Assessing the Cost Reduction Potential of CCUS Cluster Projects in China: A Case Study

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Abstract

Carbon capture, utilisation, and storage (CCUS) have garnered extensive attention as a target of carbon neutrality in China. The development trend of international CCUS projects indicates that the cluster construction of CCUS projects is the main direction of future development. The cost reduction potential of CCUS cluster projects has become a significant issue for CCUS stakeholders. The Pearl River Mouth Basin, adjacent to Guangdong province, is a suitable region for CCUS cluster project construction. To assess the cost reduction potential of CCUS cluster projects, we selected three coal-fired power plants in the coastal area of Guangdong as research targets. We initially assessed the costs of building individual CCUS projects for each plant and subsequently designed a CCUS cluster project for these plants. By comparing individual costs and CCUS cluster project costs, we assessed the cost reduction potential of CCUS cluster projects. The results show that CCUS cluster projects can significantly reduce costs by sharing pipelines and storage facilities. Furthermore, we conducted a simulation for the scenario of a larger designed capture capacity for each plant. We found that as the capture scale increases, the cost reduction potential is higher in the future, considering large-scale CCUS cluster projects.

1. Introduction

The 26th UN Climate Change Conference (COP26) concluded on 12 November 2021. The COP26 adopted a resolution and reached consensus on the implementation rules of the Paris Agreement for investing billions in climate finance and to phase-down coal-fired generation in the following decades. The Contracting Parties need to take joint actions to effectively address the crisis and challenges brought by climate change (COP26, 2021a). The importance of carbon capture, utilisation, and storage (CCUS) was widely recognised during the COP26. More than 30 CCUS events were took place at the COP26, covering policy, business, and social and technical challenges. The United States and China, the world's top greenhouse gas emitters, announced the US-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s to cooperate in fighting climate change. One major commitment was to work together on the 'deployment and application of technology such as CCUS and DAC' (COP26, 2021b). The fact that CCUS has been repeatedly discussed at the COP26 indicates it will be indispensable to the global response to future climate change.

CCUS has already been proven and used across a variety of industries, including coal-fired plants, the cement industry, and the natural gas processing and refinery industry (Vikram et al., 2021). Under the global trend of carbon neutrality, the range of industrial applications will grow further to more industries. The International Energy Agency (IEA) announced that 15 per cent of the world's emission reductions between now and 2050 will be delivered by CCUS to meet ambitious climate goals. This equates to 2,000 large-scale facilities being deployed by 2050—around 100 facilities commissioned each year (IEA, 2020).

On 12 March 2021, China released the outline of the 14th Five-Year Plan for National Economic and Social Development and the Long-term Goal of 2035, wherein 'carbon peak' and 'carbon neutrality' have become the main targets in the next five years. During the 14th Five-Year Plan, the Chinese government emphasised that CCUS is a crucial green technology in the fight against climate change, and large-scale CCUS projects must be deployed in the next five years (China State Council, 2021a; Xin et al, 2021). Notably, after China proposed a carbon neutrality climate target in September 2020, many scholars and research institutes started conducting research on China's carbon neutralisation pathway to distinguish the development prospects of the various low-carbon technologies. The number released by the Ministry of Science and Technology shows that China has to

capture at least 1 billion tons of carbon dioxide (CO₂) per year in 2060 to guarantee a carbon neutrality target (Xian, 2021). Therefore, CCUS plays a key role in China's low-carbon transition process (Yuan et al., 2021; Huijuan et al., 2021).

There are many existing large-scale CCUS projects can capture millions of tons of CO₂ each year. However, not all industry sources of emissions can be used to build megaton scale CCUS projects. There are a huge number of small-scale industry plants only emit relative lower emissions individually. The combined emissions from such smaller-scale facilities accounts for a significant portion of global emissions, but it may be uneconomical for any individual facility to deploy the full-chain CCUS project. Smaller full-chain CCUS projects lead to higher unit emission reduction cost. For example, in the United States in 2019, approximately 298 Mtpa of CO₂ was produced by 4,931 individual facilities, each emitting under 200,000 tons of CO₂ per year. Smaller-scale emission facilities represented nearly 16 per cent of the US industrial facility emissions (GCCSI, 2021a). Other parts of the world also have significant volumes of CO₂ spread across smaller facilities. Carbon neutrality targets require decarbonisation from these facilities, proper solutions must be proposed to help these smaller facilities deploying CCUS projects if CCUS is still a necessary technology for them.

