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A proposed layout of CO_2 capture utilization and storage for coal fired power plants in China

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ABSTRACT

This study aims to decarbonize coal-fired power plants (CFPPs) in China through CO_2 source-sink matching analysis. A comprehensive assessment of CO_2 emissions from China's CFPPs and the CO_2 sequestration potential of oil and gas fields in China is investigated. A detailed CO_2 source-sink matching analysis is performed. Afterwards, the pros and cons of the associated CO_2 capture, utilization and storage (CCUS) deployment are discussed. There are CO_2 emissions of 4,814.23 Mtpa from 972 existing CFPPs in China. The estimated CO_2 storage capacity of 556 oil fields and 164 gas fields is 5.31 Gt and 5.50 Gt, respectively. Furthermore, there is a CO_2 reduction potential of 1.03 Gt to 5.12 Gt in the oil and gas fields in China by 2060. The investment cost for CCUS projects between 2030 and 2060 ranges from $26.5 billion to $167 billion. A net present value (NPV) of $12.4 billion to $68.3 billion can be generated by deploying the CCUS projects. Finally, the top ten CCUS projects for the CFPPs in China are proposed.

1. Introduction

193 Parties have submitted autonomous contributions to climate change, covering 99 percent of global greenhouse gas emissions [1,2]. China has pledged to strengthen its contributions by adopting ambitious policies. It has set a strategic goal to reach peak CO_2 emissions by 2030 and attain carbon neutrality by 2060 [3–6]. As the world's largest CO_2 emitter, China accounts for around 30% of global CO_2 emissions [7,8]. Of this, carbon emissions from coal consumption account for 75% of China's total CO_2 emissions [9]. The power sector's carbon emissions are predominantly from coal-fired power generation, which contributes about 48% of China's total 12.1 billion tonnes of CO_2 emissions in 2021 [10]. The decarbonization of coal-fired power plants (CFPPs) over the next 40 years in China is important in achieving the climate target of the Paris Agreement [11,12].

While various decarbonization technologies exist, such as energy efficiency improvements, hydrogen production and utilization, and renewable energy sources, carbon capture, utilization, and storage (CCUS) stands out as a unique and indispensable technological pathway [13]. One of the key advantages of CCUS is its seamless integration with existing energy infrastructure. For instance, in high-emission industrial

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Nomenclature

API	Oil gravity, °
BCF	Billion cubic feet
CCUS	Carbon capture, utilization and storage
CFPPs	Coal fired power plants
CO_2 EOR	Carbon dioxide enhanced oil recovery
GIS	Geographic information systems
IEA	International energy agency
MMP	CO_2 minimum miscibility pressure, MPa
MMbbl	Million barrels
NPV	Net present value, $
USD	United states dollar, $
Gt	10^9 tonnes
Gtpa	10^9 tonnes per year
Mtpa	10^6 tonnes per year
Mt	10^6 tonnes
MW	10^6 W
T	Temperature, °F

sectors such as steel, cement, and chemicals, CCUS can directly capture CO_2 emissions generated during production processes [14]. In addition, CCUS complements emerging low-carbon energy carriers like green hydrogen by facilitating carbon recycling, thereby improving overall resource efficiency.

Moreover, CCUS occupies both competitive and complementary positions within the broader decarbonization landscape [15]. Hydrogen energy is considered a critical alternative to fossil fuels [15]. However, hydrogen energy continues to face significant cost challenges in production, storage, and transportation. Most hydrogen production methods still rely on fossil fuels, which result in substantial carbon emissions and limit their net decarbonization potential. In contrast, CCUS can directly capture and permanently store CO_2, thereby enhancing overall emission reduction outcomes. Furthermore, while renewable energy sources such as wind and solar offer promising decarbonization options, their intermittent nature constrains their ability to provide a stable and reliable power supply. CCUS provides a dependable solution for mitigating emissions from CFPPs without compromising power system reliability [16].

Retrofitting the CFPPs with CCUS is a reliable way for decarbonization needs [17]. The total installed capacity of CFPPs is 1,080 GW in China. Over 50% of the global CFPPs were located in China in 2020 [18]. Notably, a large proportion of the CFPPs are relatively new. Around 80% of the CFPPs are in operation for less than 15 years [19]. The International Energy Agency (IEA) states that all unabated CFPPs without CCUS should be retired in China by 2045 to meet climate target [20]. The CCUS is broadly recognized as an essential technology for CFPPs to mitigate carbon emissions and progress toward net-zero targets [21,22]. Furthermore, the CCUS provides a viable solution for extending the operational lifespan of the CFPPs [23].

One of the challenges to retrofit the CFPPs with CCUS is the high cost [24]. The policy incentives of CCUS have been proposed [25]. The United States provides financial incentives for CCUS projects through the 45Q Tax Credit Act [26]. The European Union imposes a high carbon tax[27]. Besides, Canada plans to increase its carbon tax to $134 per tonne [24,28]. The national emissions trading scheme (ETS) in China is the world's biggest carbon market [29]. On the other hand, carbon dioxide enhanced oil recovery (EOR) enables large-scale CO_2 sequestration. It also generates economic benefits by improving oil and gas recovery and helps to offset the CCUS cost [30,31]. The CCUS projects have been successfully deployed in the Shengli oil field, Changqing oil field and Jilin oil field, etc [32–34]. CO_2 storage in the saline aquifers is an alternative option for CCUS without the economic benefits of the

Table 1
Previous studies on CO_2 source-sink matching in China.

Studies	CO_2 sources and sinks	Main conclusions
Lin et al., 2024[41]	Source: 481 steel mills in China; Sink: saline aquifers	The average unit costs of CCUS under the low (30 %), medium (60 %) and high CO_2 capture (90 %) targets are $83, $91 and $118 per ton of CO_2, respectively.
Gu et al., 2024[42]	Source: 135 steel mills; Sinks: 97 oil fields and 58 saline aquifer blocks	CO_2 source-sink matching of the 111 steel mills screened can achieve a total of 420.07 million tons per year of CO_2 reduction.
Wang et al., 2024[43]	Source: Cement factories; Sink: 867 oil fields and saline aquifers in 24 sedimentary basins	To achieve carbon emission reductions of 20 %, 40 %, and 60 % in China's cement industry, the CCUS should be deployed in 229, 445, and 627 cement plants, respectively. The corresponding estimated economic costs for these scenarios are CNY 79.4 billion, 167.9 billion, and 269.5 billion, respectively.
Wang et al., 2024[44]	Source: 3,745 stationary plants in the power, steel and cement industries; Sink: onshore oil fields, saline aquifers, non-minable coal seams	The CCUS deployment capacity of 601.8 million tons per year to 1203.5 million tons per year is planned. The unit supply chain cost ranges from $28.5 per tonne to $36.0 per tonne of CO_2.
Sun et al., 2024[45]	Source: 635 CFPPs; Sink: Offshore oil and gas basins	The CO_2 storage capacity of China's offshore sedimentary basins is estimated to be 767.3 Gt, and the storage potential can reach 721.9 million tons per year through CO_2 source-sink matching.
Tang et al., 2023[3]	Source: 484 stationary CO_2 emission plants (coal-fired power generation, steel mills and cement factories, ammonia synthesis); Sink: Oil fields, saline aquifers	Capturing 174 million tons of CO_2 annually by 2050 requires nearly 19,000 km of pipelines. 12, 16, 20, and 24 inches pipelines account for more than 65 % of the total pipeline length.
Dai et al., 2023[46]	Source: 18 coal to oil projects; Sink: saline aquifers and oil fields	The deployment of CO_2 EOR and storage in saline aquifers necessitates the construction of 36 pipelines, with an average transport distance of 319.13 km.
Sun et al., 2022[47]	Source: 1,591 power plants, 86 steel plants, 335 cement plants, 70 oil refineries and 581 ammonia plants; Sink: oil fields, coal seams and saline aquifers	The CO_2 storage potential is approximately 3.6–4.6 Gt when utilizing all onshore oil fields for CO_2 EOR.
Li et al., 2022[48]	Source: 584 CFPPs; Sink: oil fields, saline aquifers	The best window for retrofitting China's existing CFPPs will be closed soon. The cumulative CO_2 mitigation potential will drop by 3.76 Gt–17.14 Gt (over 40%) if the CCUS deployment time is delayed by 10 years from 2025.
Zhang et al., 2022[49]	Source: 194 fossil fuel power plants, 32 iron and steel plants, 39 cement plants, and 13 oil refineries; Sink: gas and oil fields and saline aquifers in the offshore sedimentary basins in China between Shanghai and Hainan	The CO_2 storage capacity of China's offshore sedimentary basins is estimated at 76.73 Gt. These basins have the potential to store up to 721.9 million tons of CO_2 annually.
Fan et al., 2021[50]	Source: 607 CFPPs; Sink: saline aquifers and 412 oil fields	The storage capacity for CO_2 in saline aquifers and oil fields exceeds 1,000 Gt and 5 Gt, respectively. 401 CFPPs can be matched for CCUS within 100 km. The annual capacity for CO_2 sequestration is estimated to reach approximately 1,204 million tons.

(continued on next page)

Table 1 (*continued*)

Studies	CO_2 sources and sinks	Main conclusions
Nakaishi , 2021[51]	Source: 316 CFPPs; Sink: none	The implementation of carbon capture technologies in 316 coal-fired power plants across China could lead to a reduction in CO_2 and SO_2 emissions by 52 % and 39 %, respectively. The corresponding reduction potentials for CO_2 and SO_2 are 1.517 million tons and 3,773 tons, respectively.
Fan et al., 2020[52]	Source: 607 CFPPs; Sink: 17 onshore sedimentary basins	The near-term CCUS projects can be deployed in Hebei, Xinjiang, Tianjin, Jiangsu, and Anhui.
Wang et al., 2020[53]	Source: 765 CFPPs; Sink: saline aquifers and oil fields	Most of the captured CO_2 can be stored in the Songliao, Bohai Bay, and North Jiangsu basins, especially in the saline aquifers. The total abatement cost for implementing CCUS is estimated to be $121.2 billion.
Li et al., 2019[54]	Source: Coal chemical industry; Sink: saline aquifers	CO_2 enhanced water recovery in China can mitigate 269 Mt of CO_2 at a unit cost of $12/ton to $30/ton for industrial separation processes.
Wang et al., 2018 [55]	Source: 108 CFPPs; Sink: 6 sedimentary basins in North China.	The CO_2 capture capacity from CFPPs in North China is estimated to total approximately 22.8 Gt. The CCUS cost is estimated at around $78 per tonne of CO_2. The required CO_2 transportation pipeline network is about 52,876 km.
Sun and Chen, 2017[56]	Source: 218 fossil fuel power plants; Sink: 12 coalbed seams, 4 oil field, 7 saline aquifers.	An investment of about $1.6 billion is required for CO_2 storage of 1,620 Mt in the Beijing-Tianjin-Hebei region in 2020–2050. 2,200 km of pipelines need to be constructed for CO_2 transportation.

additional oil recovery [35,36]. Therefore, oil and gas reservoirs are the preferable candidates for the CCUS projects in China.

