning were combined to propose the following suggestions for accelerating the development and improvement of CCUS projects in the Yangtze River Delta.

1. **Accelerate technological innovation, transform development methods, and alleviate CCUS pressure from the source.** While ensuring their original economic benefits, carbon emissions can be directly reduced by various industries at their source via advanced green production technology and industrial development models. The YRD should make full use of the existing abundant scientific research resources and at the same time vigorously introduce advanced foreign technologies to help develop green industries such as new energy, infrastructure greening and clean production.
2. **Conduct all-round analyses of completed projects and quickly form an understanding of their progress and influence in the YRD.** The existing CCUS projects in the YRD have a wide spatial layout and large-scale span and are of diverse types. They are valuable samples for CCUS-related research. Therefore, the relevant departments in the YRD should conduct real-time evaluations and investigations of existing projects and compare them with regional projects and cross-regional projects in multiple dimensions. This process can identify the advantages and shortcomings of existing projects and form a unique understanding of CCUS development in the YRD.
3. **Comprehensively and accurately evaluate the carbon emission reduction needs and carbon storage potential in the YRD.** A scientific CCUS industry layout in the YRD is inseparable from an accurate grasp of the natural environment, social environment and economic development. The most important of the carbon storage location conditions is the carbon storage potential, and key data on the carbon storage potential of each place are required to realize the planning of carbon storage industrial sites for the YRD as a whole. YRD should not only theoretically predict the carbon storage potential of each place from coarse to fine, but also increase the intensity of field surveys and form a detailed report.
4. **Accelerate research on the economic benefits of carbon storage in the YRD, so that it can help CCUS project decision-making and layout.** The first purpose of CCUS projects is to reduce carbon emissions and alleviate environmental pollution, but projects will be affected by the international and domestic political and economic

environment. Therefore, CCUS projects have complex cost and benefit evolution mechanisms, such as the fluctuation law of various costs in CCUS, the economic benefits of different carbon storage methods, and the influence mechanism of various factors on carbon trading prices. An accurate understanding of the development law of CCUS projects would be very helpful for establishing analysis and mathematical models that can address CCUS project planning and greatly improve the authenticity and reliability of modeling. CCUS project development decisions based on the relevant laws can create the highest possible benefits at the lowest possible cost. In turn, the constructed model and the corresponding solution results will also promote the understanding of the development law of CCUS.

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Conflict of Interest

The authors declare no conflict of interest.

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