One solution to this problem is the implementation of CCUS cluster projects, wherein several industrial facilities share CCUS infrastructure and knowledge, thereby reducing their costs compared to each facility attempting to individually reduce emissions. Clustering creates a network of smaller emitters and centralises the parts of the CCUS infrastructure shared by all individual contributors.

The international development of CCUS projects also shows a trend of 'transferring individual projects to cluster projects'. For example, the United Kingdom government announced in November 2020 that they will provide 1 billion pounds to fund four CCUS cluster projects before 2030 (UK GOV, 2020), and they also began the CCUS cluster sequencing project to identify the best potential CCUS cluster projects in May 2021 (UK GOV, 2021). The Global Carbon Capture and Storage Institute (GCCSI) followed the example of Northern Lights CCUS Project in Norway to study the impact of cluster construction on the cost reduction of CCUS projects, and suggested that more regional or inter-country CCUS cluster projects should be implemented in the future (GCCSI, 2021b). The UK GOV (2017) investigated seven industrial clusters in the United Kingdom and scored all these areas by using the diamond model to evaluate whether these areas have unique advantages for CCUS project construction. The results showed that building CCUS cluster projects in these areas had obvious cost reduction potential for large-scale CCUS projects. In 2019, the Ministry of Science and Technology of China (2019) published the China CCUS Roadmap 2021, and proposed six suitable regions for CCUS cluster projects in China and officially started CCUS cluster project research. Guided by the Roadmap, China National Petroleum Corporation (CNPC) established the first CCUS cluster project in Xinjiang province in October 2019, which aims to capture 3 million tons CO₂ per year by 2030 (OGCI, 2019).

However, although many scholars believe that cluster construction can promote the development of CCUS projects and has great potential to reduce the overall cost, there is still a lack of quantitative financial evaluation for CCUS cluster projects. A clear assessment of the cost reduction potential of CCUS cluster projects will benefit stakeholders in their investment decisions.

Considering the current situation and the long-term targets, this paper reviews and summarizes most of the latest international CCUS cluster development studies, and establishes a CCUS cluster project cost analysis model.

Moreover, this study also selected a typical industrial cluster area as a case study. This area, located in Shanwei City, Guangdong province, contains a large number of high-emission industrial enterprises. Assuming the implementation of a CCUS cluster project in the area in the next three years, we evaluated the cost reduction potential of CCUS cluster projects compared to the 'point-to-point' CCUS projects. Ultimately, this study provides practical suggestions for building CCUS cluster projects. The results of the case study in this paper could serve as a reference for other regions considering CCUS cluster projects in China to accelerate CCUS deployment and help achieve carbon neutrality.

2. Global Ccus Cluster Projects

For the past few years, an increasing number of countries have begun to pay attention to the construction of CCUS cluster projects. GCCSI (2021a) announced that there are 33 CCUS cluster projects by 2021. However, some projects listed in the GCCSI report are in the conceptual phase without a clear implementation plan. Table 1 presents the CCUS cluster projects which have a clear construction schedule.

Table 1
Planned CCUS cluster projects up to 2021

No.	Project	Country	Industry	Capture Capacity Mtpa CO ₂	Transportation Type	Storage Code	Operation Year
1	Summit Carbon Solutions	United States	Bioethanol	7.9	Pipeline	Deep Saline Formations	2024
2	Valero Blackrock	United States	Bioethanol	5.0	Pipeline	To Be Determined	2024
3	Integrated Mid-Continent Stacked Carbon Storage Hub	United States	Coal Fired Power, Cement Production, Ethanol Production, Chemical Production	1.9–19.4	Pipeline	Various options Considered	2025–2035
4	CarbonSafe Illinois Macon County	United States	Coal Fired Power, Ethanol Production	2.0–15.0	Pipeline	Various options Considered	2025–2035
5	Illinois Storage Corridor	United States	Coal Power, Bioethanol	6.5	Pipeline	Deep Saline Formations	2035
6	Houston Ship Channel CCS Innovation Zone	United States	Various	100.0	Pipeline	To Be Determined	2040
7	Acorn	United Kingdom	Hydrogen Production, Natural Gas Power, Natural Gas Processing, DAC	5.0–10.0	Pipeline	Deep Saline Formations	By the mid of 2020s
8	Humber Zero	United Kingdom	Hydrogen Production, Natural Gas Power	8.0	Pipeline	Deep Saline Formations	2030
9	Hynet North West	United Kingdom	Hydrogen Production	1.0	Pipeline	Deep Saline Formations	2030