CCUS source-sink matching can help to reduce the cost and increase the profit by considering the shared infrastructure, projected lifetime of CFPPs, CO_2 transport distance, CO_2 EOR potential, etc [37,38]. The successful implementation of CCUS depends on several critical factors, including effective CO_2 source-sink matching, CO_2 cost and oil price, cooperation among different companies, and policy support [39,40]. A summary of previous research on CO_2 source-sink matching in China is presented in Table 1.

Previous studies on CCUS mainly focus on cost and benefits estimation, CO_2 transport pipeline networks planning at regional scales [3,41,57], and point-to-point source-sink matching analysis within specific regions[48]. The above studies in Table 1 primarily consider saline aquifers as the main CO_2 sinks. However, the large-scale CCUS deployment in saline aquifers in China is challenging due to the CCUS cost [58,59]. The economic benefit of CO_2 EOR in the oil and gas fields is important for large-scale CCUS deployment in China [60].

This study addresses a critical gap in the existing research by optimizing CO_2 source-sink matching between CFPPs and oil and gas fields in China. A comprehensive analysis of CO_2 storage in China's oil and gas fields is conducted. Afterwards, an economic analysis in different scenarios is performed based on the CO_2 source-sink matching. Most importantly, a layout of top ten CCUS projects considering the CFPPs lifetime, CO_2 transport distance, and CO_2 EOR potential is proposed.

2. Methodology

This study aims to establish an optimal CO_2 source-sink matching framework for CCUS between CFPPs and oil and gas fields in China by 2060. As shown in Fig. 1, a comprehensive assessment of CO_2 emissions is conducted for 972 stationary CFPPs in China. Afterwards, the CO_2 storage capacity in 556 oil fields and 164 gas fields is evaluated. The CO_2 source-sink matching for CCUS in China is analyzed under varying constraints, including deployment timelines and source-sink distance. Finally, the economic feasibility of the CCUS deployment in China is investigated. Thus, the layout of the top ten CCUS projects is proposed.

2.1. CCUS source-sink matching modeling

In this study, a comprehensive investigation is carried out on 972 CFPPs across China, with a combined installed capacity of 1,034.09 GW. CO_2 emissions of the power plants are recorded [61,62].

On the other hand, the CO_2 emissions from these CFPPs can be captured and sequestered in nearby oil and gas reservoirs. The amount of CO_2 sequestered in the oil and gas fields can be estimated using the equations provided below [24,33,63]:

$$m_{CO_2} = \rho_{CO_2} \times OGIP \times B_g \times R \tag{1}$$

$$m_{CO_2} = \rho_{CO_2} \times OOIP \times B_o \times (R + R_{CO_2}) \tag{2}$$

In this context, m_{CO_2} represents the mass of CO_2 stored, measured in kilograms; ρ_{CO_2} denotes the CO_2 density under reservoir conditions in kg/m^3. *OGIP* refers to the original gas in place at standard conditions in m^3, while *OOIP* indicates the original oil in place within the reservoir under standard conditions in m^3. B_g represents the gas formation volume factor as a fraction, and R is the recovery factor prior to tertiary recovery in%; R_{CO_2} refers to the CO_2 EOR factor in fraction; B_o is the oil formation volume factor in rm^3/Sm^3.

CO_2 EOR is advised for oil fields where the oil API gravity exceeds 27° [24,64]. For oil fields with API gravity below this threshold, the CO_2 EOR is not recommended. If the oil sample is not available, the minimum miscibility pressure (MMP) for CO_2 EOR can be estimated by the following equation [65,66]. If reservoir pressure surpasses the MMP, the CO_2 EOR is assumed to be in miscible phase when estimating CO_2 storage in the oil fields. Otherwise, the CO_2 EOR is considered in immiscible phase.

$$MMP = -329.558 + \left[7.727\left(\frac{8864.9}{API}\right)^{\frac{1}{1.012}}(1.005^{T})\right] - 4.377\left(\left(\frac{8864.9}{API}\right)^{\frac{1}{1.012}}\right) \tag{3}$$

Where API is the specific gravity of crude oil; T represents the temperature of the reservoir in°F.

Table 2 presents the parameters employed to calculate the CO_2 storage capacity of the oil and gas fields. In gas fields, CO_2 injection not only enhances natural gas recovery but also directly affects the ultimate storage capacity and injection efficiency. The initial recovery factor for gas fields typically ranges from 70% to 80% [24,67], with a value of 75% adopted in this study [67].

In oil fields, secondary recovery techniques typically involve water or gas injection to maintain reservoir pressure and enhance oil production. For secondary recovery, the recovery factor generally ranges from 30% to 40% [24,68], and a value of 35% is used in this study [24]. During the CO_2 EOR process, the recovery factor increases depending on whether miscible or immiscible CO_2 injection is applied. Studies show that in immiscible CO_2 flooding, the recovery factor ranges from 4.7% to 12.5%, with 8.5% adopted in this study [69,70]. In contrast, for miscible CO_2 flooding, the recovery factor typically ranges from 8% to 15%, and a value of 12% is employed here [24,71].

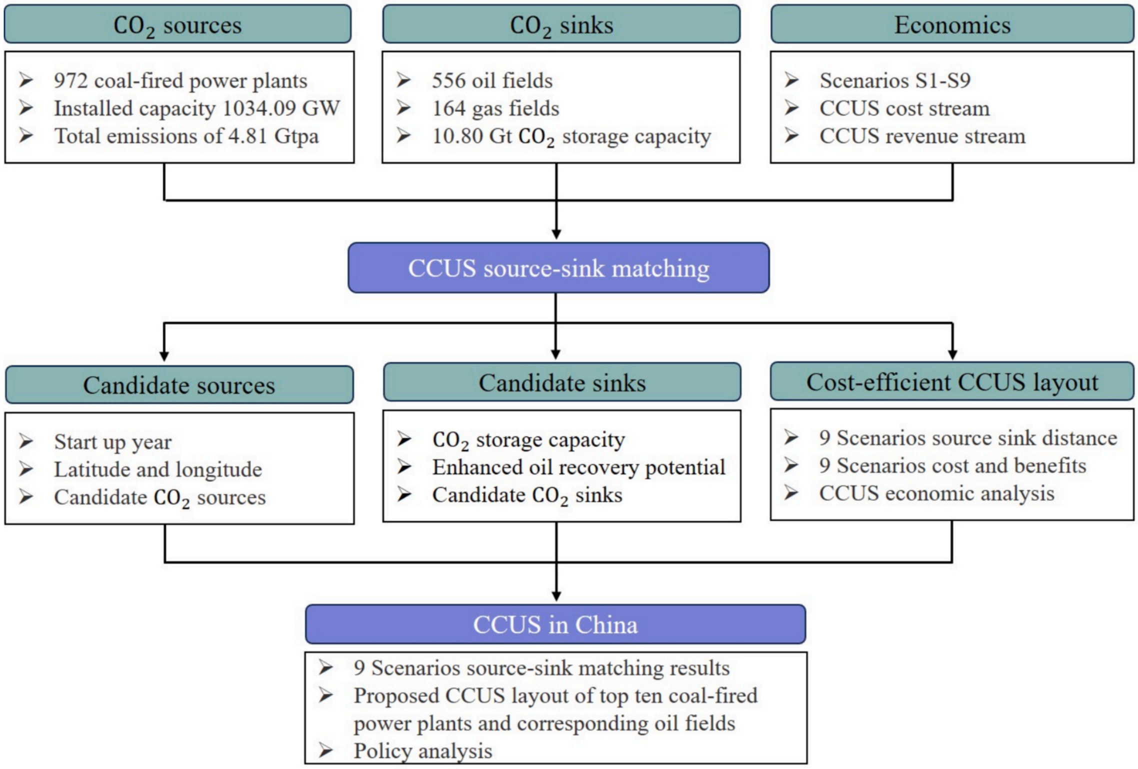

Fig. 1. Proposed research framework for CCUS source-sink matching in China.

Table 2
Parameters for estimating CO_2 storage capacity in oil and gas fields.

Type of fields	Recovery factor	Input data
Gas fields	The initial recovery factor in gas fields	75 [24,67]
Oil fields	Oil recovery factor in the secondary oil recovery	35 [24,68]
	Immiscible CO_2 EOR	8.5 [69,70]
	Miscible CO_2 EOR	12 [24,71]

2.2. Economic analysis

The CO_2 source-sink matching model for CCUS deployment includes the cost of capture, transportation, and sequestration [72,73]. The objective is to minimize the CCUS cost and maximize the CCUS profits. Economic assessment is integral to determining the viability of CCUS projects [74]. It includes CO_2 capture, compression, pipeline, geo-utilization and storage [75,76]. A representative source-sink model is employed to estimate the costs and net present value (NPV) of the CCUS implementation in China from 2030 to 2060 [77,78].

Table 3
Parameters for CCUS economic analysis.