No.	Project	Country	Industry	Capture Capacity Mtpa CO ₂	Transportation Type	Storage Code	Operation Year
10	Net Zero Teesside	United Kingdom	Natural Gas Power, Iron and Steel Production, Chemical Production	1–6.0	Pipeline	Deep Saline Formations	2030
11	Zero Carbon Humber	United Kingdom	Hydrogen Production, Iron and Steel Production, Chemical Production, Cement Production, Ethanol Production	10	Pipeline	Deep Saline Formations	2030
12	South Wales Industrial Cluster	United Kingdom	Natural Gas Power, Hydrogen Production, Oil Refining, Chemical Production	9.0	Pipeline, Ship	Deep Saline Formations	2040
13	Porthos	Netherlands	Hydrogen Production, Chemical Production	2.0–5.0	Pipeline	Depleted Oil & Gas Reservoirs	2024
14	Athos	Netherlands	Hydrogen Production, Iron and Steel Production, Chemical Production,	1.0–6.0	Pipeline	Various options Considered	2026
15	Aramis (tie up Athos Project and Porthos Project)	Netherlands	Oil refining, Hydrogen Production, Waste Incineration, Chemical Production, Steelmaking	20	Pipeline, Ship	Deep Saline Formations	2030
16	Alberta Carbon Trunk Line (ACTL)	Canada	Fertiliser Production, Hydrogen Production, Chemical Production	1.7–14.6	Pipeline	EOR	2020

No.	Project	Country	Industry	Capture Capacity Mtpa CO ₂	Transportation Type	Storage Code	Operation Year
17	Edmonton Hub	Canada	Natural Gas Power, Hydrogen Production, Oil Refining, Chemical Production, Cement Production	10.0	Pipeline	Deep Saline Formations	2030
18	C4 Copenhagen	Denmark	Waste Incineration, Natural Gas Power	3.0	Pipeline	Deep Saline Formations	2030
19	Greensand	Denmark	Waste Incineration, Cement Production	3.5	Pipeline, Ship	Depleted Oil & Gas Reservoirs	2030
20	Carbon Connect Delta	Belgium& Netherlands	Steelmaking, Chemical Production	6.5	Pipeline, Ship	Under Evaluation	2026–2030
21	Antwerp@C	Belgium	Hydrogen Production, Chemical Production, Oil Refining	9.0	Pipeline	Deep Saline Formations	2030
22	Langskip	Norway	Waste Incineration, Cement Production	1.5-5.0	Pipeline, Ship	Deep Saline Formations	2024–2030
23	Ravenna Hub	Italy	Hydrogen Production, Natural Gas Power	4.0	Pipeline	Depleted Oil & Gas Reservoirs	2026
24	Abu Dhabi Cluster	United Arab Emirates	Natural Gas Processing, Hydrogen Production, Iron and Steel Production	2.7-5.0	Pipeline	EOR	2030
25	CarbonNet	Australia	Natural Gas Processing, Hydrogen, Fertilizers, Waste to Energy, DAC	2.0–5.0	Pipeline	Deep Saline Formations	2030

No.	Project	Country	Industry	Capture Capacity Mtpa CO ₂	Transportation Type	Storage Code	Operation Year
26	Xinjiang Junggar Basin CCUS Hub	China	Coal Fired Power, Hydrogen Production, Chemical Production	3.0	Pipeline, Tank Truck	EOR	2030
<p>* Most data are obtained from the official websites of each project or the websites of the relevant competent department and GCCSI's Global CCUS Status Report 2021.</p> <p>* The items in the table are only those with a clear implementation schedule, and some conceptual projects without substantive arrangement are not listed here.</p>							

As presented in Table 1, the United States and the United Kingdom are the most active countries to deploy CCUS cluster projects, and they have released six projects separately. The impetus for CCUS cluster project deployment in the United States is largely due to the Form 45Q policy. Form 45Q provides tax refunds of 35 US dollars per tonne of utilized CO₂, such as in enhanced oil recovery (EOR), and 50 US dollars per tonne of geologically stored CO₂ (U.S. GOV, 2018). This has greatly increased the economic motivation to deploy large-scale CCUS projects. The Prime Minister of the United Kingdom outlined the United Kingdom's Ten Point Plan for a Green Industrial in November 2020, which plans to mobilise 12 billion pounds of government investment to support clean energy, transport, nature, and innovative technologies. One main target of the plan is to promote the United Kingdom to become a world leader in technology related to the capture and storage of carbon emissions away from the atmosphere, which aims to remove 10 million tons of CO₂ by 2030 (UK GOV, 2020).