Parameters	Value	References
CO_2 capture cost in CFPPs ($/t)	46	[79–81]
Onshore – pipeline transportation cost ($/t/km)	0.03	[82,83]
Onshore –storage cost ($/t)	6	[81,83,84]
Onshore – pipeline construction cost ($/km)	1,004,545	[85]
Conversion factor of oil from tons to barrel	7.3	[24,53]
Oil production/CO_2 injection (ton/ton)	0.15(Low) , 0.2(Mid) , 0.25(High)	[24,53]
Oil price ($/bbl)	80	

$$y_1 = min\sum\nolimits_{t=1}^{k}\sum\nolimits_{i=1}^{m}\left(\frac{a_i^tC_i^t + a_i^tT_i^td_i^t + a_i^tS_i^t}{(1+r)^t}\right) \tag{4}$$

$$y_2 = max\sum\nolimits_{t=1}^{k}\sum\nolimits_{j=1}^{n}\left(\frac{b_j^tf_j^t\eta_j^tO_j^t}{(1+r)^t}\right) \tag{5}$$

$$NPV = \max(y_2 - y_1) \tag{6}$$

In the cost stream, y_1 represents cost of the CCUS projects, encompassing CO_2 capture, transportation, and storage in $; a_i denotes quantity of CO_2 captured in tons; C_i denotes unit cost of CO_2 capture in $/t; T_i is the cost of CO_2 transportation in $/t/km; d_i denotes distance between the CO_2 source and sink in km; S_i indicates cost of CO_2 storage in $/t; r is expressed as a percentage, with a 5% discount rate included in this analysis.

In the revenue stream, y_2 denotes the total income generated by CCUS projects, incorporating supplementary CO_2 EOR in $;$b_i$ represents the CO_2 volume stored within a CO_2 EOR project in tons; f_j indicates the oil-to-CO_2 injection ratio in the CO_2 EOR project in ton/ton; η_j indicates the conversion factor for oil quantities, translating tons to barrels in bbl/t; O_j corresponds the market value of oil price in $/bbl; c_j refers to the amount of CO_2 retained in oil and gas reservoirs in tons.

The implementation of CCUS is projected to span the period from 2030 to 2060.

$$2030 \leq k \leq 2060 \tag{7}$$

The number of CFPPs for CO_2 emissions to be captured is 972.

$$0 \leq m \leq 972 \tag{8}$$

There are 720 CO_2 storage candidates nationwide, including 556 in oil fields and 164 in gas fields.

$$0 \leq n \leq 720 \tag{9}$$

All captured CO_2 is permanently sequestered in the oil and gas fields.

Table 4
Nine different CCU matching scenarios.

Scenarios	CCUS deployment time			Maximum CO_2 transportation distance (km)		
	2030	2035	2040	100	250	800
S1	√			√		
S2	√				√	
S3	√					√
S4		√		√		
S5		√			√	
S6		√				√
S7			√	√		
S8			√		√	
S9			√			√

$$\sum_{t=1}^{k}\sum_{i=1}^{m}a_i^t = \sum_{t=1}^{k}\sum_{j=1}^{n}c_j^t \quad (10)$$

Not all of the CO_2 captured can be stored in the oil fields. Most of the CO_2 is stored for CO_2 EOR in the oil fields. The rest is stored in the gas fields.

$$\sum_{t=1}^{k}\sum_{j=1}^{n}b_j^t \leq \sum_{t=1}^{k}\sum_{j=1}^{n}c_j^t \quad (11)$$

The components analyzed in the economic study of CCUS use are shown in Table 3.

2.3. Basic assumption

The following assumptions are proposed in the CCUS source-sink matching. (1) This study focuses on CFPPs with an installed capacity of at least 600 MW, annual CO_2 emissions exceeding 3 Mtpa, and a remaining operational lifespan of 15 years or above in 2030. The lifetime of the CFPPs is 40 years [48,86]. (2) CO_2 EOR is considered as the top priority in the CO_2 source-sink matching [87]. (3) When selecting storage sites, priority is given to oil and gas fields that are located near emission sources and have sufficient storage capacity [33]. (4) In the source-sink matching process, CFPPs with higher CO_2 emissions are prioritized to optimize CO_2 transportation and storage. Specifically, each CFPP is paired with a storage site in descending order of its CO_2 emissions [52]. (5) The CO_2 capture rate is 90% for the CFPPs [48,52,88]. (6) A discount rate of 5% is used in the economic analysis [24]. (7) The annual CO_2 emissions of the CFPPs are the same each year between 2030 and 2060 [87]. (8) The transportation distance between the CO_2 source and sink is assumed to be 1.1 times the crow flies. It accounts for potential topographical barriers that may hinder the construction of the CO_2 pipeline, such as rivers, roads, railroads, and mountains [43].

2.4. Scenario description

This study develops nine distinct scenarios for analyzing the CCUS source-sink matching (Table 4). For example, S1 scenario means the CCUS projects in the CFPPs in China are deployed between 2030 and 2060. Only the distances between CO_2 sources and sinks within 100 km are considered in the S1 scenario. While the CO_2 source sink distances within 250 km and 800 km are considered in the S2 and S3 scenarios, respectively. S4-S6 scenarios indicate that CCUS projects in the CFPPs in China are deployed between 2035 and 2060. S7-S9 scenarios represent the CCUS projects in the CFPPs in China that are deployed between 2040 and 2060 [54,89].

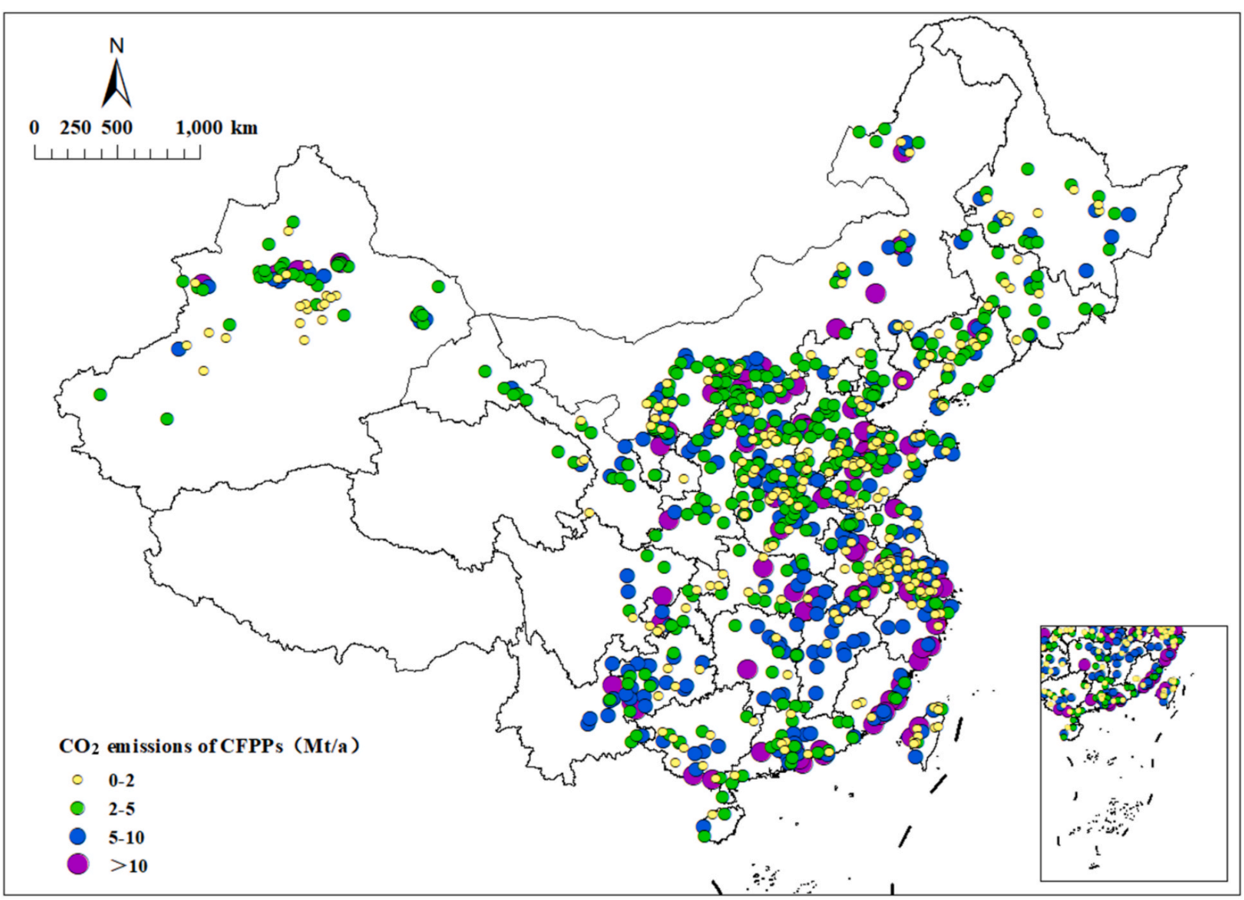

Fig. 2. CO_2 emissions in China's 972 CFPPs (This map is based on a standard map from the Map Technical Review Center of the Ministry of Natural Resources (Review No. GS(2024)0650), and the boundaries of the base map have not been modified).