The European Commission (2019) launched the European Green Deal in December 2019, which aims to reduce carbon emissions by 55% by 2030. It also promotes a number of countries accelerating the deployment of CCUS, such as Norway, Denmark, Belgium, the Netherlands, and Italy. Some countries in other regions are also actively exploring the construction of CCUS cluster projects, such as China, Australia, Canada, and the United Arab Emirates.

3. Development Trend Of Ccus Cluster Projects

The clustering trend of CCUS projects indicates that CCUS technology has entered a new stage in industrial applications. Projects are becoming larger and more sustainable. All projects have an annual capture capacity of more than 1 million tons, and the designed capacity of 12 projects is over 5 million tonnes per year. Ten projects made an elastic capacity design, which implies that they are open for more enterprises to join. Compared with existing individual CCUS projects, the gradual increase in the CCUS cluster project capture scale not only highlights the key role of the CCUS project in achieving carbon neutrality, but also reflects the strong inclusiveness and sustainable development potential of CCUS cluster projects. For example, in the second phase of Canada's Alberta Carbon Trunk Line (ACTL), 12 CCUS projects that are under construction have expressed their intention to join ACTL in the future, involving cement, power, natural gas processing, refinery, and other industries (Faubert P., et al, 2020; World Bank, 2020).

An increasing number of industries are involved in CCUS cluster projects, and various ways of cooperation exist between enterprises. Among 27 existing large integrated CCUS projects in 2021, 17 projects capture CO₂ from natural gas processing or fertilizer production. The main reason for this trend is that these sources have higher initial CO₂ concentrations from the flue gas, lower capital cost, and lower operating cost. These projects only aim to demonstrate the feasibility of the technology, and most business models of these projects are given priority with energy enterprise self-raised funds. However, the CCUS cluster projects shown in Fig. 1 reflect a new trend of more industries participating in CCUS projects, such as steelmaking, cement production, hydrogen production, and bioethanol production. Meanwhile, under the guidance and financial support from the government, each CCUS cluster project invites multiple enterprises to jointly invest or set up specialised operation agencies to finance the project. The increasing number of participating industries reflects the urgency of the industrial sector for low-carbon transformation, and the joint investment of enterprises reflects the improvement in the risk resistance ability of CCUS projects.

Geological utilisation or sequestration has become the primary method of CO₂ utilisation in CCUS cluster projects. Generally, captured CO₂ can be utilised in a variety of ways, including biological, chemical, and geological utilisation. Owing to the high cost, low demand, and other factors, biological utilisation and chemical utilisation cannot be applied to ten million tonnes or even one million tonnes of CO₂ from CCUS projects in the short term. Therefore, all 22 projects with clearly planned CO₂ modes adopted geological utilisation, including deep saline formation storage, depleted oil and gas reservoir storage, and CO₂-enhanced oil recovery (EOR). Among these 22 projects, there are 19 deep saline formation storage and depleted oil and gas reservoir storage projects, with only three EOR projects. Storage of deep saline formations and depleted oil and gas reservoirs cannot provide any economic return, and these storage modes only aim to achieve absolute CO₂ emission reduction. This trend also indicates that when making investment decisions for CCUS cluster projects, stakeholders should consider the emission reduction of the projects rather than the potential profits that can be made.

4. Ccus Cluster Projects In China

The Xinjiang Junggar Basin CCUS Hub Project is the only clearly planned CCUS cluster project in China. This project was led by the China National Petroleum Corporation (CNPC) and supported by the Oil and Gas Climate Initiative (OGCI). OGCI is an international industry-led organisation which includes 12 member companies in the oil and gas industry: BP, Chevron, CNPC, Eni, Equinor, ExxonMobil, Occidental, Petrobras, Repsol, Saudi Aramco, Shell, and Total, representing over 30% of the global operated oil and gas production. OGCI members collectively invest over \$7 billion each year in low-carbon solutions, and CCUS is one of the top priorities of OGCI. OGCI launched the CCUS Kickstarter Project in 2019 to enable the CCUS industrial clusters and hubs (OGCI, 2019). The Xinjiang Junggar Basin CCUS Hub Project is one of five CCUS cluster projects supported by OGCI, which aims to capture 3 million tons of CO₂ by 2030, and most of the captured CO₂ will be used to enhance oil recovery. The long-term plan of this project is to capture 10 million tons of CO₂ by 2060 to help Xinjiang province achieve carbon neutrality.

Currently, there is only one clear plan for the CCUS cluster project in China, the Ministry of Science and Technology suggested six suitable CCUS cluster regions in 2019 (Table 2 and Fig. 1). In addition to the Xinjiang

Junggar Basin, it includes the Ordos Basin, Songliao Basin, Bohai Bay Basin, Pearl River Mouth Basin, and Sichuan Basin.

Table 2
Overview of the suggested CCUS cluster regions in China

No.	Region	CO ₂ Sources	Potential Storage Code
1	Xinjiang Junggar Basin	Chemical Production, Cement Production, Power Generation, Iron and Steel Production	Chemical Utilization; EOR; In-situ Leaching of Uranium; Enhanced Coal-bed Methane Recovery; Enhanced Deep Salt Water Recovery; Enhanced Shale Gas Recovery; Deep Saline Formations Storage; Depleted Oil and Gas Reservoirs Storage
2	Ordos Basin	Chemical Production, Power Generation	Biological Utilization; EOR; In-situ Leaching of Uranium; Enhanced Coal-bed Methane Recovery; Enhanced Deep Salt Water Recovery; Enhanced Shale Gas Recovery; Deep Saline Formations Storage; Depleted Oil and Gas Reservoirs Storage
3	Songliao Basin	Chemical Production, Cement Production, Power Generation, Iron and Steel Production, Oil Refining, Biofuel	Chemical Utilization; EOR; In-situ Leaching of Uranium; Enhanced Coal-bed Methane Recovery; Enhanced Deep Salt Water Recovery; Enhanced Shale Gas Recovery; Deep Saline Formations Storage; Depleted Oil and Gas Reservoirs Storage
4	Bohai Bay Basin	Chemical Production, Cement Production, Power Generation, Iron and Steel Production, Oil Refining, Biofuel	EOR; In-situ Leaching of Uranium; Deep Saline Formations Storage; Depleted Oil and Gas Reservoirs Storage
5	Pearl River Mouth Basin	Cement Production, Power Generation, Oil Refining	EOR (offshore); Enhanced Geothermal Production; Deep Saline Formations Storage (offshore); Depleted Oil and Gas Reservoirs Storage (offshore)
6	Sichuan Basin	Chemical Production, Cement Production, Power Generation, Iron and Steel Production, Oil Refining, Biofuel	Enhanced Natural Gas Recovery; Enhanced Shale Gas Recovery; Deep Saline Formations Storage; Depleted Oil and Gas Reservoirs Storage

As evident from Table 2 and Fig. 1, the six suggested regions have a large number of CO₂ emission sources, and these regions are all in the vicinity of the proper storage geological sites. However, except for the Xinjiang Junggar Basin, all other regions are relatively densely populated. Therefore, only the Xinjiang Junggar Basin has the only clear planned CCUS cluster project to date.

The China State Council (2021b) issued the Instructions on Fully, Accurately, and Comprehensively Implementing New Development Concept to Achieve Carbon Peak and Carbon Neutrality on 24 October 2021. The instructions emphasise the key role of large-scale commercial CCUS demonstrations in achieving carbon neutrality. The Ministry of Science and Technology subsequently reiterated six suggested CCUS cluster regions and officially decided to build multiple cluster CCUS demonstrations in these areas in stages.

5. Assessing The Cost Reduction Potential Of Ccus Cluster Project: A Case Study

A CCUS cluster project provides the opportunity for CO₂ emitters located in relatively close proximity to each other to join together to reduce large amounts of carbon emissions. CCUS cluster projects can achieve cost reduction through the scale economy effect and business synergy effect. The costs of a pipeline, possible compression facilities, and associated activities such as community consultation, government approvals, negotiations with property owners, and others, can be reduced on a per-user basis if the costs are shared or only spent once rather than multiple times.