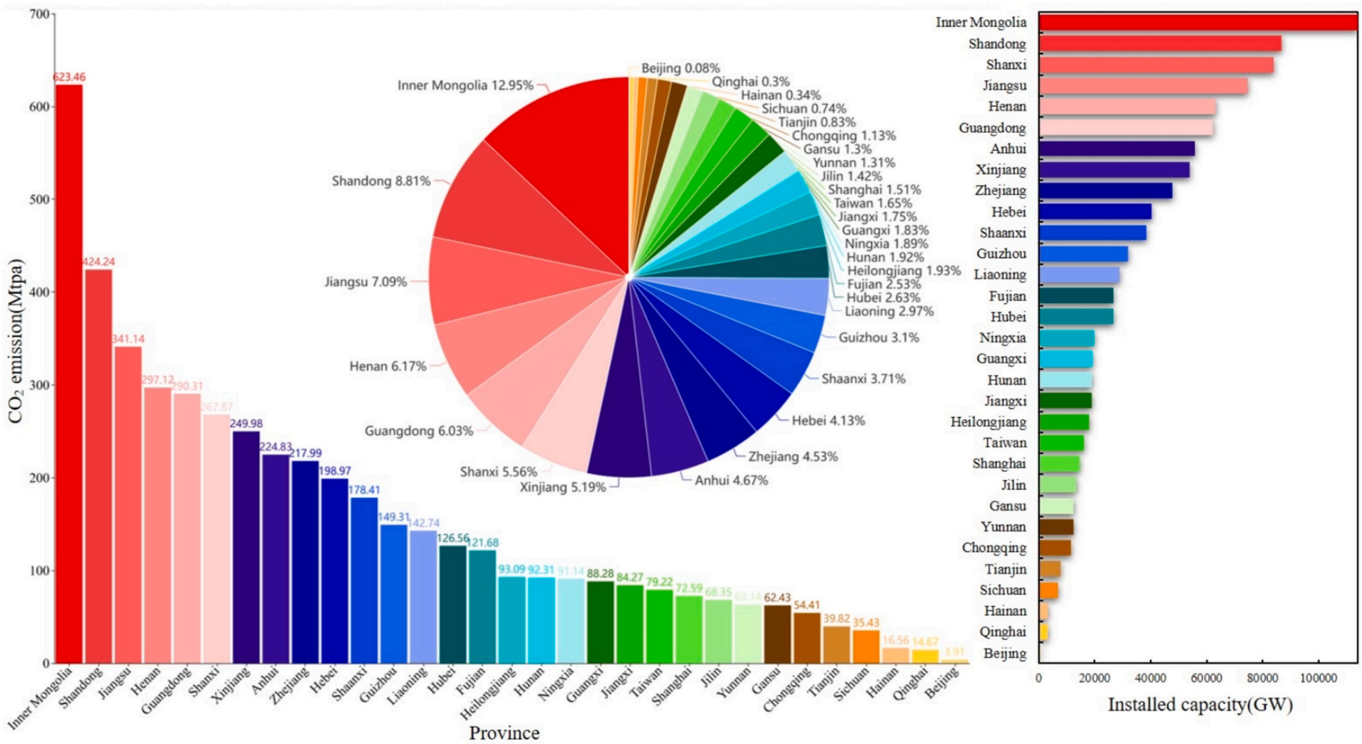

Fig. 3. The CO_2 emissions and installed capacity in China's 972 CFPPs.

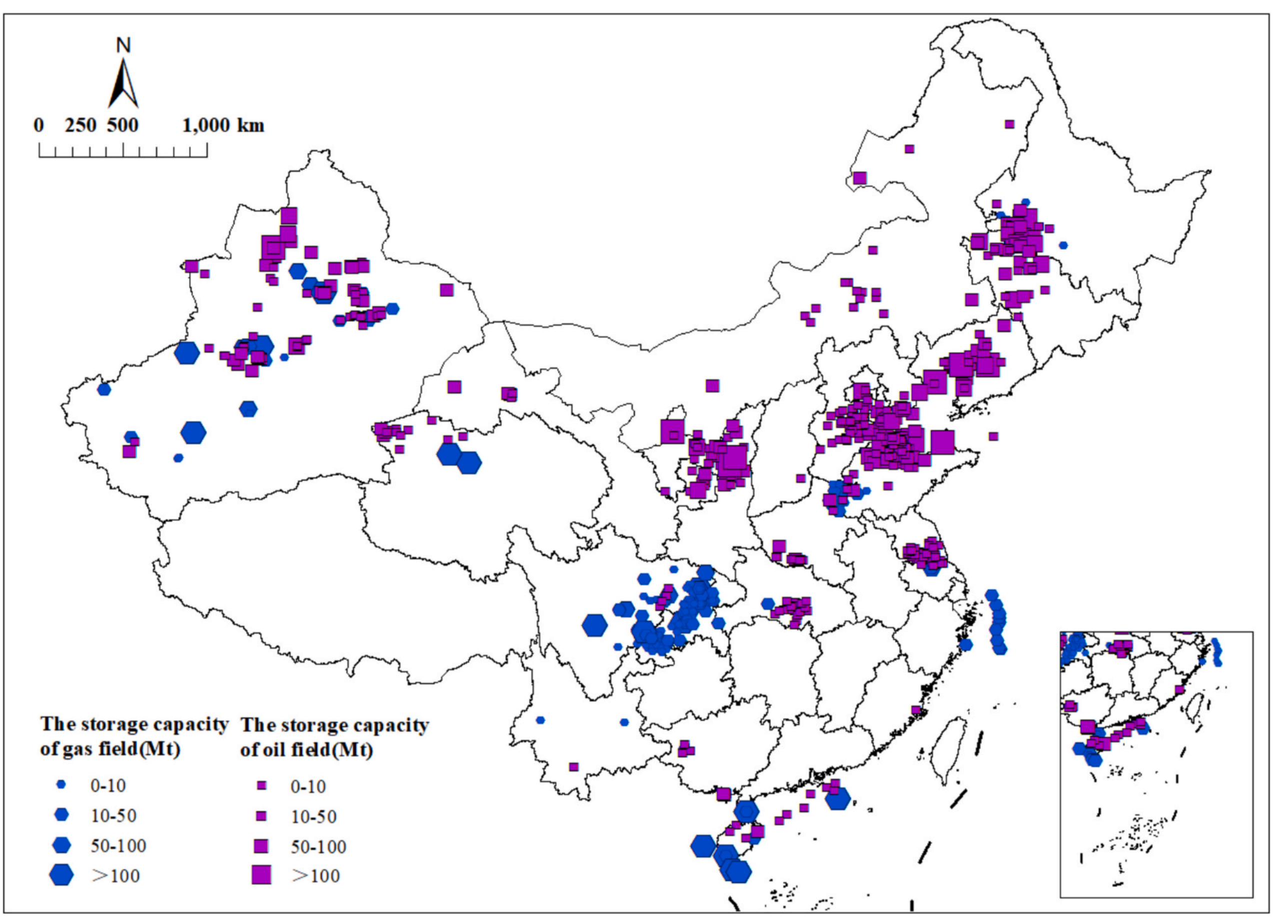

Fig. 4. CO_2 storage capacity of 556 oil fields and 164 gas fields in China (This map is based on a standard map from the Map Technical Review Center of the Ministry of Natural Resources (Review No. GS(2024)0650), and the boundaries of the base map have not been modified).

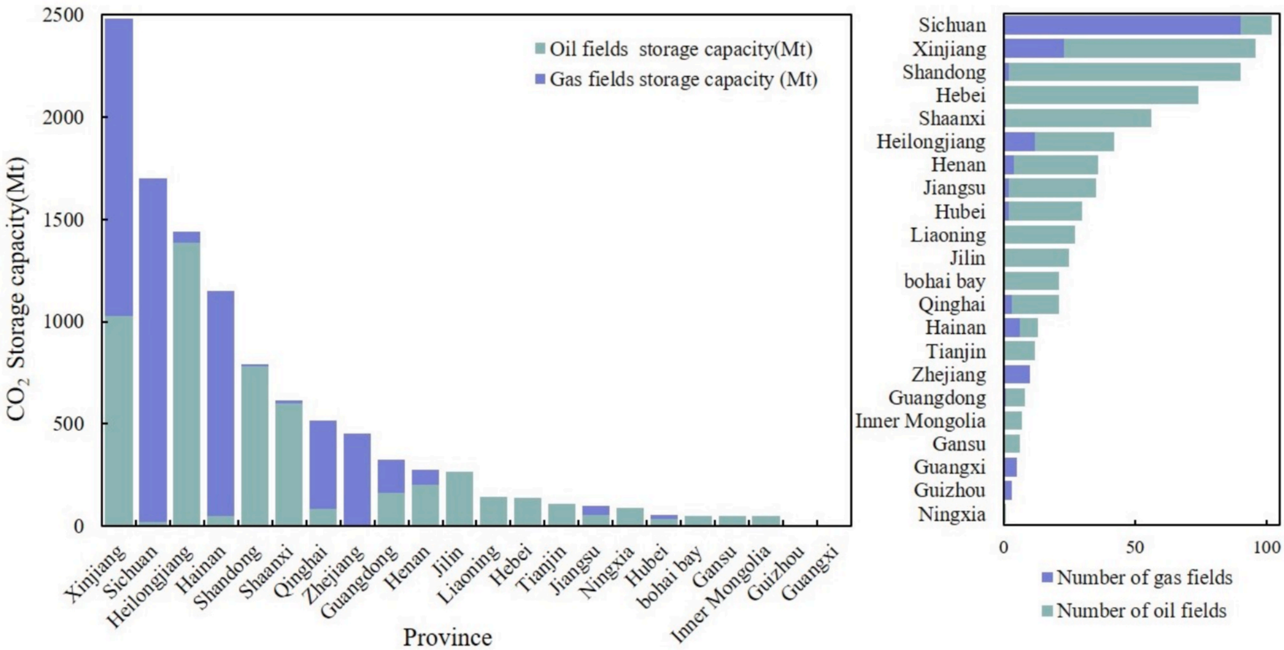

Fig. 5. The number and CO_2 storage potential of 556 oil fields and164 gas fields in China.

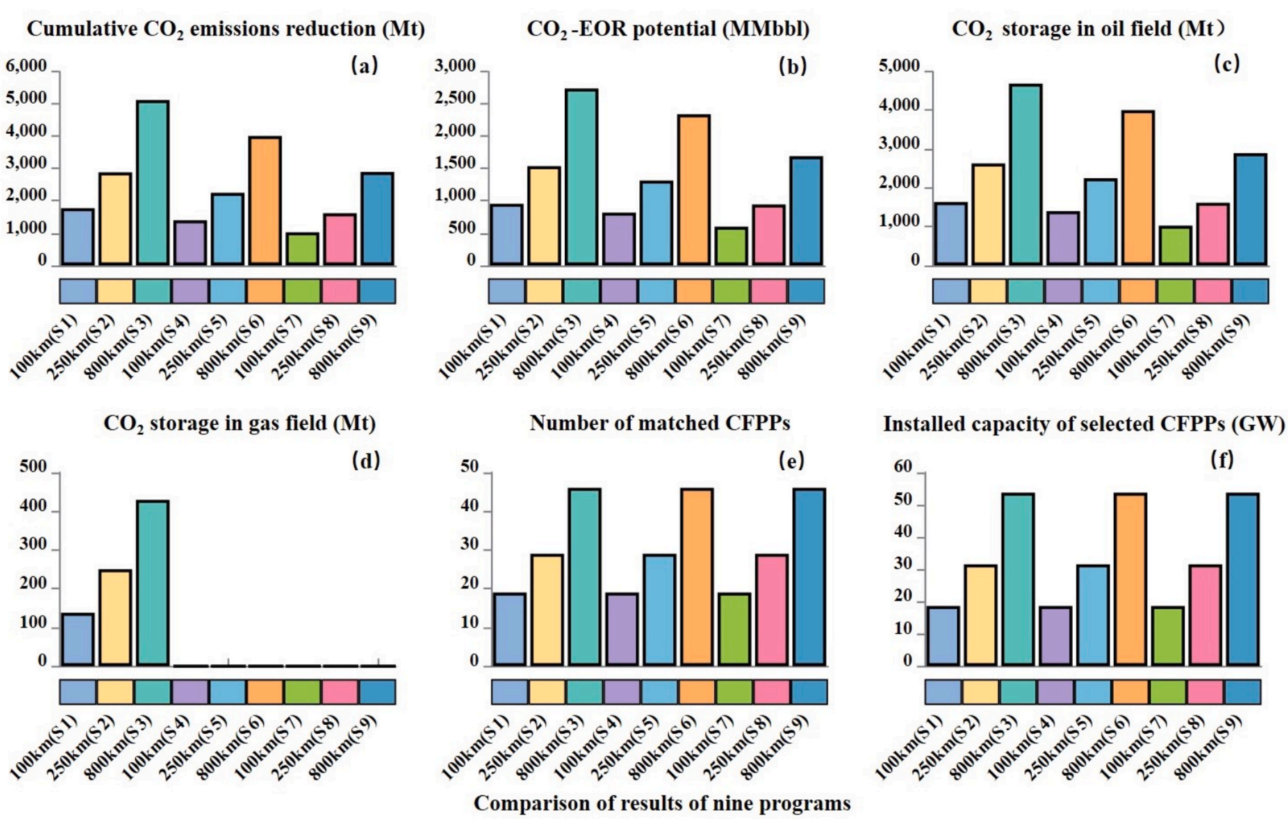

Fig. 6. Comparison of CO_2 source-sink matching results for nine scenarios.

3. Results

3.1. Identification of CO_2 sources and CO_2 sinks

A comprehensive analysis is conducted on 972 CFPPs across China in this study. The CO_2 emissions data for the CFPPs are compiled from various sources, including official websites, reports, and peer-reviewed journal publications [7,11,90–94]. Fig. 2 illustrates the spatial arrangement of CFPPs. There are CO_2 emissions of 4,814.23 Mtpa and an installed capacity of 1,034.09 GW from 972 existing CFPPs. The five leading provinces possess the greatest installed capacity and CO_2 emissions from existing CFPPs: Inner Mongolia, Shandong, Jiangsu,

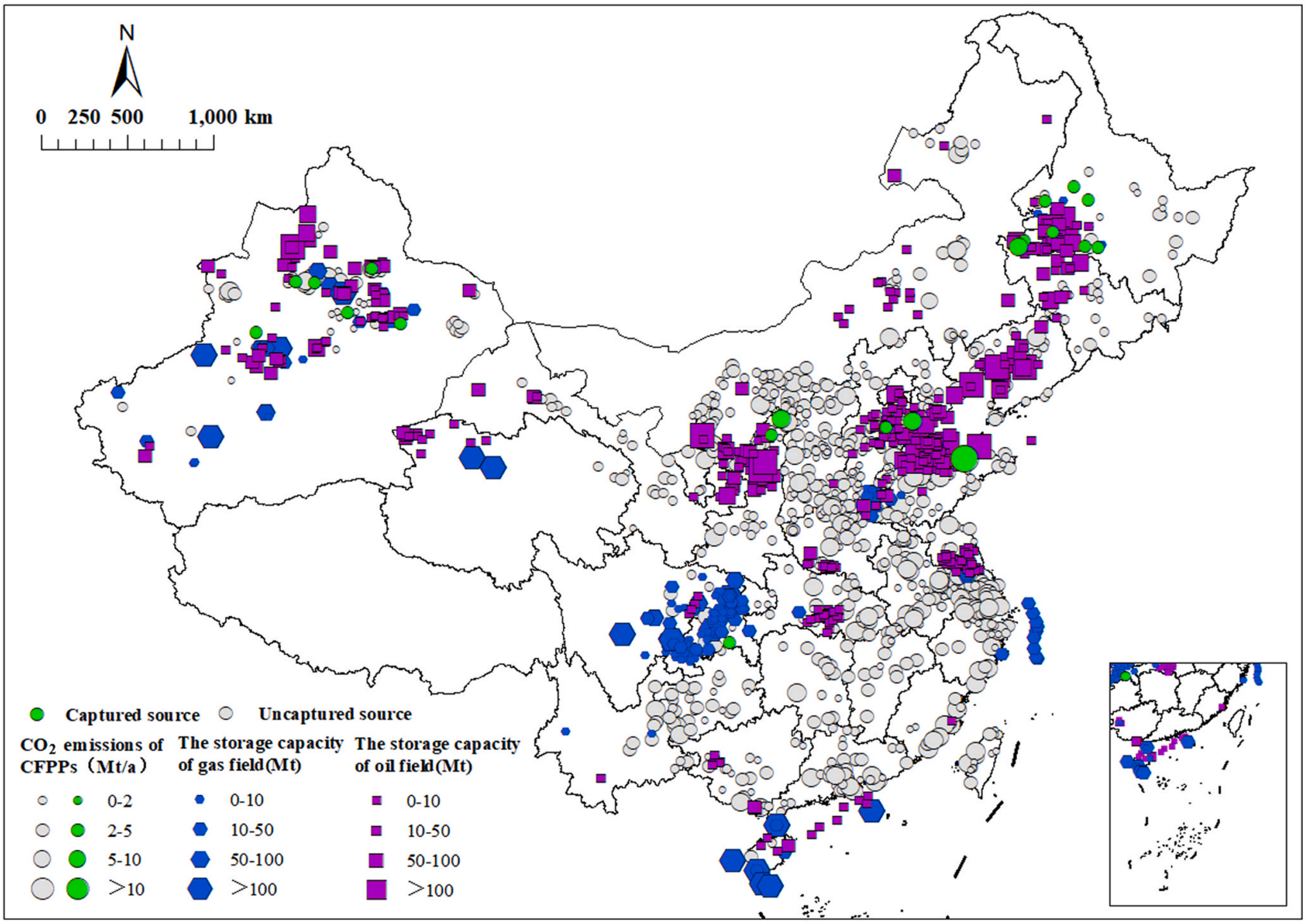

Fig. 7. CO_2 source sink matching within 100 km in scenarios S1, S4, and S7(This map is based on a standard map from the Map Technical Review Center of the Ministry of Natural Resources (Review No. GS(2024)0650), and the boundaries of the base map have not been modified).

Guangdong, and Zhejiang (Fig. 3). While the CO_2 emissions from the CFPPs in western China are relatively lower than those in the eastern and central China.

The oil and gas database is derived from a variety of sources, such as reports, books, and journal publications [95–100]. The spatial distribution of the 556 oil fields and 164 gas fields is shown in Fig. 4. The CO_2 storage capacity of 556 oil fields is estimated at 5.31 Gt. There is a potential for CO_2 EOR of 7,594.79 million barrels (MMbbl). Specifically, the CO_2 storage capacities of oil fields in Heilongjiang, Xinjiang and Shandong Province are 1,388 Mt, 1,028 Mt and 783 Mt, respectively (Fig. 5). Natural gas resources are primarily concentrated within the Sichuan, Junggar, Tarim, and Qiongdongnan basins. The total CO_2 storage capacity amounts to 5.50 Gt across 164 gas fields. Among that, the CO_2 storage capacities are 1,676 Mt, 1,450 Mt and 1,100 Mt in Sichuan, Xinjiang and Hainan provinces, respectively.

3.2. CO_2 source-sink matching

This study selects 169 of 972 CFPPs with an installed capacity above 600 MW. The annual CO_2 emissions from a single CFPP of the 169 CFPPs are greater than 3 Mtpa. The remaining lifetimes of the CFPPs exceed 15 years in 2030. This corresponds to a retrofit potential of 18.62 GW to 53.70 GW. The findings of CO_2 source-sink matching using GIS-based methods across various scenarios are illustrated in Figs. 7-9. The results from nine scenarios of the CCUS source and sink matching are summarized in Table 5. The CO_2 emissions mitigation by CCUS between 2030 and 2060 ranges from 1,025.60 Mt in S7 scenario to 5,116.51 Mt in S3 scenario (Fig. 6). The corresponding CO_2 EOR potential ranges from 598.95 MMbbl to 2,737.52 MMbbl.

In scenarios S1, S4, and S7, the CO_2 transportation distance is limited to within 100 km. The spatial distribution of the selected CO_2 sources and sinks for these scenarios is presented in Fig. 7. The cumulative CO_2 emissions mitigation by 2060 is 1,771.07 Mt, 1,398.34 Mt, and 1,025.60 Mt in the S1, S4, and S7 scenarios, respectively. Because the CCUS is proposed to be deployed since 2030, 2035 and 2040 in the S1, S4, and S7 scenarios, respectively. The CFPPs are mainly located in Xinjiang, Heilongjiang, Jilin, Hebei, and Shandong, etc. The CO_2 EOR potential is mainly located in Xinjiang, Shandong, Heilongjiang, and Jilin.

If the maximum CO_2 transportation distance increases to 250 km, more CO_2 emissions can be mitigated by CCUS. The geographical distribution of the selected CO_2 sources and sinks for scenarios S2, S5 and S8 is shown in Fig. 8. The cumulative CO_2 emissions mitigation by 2060 is 2,879.60 Mt, 2,247.40 Mt and 1,615.19 Mt in the S2, S5, and S8 scenarios, respectively.

The CO_2 transportation distance within 800 km is considered in scenarios S3, S6 and S9 (Fig. 9). The cumulative CO_2 emissions mitigation by 2060 is 5,116.51 Mt, 4,004.78 Mt and 2,893.06 Mt in S3, S6 and S9 scenarios, respectively. However, the offshore CCUS is recommended in southeastern China including Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan [49,101,102].