Guangdong province is located on the south coast of China and is one of the most economically developed regions in China; its GDP achieved 11 trillion CNY (1.72 trillion USD) in 2020 (Chao et al., 2021). Guangdong is also outstanding in its low-carbon transition. Guangdong province was set up as one of China's first low-carbon pilot provinces in 2010. By 2020, the province had exceeded its carbon reduction target, with a cumulative decline of more than 44% over the past decade. Guangdong province was also one of the earliest regional carbon emission trading pilots. According to the newly released Implementation Plan for Carbon Emission Quota Allocation in Guangdong Province in 2020, 245 enterprises are included in the trading system, encompassing six industries including power, cement, steel, petrochemical, paper, and civil aviation, with a total quota of 465 million tons (Yuejun et al., 2021).

Guangdong is also a leader in the development and deployment of the CCUS technology. Guangdong Kickstarted Guangdong Carbon Capture Technology Centre (GCCT) in Shanwei City in 2013, and GCCT is China's first offshore storage CCUS project. The first phase of this project was completed in 2019, with a capital investment of 120 million CNY (18.77 million USD) from China Resources Power. GCCT using post-combustion capture technology is the first of its kind to be built in an ultra-supercritical coal-fired power plant in Asia. The first phase of GCCT involves building two sets of carbon capture facilities: a compatible amine CO₂ capture unit and a compatible designed membrane separation CO₂ capture unit. The designed capture capability of GCCT is 20,000 tons per year; this project also reserves the test interface and space for other innovative carbon capture technologies, such as physical adsorption CO₂ capture technology.

According to research by Di et al. (2018), Guangdong province lacks onshore storage conditions, with only 20 million tons of storage potential in the central part. The potential of CO₂ storage in the Pearl River Mouth Basin is over 300 billion tons (including saline formation storage and EOR), and the nearest potential storage area is within 100 km of the coastline. Shanwei is located in the southernmost part of Guangdong Province, adjacent to the Pearl River Mouth Basin. Therefore, building CCUS projects near coastal areas with offshore storage is a critical direction for Guangdong to deploy more CCUS projects.

Coal-fired power plants are the primary carbon emitters, which are also the pillars of China's power industry. Renewable energy or clean energy cannot guarantee a country's power supply by 2060. Therefore, coal-fired power plants are an important field of emission reduction under the climate targets of carbon peaks and carbon neutrality. According to the Implementation Plan of Guangdong province's Carbon Emission Quota Allocation for 2020, three enterprises in Shanwei have been included in the emission trading system, and these are all coal-fired power plants: Haifeng, Honghaiwan, and Jiahuwan. This study considers the aforementioned three coal-fired plants as the research targets. We initially assessed the costs of building individual CCUS projects for each plant, and subsequently designed a CCUS cluster project for these plants, including the design of a shared pipeline network and selecting proper storage sites best suited to these plants in the Pearl River Mouth Basin. Comparing the individual costs and CCUS cluster project costs, we assessed the cost reduction potential of the CCUS cluster

projects. The results could provide a reference for more regions intending to deploy CCUS cluster projects in the future.

5.1 Information on Research Targets

The three coal-fired power plants are located in the coastal area of Shanwei. The straight-line distance of each power plant from the coastline was within 1 km. The total installed capacity of each power plant is above 2000 MW (Table 3), and the theoretical carbon emissions are above 5 million tons CO₂/a. The LF-2A structure of the Lufeng Depression in the Pearl River Mouth Basin is the closest potential storage area to the three coal-fired power plants. The LF-2A structure is located in northwest Lufeng Sag, controlled by NW-trending faults, and forms three depressional uplifts with an average trap area of 151.55 km². The trap amplitude is 121.67 m, the reservoir thickness is 145 m, and the porosity is 22.84%. Previous studies have shown that the structure has a good CO₂ storage capacity, with a total storage potential of more than 500 million tons. The LF-2A structure is the best candidate for deploying CO₂ saline formation storage for the three coal-fired power plants.

Table 3
Basic information of the three coal-fired plants in Shanwei

No.	Plant	Total Investment (RMB, billion)	Capacity (MW)	Commissioning Year	Distance from coastline (km)	Distance from LF-2A (km)	Distance from CO ₂ treatment centre (km)
1	Haifeng Plant	8.50	2×1000	2015	< 1	164.96	62.67
2	Jiahuwan Plant	8.83	2×1000	2019	< 1	122.30	52.11
3	Honghaiwan Plant	11.00	4×600	2 units in 2008; 2 units in 2011	< 1	118.56	5.05
* The distance between CO ₂ treatment centre and LF-2A structure is 113.56 km.							