3.3. Economic analysis

Following the alignment of CO_2 sources and sinks, an economic evaluation of CCUS implementation is conducted. The outcomes are depicted in Fig. 10 and Table 6. For example, initiating CCUS

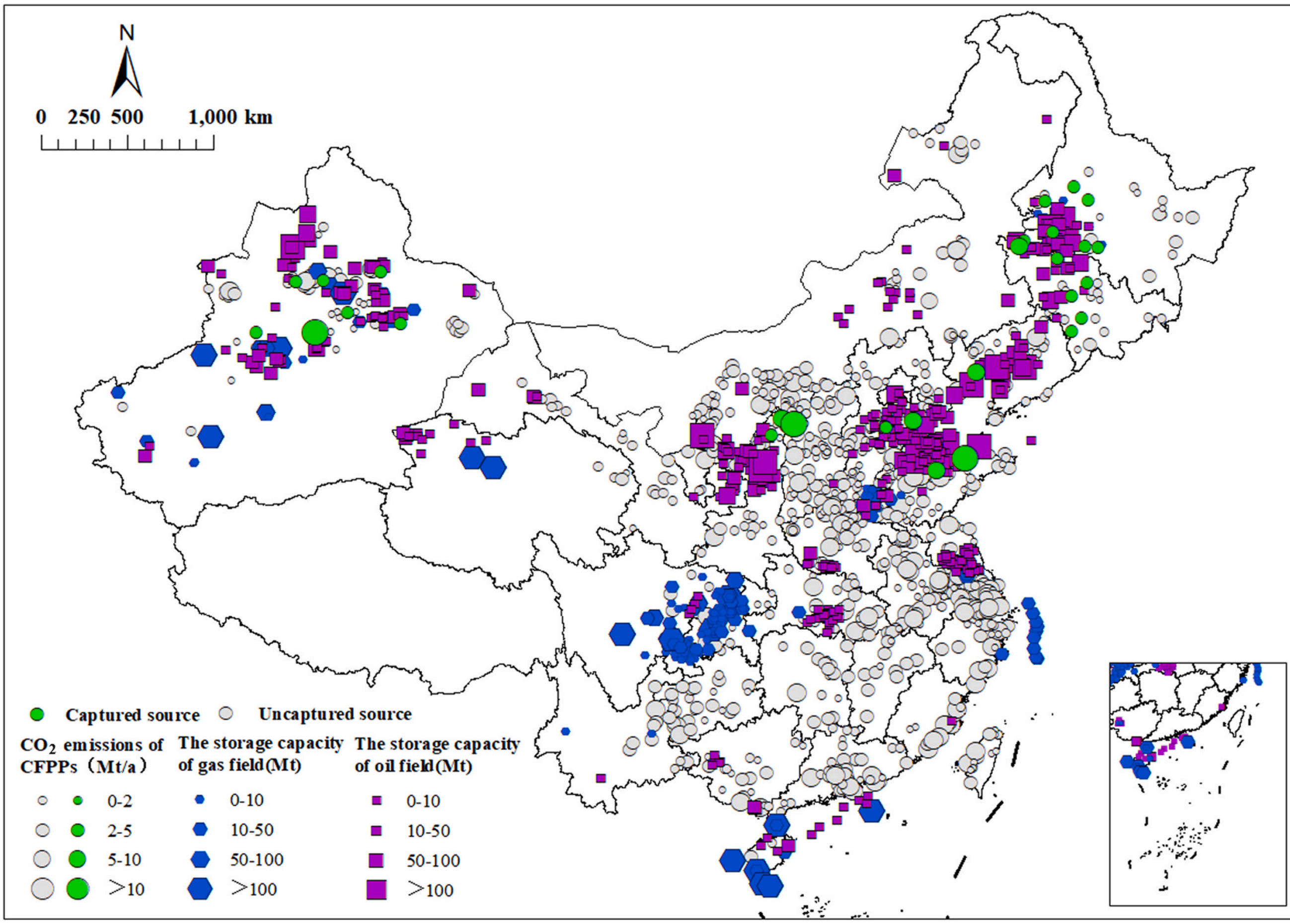

Fig. 8. CO_2 source sink matching within 250 km in scenarios S2, S5, S8(This map is based on a standard map from the Map Technical Review Center of the Ministry of Natural Resources (Review No. GS(2024)0650), and the boundaries of the base map have not been modified).

deployment in 2030 entails total investment costs of $58.8 billion, $97.7 billion and $167 billion for the S1, S2, and S3 scenarios, respectively. Under a 5% discount rate, the NPVs for the S1, S2, and S3 scenarios are $23.8, $37.9, and $68.3 billion, respectively.

The CCUS cost includes four primary components (Fig. 10). The CO_2 capture cost dominates in all CCUS scenarios, accounting for more than 65% of the total cost. CO_2 pipeline transportation costs accounted for about 10%-20% of the total costs in all scenarios. CO_2 storage costs range from 5% to 10% of the total costs for each scenario.

Most of the CO_2 can be stored in oil reservoirs for CO_2 EOR in Scenarios S1, S2, and S3. This is because the CO_2 storage capacity in the nearby oil fields is not enough. 137.75 Mt, 250.07 Mt, and 428.97 Mt of CO_2 are stored in the gas fields, respectively (Table 5). Every instance of CO_2 storage is implemented within oil fields across scenarios S4 to S9. Delaying CCUS deployment from 2030 to 2040 reduces cumulative NPV (Table 6). Compared to the NPV in the scenarios S1, S2, and S3 ($23.8 billion – $68.3 billion), the NPV of CCUS deployment is lower in the scenarios S7, S8, and S9 ($12.4 billion – $35.6 billion). Furthermore, the NPV increases as the maximum CO_2 transport distance extends from 100 km (S1) to 800 km (S3). Specifically, the cumulative NPV of scenarios S3, S6, and S9 ($35.6 billion – $68.3 billion) is higher than that of scenarios S1, S4, and S7 ($12.4 billion – 23.8 billion).

4. Discussion

The top ten CCUS projects proposed for 2030 are illustrated in Fig. 11 and detailed in Table 7. The CFPPs are distributed across eight provinces in China, including Xinjiang, Shandong, Ningxia, and Shaanxi. CO_2 emissions from the ten CFPPs are 103.73 Mtpa, with a cumulative CO_2 reduction potential of up to 2,058.29 Mt. Notably, CO_2 emissions from the CFPPs in Xinjiang and Shandong provinces account for 47% of the ten power plants by 2060, at 24.68% and 22.38%, respectively. The CO_2 storage capacity and CO_2 EOR potential of the oil fields are estimated at 2,286.30 Mt and 3,231.41 MMbbl, respectively.

The total NPV of the proposed ten CCUS projects is $33.2 billion (Table 7). Among these, the NPVs of CCUS in Xinjiang and Shandong provinces are $7.75 billion and $7.21 billion, respectively, accounting for 45% of the total NPV. Furthermore, the CCUS projects are proposed to be materialized in four groups (Fig. 11). The CCUS plans interconnect multiple CO_2 emission points and storage sites using shared networks. In group I, the CCUS proposal covers Shandong, Henan and Hebei provinces, including Huadian Laizhou, Yantai Bajiao, Pingdingshan Luyang, and Caofeidian power plants. CO_2 emission from the CFPPs is 37.97 Mtpa. CO_2 EOR candidates include the Shengtuo, Gudao, Jing'anpu, Dongxin, and Gudong oil fields. In group II, CCUS projects are proposed at Wujiaqu and XPCC Shihezi Cogen power plants in the Xinjiang province. CO_2 emissions from the CFPPs of Xinjiang are 25.93 Mtpa. CO_2 EOR candidates include the Kelamayi, Tahe, Baikouquan, Luliang and Niuquanhu oil fields. In group III, the CCUS proposal covers Ningxia and Shaanxi, including Shenhu Yuanyang and Leilongwan power plants. CO_2 emissions from the two CFPPs of Ningxia and Shaanxi are 22.68 Mtpa. CO_2 EOR candidates include the Ansai, Jing'an, Yongning and Xifeng oil fields. In group IV, CCUS projects are implemented at Huolinhe Zhanute power plant in Inner Mongolia and CPI Baicheng power plant in Jilin. CO_2 emissions from the CFPPs in the Inner Mongolia and Jilin are 17.15 Mtpa. CO_2 EOR candidates include the Lamadian, Daqingzijing, Qian'an