To reduce the transportation distance, a CO₂ treatment centre was set up at the seaside 5 km away from Honghaiwan Plant; the distance between the CO₂ treatment centre and the LF-21 structure is 113.56 km. The compressed and purified CO₂ from three coal-fired power plants is initially transported to the treatment centre and then transported together to LF-2A in the Lufeng Depression for saline formation storage. Transportation from the Honghaiwan Plant to the treatment centre is through onshore pipelines, and the transportation modes of the other two plants are offshore pipelines. Figure 2 shows the specific locations of the three coal-fired plants and the treatment centre.

Theoretically, the expansion of the capture scale is beneficial for the reduction of unit cost. Thus, the case study is divided into two scenarios to analyse the cost reduction potential of the CCUS cluster project. We assumed that three coal-fired power plants capture 1 and 3 million tonnes of CO₂ per year for scenarios I and II, respectively.

5.2 Methodology

The cost of CCUS cluster projects can be divided into capital cost and operation and maintenance cost. It can also be subdivided into capture cost, transportation cost and storage cost. Based on previous economic evaluation research method for CCUS projects in the iron and steel industry in China (Xi et al., 2018), the revised emission reduction cost analysis model was established for this study:

$$C = \frac{\sum_{n=0}^L \frac{(I_c + I_t + I_s + O_n + T_n + S_n)}{(1+r)^n}}{\sum_{n=0}^L \frac{(Q_n - A_n)}{(1+r)^n}} \quad (E1)$$

where C is the unit emission reduction cost (CNY/tCO₂); I_c is the capital investment of carbon capture facilities; I_t is the capital investment of transportation facilities; I_s is the capital investment of storage facilities; O_n is the fixed operating and maintenance cost of carbon capture in year n ; T_n is the fixed operating and maintenance cost of transportation in year n ; S_n is the fixed operating and maintenance cost of storage in year n ; Q_n is the total amount of CO₂ captured from the project in year n ; A_n is the total amount of CO₂ generated from an auxiliary power plant for supplying steam and electricity for capturing, compressing, and storing CO₂ in year n ; r is the discount rate; and L is the lifetime of the project.

Referring to the previous research results of other scholars, the parameter settings for this project are presented in Table 4.

Table 4
Parameter Assumptions

No.	Parameter	Reference Value	Source
1	L	20 years	/
2	r	12%	8% for general commercial projects, considering the higher risk level of CCUS projects, 12% discount rate set for this case study.
3	I_c	1290 million CNY for Scenario I 2580 million CNY for Scenario II	Reference to Lei's research on modelling the investment of coal-fired power plant retrofit with CCS (Lei et al., 2014).
4	I_t	< 50 km: 400 million, CNY <hr/> 50–100 km: 700 million, CNY <hr/> 100–200 km: 1 billion, CNY	Reference to Ning's research on Cost analysis results of one million tonnes CCUS offshore transportation pipeline construction (Wei et al., 2015).
5	I_s	431 billion CNY for Scenario I 862 billion CNY for Scenario II	Reference to Muxin's research on the economic analysis of CCUS project (Muxin et al., 2021).
6	O_n	51.60 CNY/t for Scenario I 34.4 CNY/t for Scenario II	Reference to Bong's research, the fixed operation and maintenance cost of carbon capture projects is about 4% of the total investment (Bong et al., 2020).
7	T_n	0-100 km: 0.30, CNY/t/km <hr/> 100–150 km: 0.25, CNY/t/km	Reference to Serpa's research on the economic analysis for CO ₂ pipeline transportation operating cost (Serpa et al., 2011).
8	S_n	60 CNY/t for Scenario I 120 CNY/t for Scenario II	Reference to Xi's research (Xi et al., 2018).

No.	Parameter	Reference Value	Source
9	Q_n	1 million t for Scenario I 3 million t for Scenario II	/
10	A_n	0.20 million t	Reference to Xi's research (Xi et al., 2018).

5.3 Analysis of results

To assess the cost reduction potential of CCUS cluster projects, Scenario I analysed the emission reduction costs of CCUS projects capturing 1 million tons of CO₂ per year in each coal-fired power plant. Scenario II analysed the emission reduction costs of CCUS projects capturing 3 million tons of CO₂ per year in each coal-fired power plant. We subsequently compared it with the emission reduction costs of CCUS projects of three power plants in cluster construction (Tables 5 and 6). The capture and storage capital costs of each coal-fired power plant was set as a constant value. Meanwhile, as the distance from each coal-fired power plant to the LF-2A structure is approximately 100–150 km, the transportation capital cost was also set as a constant value, as presented in Table 4. The distance between each coal-fired power plant and the LF-2A structure is different, which leads to differences in fixed operation and maintenance costs of transportation and the final unit emission reduction costs.