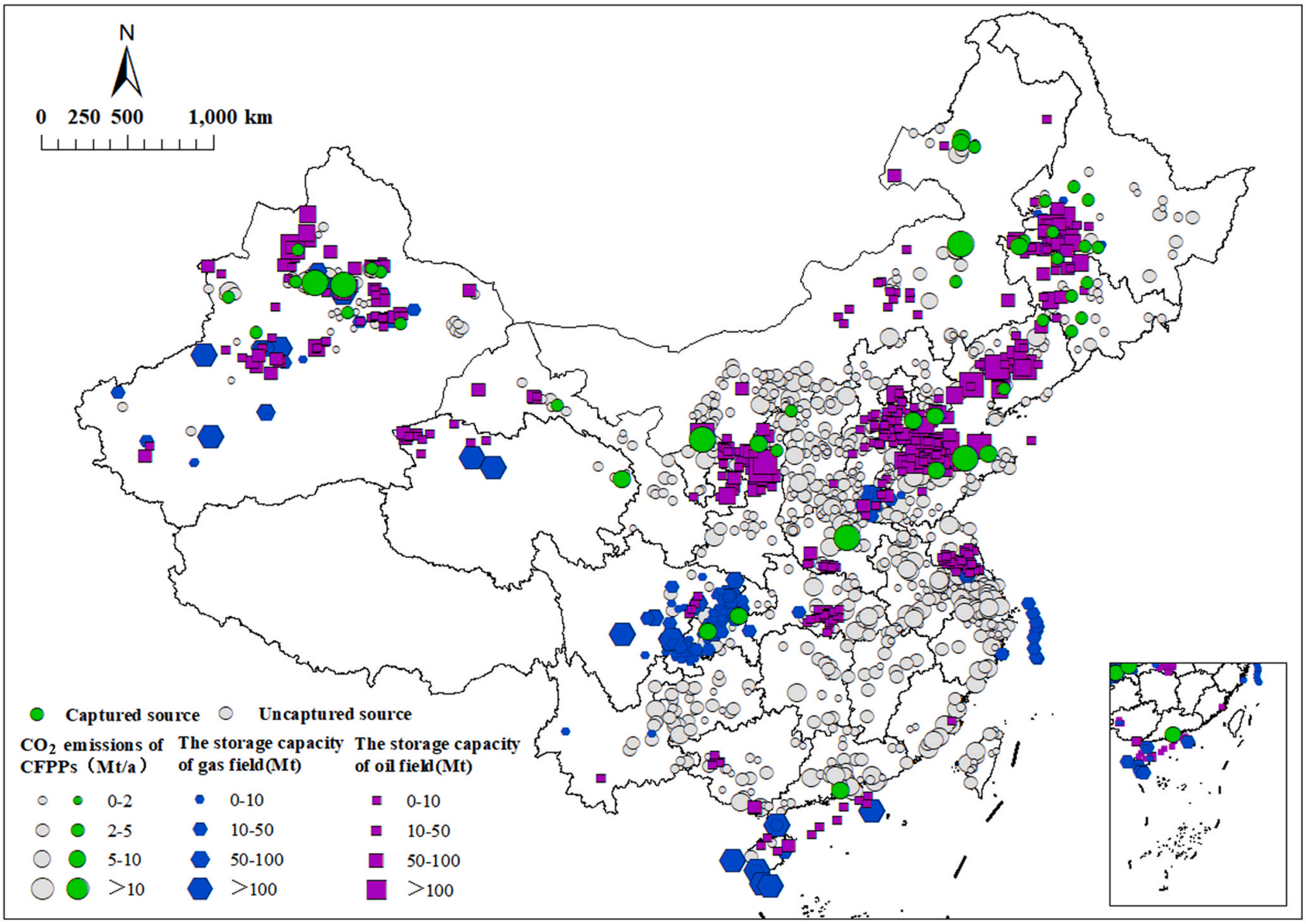

Fig. 9. CO_2 source sink matching within 800 km in scenarios S3, S6, S9(This map is based on a standard map from the Map Technical Review Center of the Ministry of Natural Resources (Review No. GS(2024)0650), and the boundaries of the base map have not been modified).

Table 5
Nine different scenarios demonstrate the results of CO_2 source-sink alignment.

Indicators (Scenarios)		Cumulative CO_2 emissions reduction (Mt)	CO_2 EOR potential (MMbbl)	CO_2 storage in oil fields (Mt)	CO_2 storage in gas fields (Mt)	Number of matched CFPPs	Installed capacity of selected CFPPs (GW)
2030–2060	100 km (S1)	1,771.07	953.86	1,633.32	137.75	19	18.62
	250 km (S2)	2,879.60	1,535.65	2,629.54	250.07	29	31.50
	800 km (S3)	5,116.51	2,737.52	4,687.54	428.97	46	53.70
2035–2060	100 km (S4)	1,398.34	816.63	1,398.34	/	19	18.62
	250 km (S5)	2,247.40	1,312.48	2,247.40	/	29	31.50
	800 km (S6)	4,004.78	2,338.79	4,004.78	/	46	53.70
2040–2060	100 km (S7)	1,025.60	598.95	1,025.60	/	19	18.62
	250 km (S8)	1,615.19	943.27	1,615.19	/	29	31.50
	800 km (S9)	2,893.06	1,689.55	2,893.06	/	46	53.70

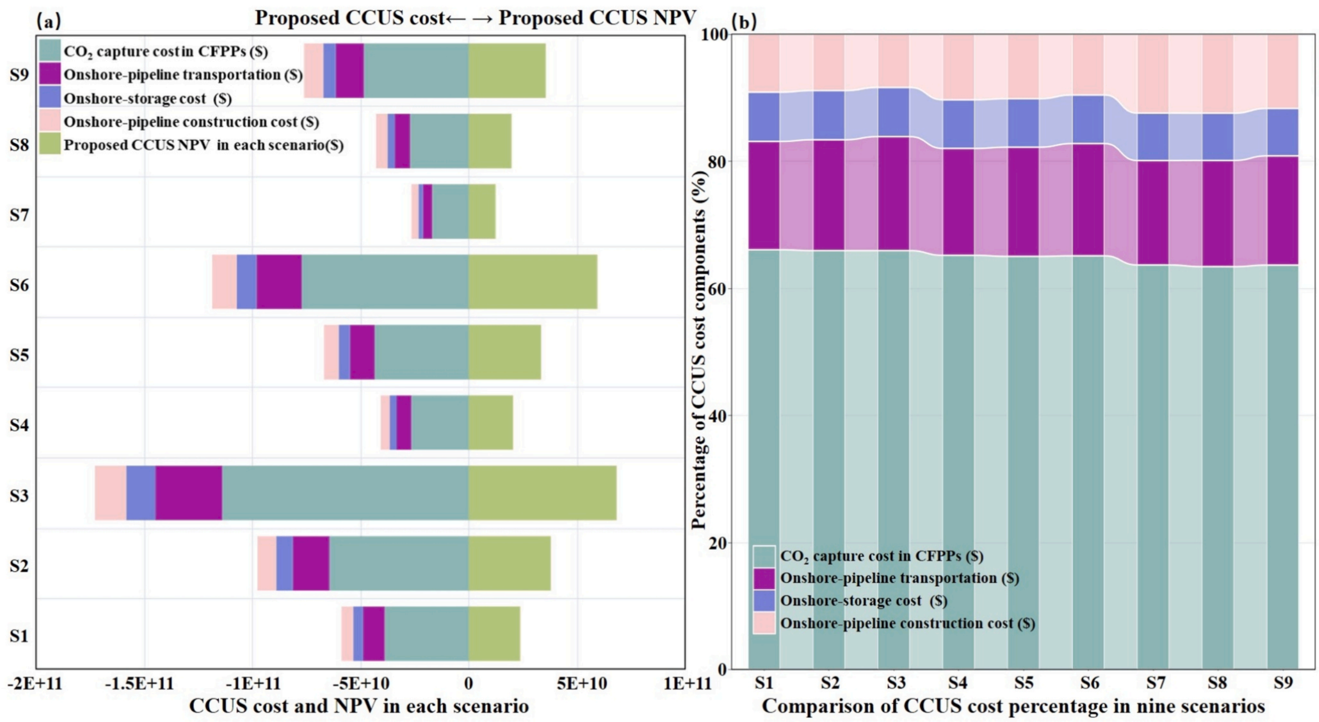

Fig. 10. CCUS costs and NPV for each scenario.

Table 6
CCUS cost and NPV results for 9 Scenarios.

Scenarios	CCUS deployment time	Total cost ($)	NPV ($)		
			Low	Mid	High
100 km (S1)	2030	5.88E + 10	3.15E + 09	2.38E + 10	4.45E + 10
250 km (S2)	2030	9.77E + 10	4.01E + 09	3.79E + 10	7.18E + 10
800 km (S3)	2030	1.67E + 11	7.35E + 09	6.83E + 10	1.29E + 11
100 km (S4)	2035	4.07E + 10	5.18E + 09	2.05E + 10	3.58E + 10
250 km (S5)	2035	6.69E + 10	8.32E + 09	3.34E + 10	5.85E + 10
800 km (S6)	2035	1.15E + 11	1.51E + 10	5.94E + 10	1.04E + 11
100 km (S7)	2040	2.65E + 10	2.68E + 09	1.24E + 10	2.22E + 10
250 km (S8)	2040	4.28E + 10	4.13E + 09	1.98E + 10	3.54E + 10
800 km (S9)	2040	7.34E + 10	7.66E + 09	3.56E + 10	6.35E + 10

and Xinmin oil fields. For all four groups, the separation between CO_2 emission points and storage locations ranges up to 800 km and numerous instances under 200 km.

5. Limitations

This research presents certain limitations that should be acknowledged. First, to calculate the CO_2 storage potential within oil and gas fields, this study posits that the reservoir's pore space is entirely filled with stored CO_2. However, the injected CO_2 can't fully displace the aquifer that intrudes into the reservoirs. The actual CO_2 storage capacity may be overestimated [24]. The degree of CO_2-oil miscibility is determined by the reservoir fluid composition and operating conditions. Due to the unavailability of oil composition data for 556 oil fields, Equation (3) is utilized to assess the CO_2-oil miscibility. Second, this study assumes that economic costs, CO_2 capture rates, and oil prices remain constant. However, economic assessments can be influenced by oil price fluctuations, carbon markets, and cost reductions in technology innovation [103,104]. Third, this paper posits that the operational status and energy consumption patterns of all CFPPs remain unchanged [87]. However, in practice, these factors may be affected by technological advancements, fluctuations in energy prices, and policy changes [105]. Specifically, as technologies mature and market conditions evolve, the operational efficiency and emissions levels of CFPPs may undergo significant changes [106,107]. Fourth, due to limited geological data, this study does not sufficiently consider environmental and geological factors that may influence CO_2 storage in different regions. Variables such as reservoir type and groundwater levels could affect both the storage capacity and the long-term stability of CO_2 [108]. Fifth, this study assumes that China has not yet implemented a carbon tax policy. As a result, the amount of CO_2 stored in oil and gas fields is relatively low, and the model does not account for alternative deployment strategies that could be employed under a carbon tax policy. As carbon tax policies are gradually implemented and market conditions evolve (e.g., fluctuations in carbon prices and policy adjustments), more CO_2 may be stored in saline aquifers [109,110]. Sixth, the study does not sufficiently consider the potential impact of the rapid expansion of renewable energy sources such as wind, solar, and hydropower on the future deployment of CCUS. As renewable energy capacity continues to increase, the operational load of conventional CFPPs may decline, thereby affecting their CO_2 emissions levels and the scale of CCUS deployment [111].

6. Policy implications

In light of the earlier CCUS source-sink matching in China, this study offers policymakers the following suggestions. First, regional coordination and CO_2 source-sink matching hubs should be established, particularly in the areas exhibiting a high concentration of CFPPs and oil fields. Strategic locations such as Jinan, Xi'an, Urumqi, and Harbin are proposed as locations for these hubs to optimize resource allocation. These hubs will serve as centers for decision-making, regulatory

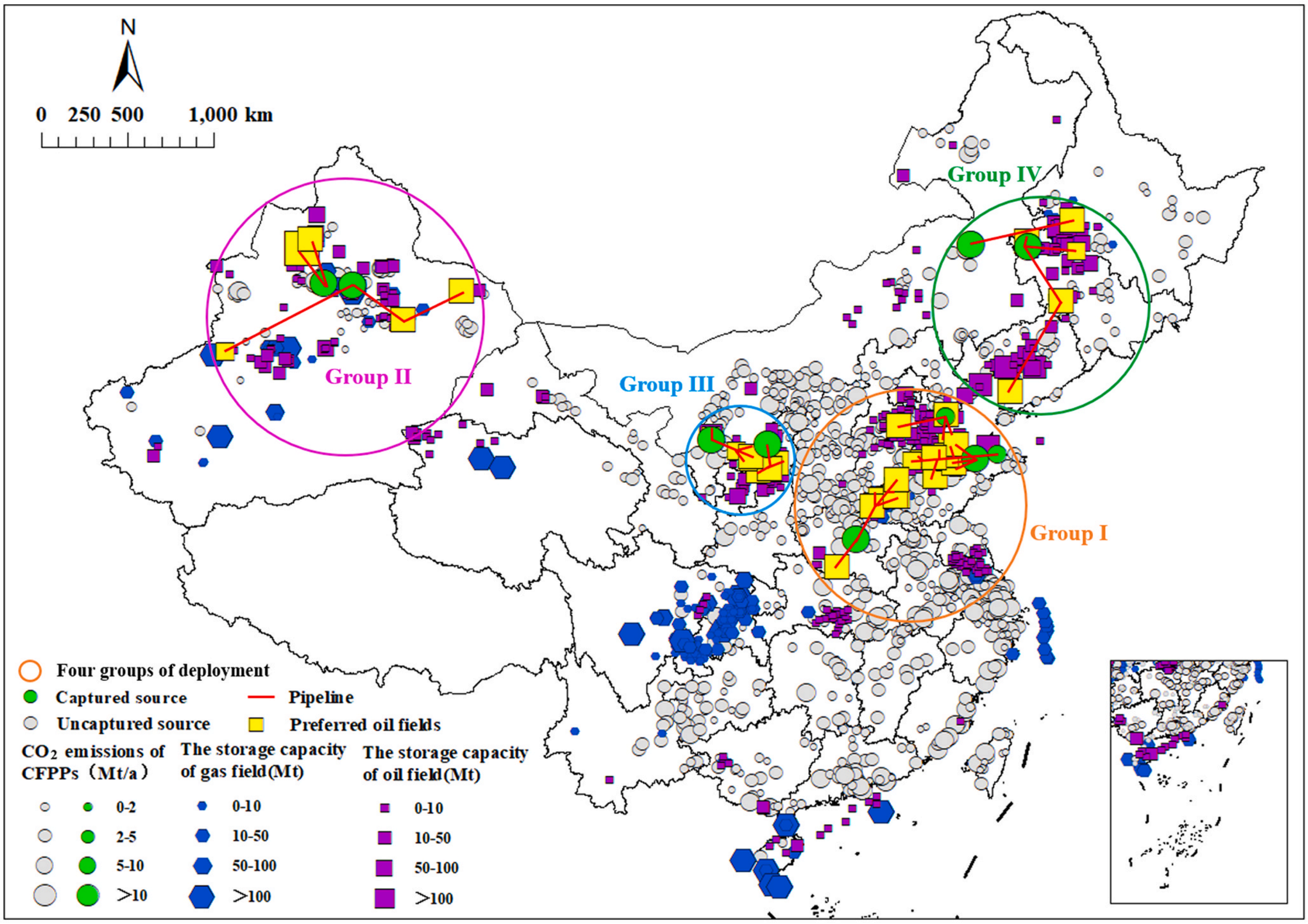

Fig. 11. Source sink matching results for the top ten preferred projects(This map is based on a standard map from the Map Technical Review Center of the Ministry of Natural Resources (Review No. GS(2024)0650), and the boundaries of the base map have not been modified).

compliance, resource management, and technical support. Their establishment will enhance CCUS deployment efficiency and help to achieve carbon reduction targets. Second, the large-scale CFPPs close to the light oil fields should be given the top priority for CCUS. For example, the CFPPs such as Wujiaqu, Huadian Laizhou, and Huolinhe Zhanute are close to the oil fields for CO_2 EOR. Third, the infrastructure for CO_2 transportation networks should be properly planned based on the CCUS source-sink matching. Policies should emphasize establishing a nationwide CO_2 transportation network that efficiently connects the high CO_2 emission regions (e.g., Shandong and Xinjiang) with suitable oil field storage sites. Fourth, policymakers should allocate government funding to drive technological innovations for CCUS costs reduction, particularly for CO_2 capture cost in the CFPPs. Government support for CCUS demonstration projects is crucial to mitigating the financial risks associated with CCUS investments. Fifth, a robust monitoring and regulatory framework should be established. This includes implementing a comprehensive monitoring, reporting, and verification system for CO_2 capture, transportation, and storage.

7. Conclusions

This study evaluates CO_2 emissions from 972 operational CFPPs and the storage potential in 556 oil fields and 164 gas fields across China. A detailed analysis of CO_2 source-sink matching has been carried out to aid China in meeting its 2060 decarbonization goals for CFPPs. The key findings of this study are as follows:

1) CO_2 emissions of 4,814.23 Mtpa and an installed capacity of 1,034.09 GW from 972 existing CFPPs are investigated in China. There is a CO_2 storage potential of 5.31 Gt in the 556 oil fields and 5.50 Gt in the 164 gas fields, respectively.
2) 169 of 972 CFPPs are selected for CCUS. There is a CO_2 reduction potential of 1.03 Gt to 5.12 Gt in the oil and gas fields in China by 2060. Expanding the maximum permissible transport range from 100 km to 800 km will increase the number of CO_2 emission sources eligible for CCUS deployment.
3) CCUS deployment for CO_2 EOR offers both economic and environmental benefits. The investment costs of the CCUS projects between 2030 and 2060 range from $26.5 billion to $167 billion, yielding an NPV of $12.4 billion to $68.3 billion. For the same maximum transportation distance, delaying CCUS deployment from 2030 to 2040 reduces the NPV by $11.4 billion to $32.8 billion at a 5% discount rate. Conversely, extending the transportation distance from 100 km to 800 km results in an NPV increase of $23.2 billion to $44.5 billion for the same deployment timeframe.
4) The top ten CCUS projects are proposed for 2030. CO_2 emissions from the ten CFPPs are 103.73 Mtpa. These CCUS projects will generate an NPV of $33.2 billion between 2030 and 2060. Based on the CO_2 source-sink matching framework, a four-group deployment strategy is outlined.

CRediT authorship contribution statement

Xudong Gao: Writing – original draft, Visualization, Investigation, Data curation. **Kai Zhang:** Writing – review & editing, Writing – original

Table 7
Proposed top ten power plants and their corresponding reservoir layouts for CCUS carbon sources in 2030.

Group	CFPPs name	Province	Annual CO_2 emissions (Mtpa)	Installed capacity (MW)	Start up year of the CFPPs	CO_2 EOR potential (MMbbl)	Total CO_2 EOR potential (MMbbl)	CO_2 storage capacity in oilfields (Mt)	Cumulative CO_2 reductions by 2060(Mt)	Mid CCUS NPV($)
I	Huadian Laizhou	Shandong	16.4	4,078	2012	Shengtuo(167.88), Gudao (138.10), Bohnan(81.75), Niuzhuang(55.06), Binnan (33.23), Shanghe(32.33)	508.35	365.59	324.72	4.67E + 09
I	Yantai Bajiao	Shandong	5.39	1,340	2018	Dongxin(96.62), Gudong (93.66), Linpan(32.33), Shangdian(48.47)	271.08	202.35	135.83	2.54E + 09
I	Pingdingshan Luyang	Henan	9.11	2,060	2010	Pucheng(96.16), Wennan (45.04), Wendong(35.05), Shuanghe(30.35), Wenzhong(26.15), Huzhuangji(18.65), Wenmingzhai (9.16)	260.57	164.15	163.98	3.07E + 09
I	Caofeidian	Hebei	7.07	1,600	2009	Jing'anpu(113.31), Renqiu (45.18), Gaoshangbao (40.81)	199.30	125.82	120.90	2.72E + 09
II	Wujiaqu	Xinjiang	16.02	3,640	2011	Kelamayi(522.46), Baikouquan(95.42)	617.88	336.51	302.78	4.41E + 09
II	XPCC Shihezi Cogen	Xinjiang	9.91	2,640	2013	Tahe(272.94), Luliang (71.45), Niuquanhu(37.38)	381.76	222.20	205.14	3.34E + 09
III	Shenhu Yuanyang	Ningxia	14.51	3,520	2010	Yongning(94.79), Xifeng (80.86), Dingbian(45.48), Xingzichuan(37.46), Maling (30.76)	289.35	268.23	261.18	3.80E + 09
III	Leilongwan	Shaanxi	8.17	2,000	2018	Ansai(117.66), Jing'an (103.39), Wayaobu(26.49)	247.55	229.48	205.88	2.67E + 09
IV	Huolinhe Zhanute	Inner Mongolia	10.81	2,300	2013	Lamadian(280.68)	280.68	260.19	223.77	3.69E + 09
IV	CPI Baicheng	Jilin	6.34	1,320	2010	Daqingzijing(73.65), Qian'an(58.01), Xinmin (43.23)	174.89	111.78	114.12	2.26E + 09
Total	/	/	103.73	24,498	/	/	3,231.41	2,286.30	2,058.29	3.32E + 10

draft, Project administration, Funding acquisition. **Dongqi Ji:** Validation, Project administration, Data curation. **Haoming Ma:** Writing – review & editing, Supervision, Resources. **Yang Meng:** Software, Investigation. **Shu Jiang:** Project administration, Funding acquisition. **Wei Tian:** Validation, Supervision. **Yuhang Tang:** Methodology, Conceptualization. **Liu He:** Investigation. **Chaohua Liu:** Methodology. **Hon Chung Lau:** Validation, Supervision. **Zhangxin Chen:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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