Table 5

Cost comparative analysis of individual CCUS projects and CCUS cluster projects: Scenario I, wherein the total emission reduction is 3 million tonnes

Parameters		Haifeng Plant	Jiahuwan Plant	Honghaiwan Plant	CCUS Cluster Project: Scenario I
Capture Capacity, million tonnes		1	1	1	3
Pipeline Length, km		164.96	122.30	118.56	228.23
Capital Cost, million CNY	Capture Facilities	1290	1290	1290	3870
	Transportation Facilities	1000	1000	1000	1500
	Storage Facilities	431	431	431	862
Fixed Operating and Maintenance cost, million CNY	Capture	51.6	51.6	51.6	1548
	Transportation	41.24	30.58	29.64	171
	Storage	60	60	60	120
NPV (Absolute Value), CNY		3863	3400	3392	9240
Cost of CO ₂ Avoidance, CNY/tCO ₂		646.41	568.82	567.66	475.81
Percentage of Cost Reduction in the Cost of CO ₂ Avoidance, %		26.39%	16.35%	16.18%	/

Table 5 shows that when three coal-fired plants separately deployed 1 million tonnes of CO₂ in the CCUS project, the unit emission reduction costs were 646.41, 568.82, and 567.66 CNY/tCO₂. The capital costs of capture facilities in different plants are the same, but those of transportation and storage facilities are greatly reduced, owing to the distance between capture point and the LF-2A structure. In the CCUS cluster project, when three projects of 1 million tonne capacity become one project of 3 million tonne capacity, the operating and maintenance cost does not simply increase linearly by three-fold. This study assumes that this cost increases only two-fold according to Xi's research, but it may be lower in practice. The distance between the Hongwan Power Plant and the CO₂ treatment centre is 5 km, and the cost of onshore pipeline transportation is relatively low, which is ignored to simplify the calculation. CO₂ captured by each power plant has been compressed and purified before being transported to the treatment centre; thus, the CO₂ treatment centre contains less large equipment and its capital cost is also negligible.

According to the pipeline network planning in Fig. 2 and parameter setting in Table 4, the unit emission reduction cost of the CCUS cluster project included three coal-fired power plants (475.81 CNY/t of CO₂) using formula E1. Compared with individual CCUS projects, the unit CO₂ reduction cost of CCUS cluster projects decreased significantly, dropping 26.39, 16.35, and 16.18% for the Haifeng Plant, Jiahuwan Plant, and Honghaiwan Plant, respectively.

Table 6

Cost comparative analysis of individual CCUS projects and CCUS cluster projects: Scenario II, wherein the total emission reduction is 9 million tonnes

Parameters		Haifeng Plant	Jiahuwan Plant	Honghaiwan Plant	CCUS Cluster Project: Scenario II
Capture Capacity, million tonnes		3	3	3	9
Pipeline Length, km		164.96	122.30	118.56	228.23
Capital Cost, million CNY	Capture Facilities	2580	2580	2580	3870
	Transportation Facilities	1000	1000	1000	1500
	Storage Facilities	862	862	862	862
Fixed Operating and Maintenance cost, million CNY	Capture	103.2	103.2	103.2	1548
	Transportation	123.72	91.73	88.92	171
	Storage	120	120	120	240
NPV (Absolute Value), million CNY		7033.30	6024.96	6004.01	173632.20
Cost of CO ₂ Avoidance, CNY/tCO ₂		392.34	336.09	334.92	298.02
Percentage of Cost Reduction in the Cost of CO ₂ Avoidance, %		24.04%	11.33%	10.93%	/

Table 5 presents that when three coal-fired plants deployed 3 million tonnes of CO₂ in the CCUS project, the CO₂ of avoidance is 392.34, 336.09, and 334.92 CNY/t, respectively. For the CCUS cluster project, the unit CO₂ reduction cost drops to 298.02 CNY/t. Compared to individual CCUS projects, this value dropped 24.04, 11.33, and 10.09% for the Haifeng Plant, Jiahuwan Plant, and Honghaiwan Plant, respectively. Compared with Scenario I, the CO₂ of avoidance of individual CCUS projects decreased rapidly with the expansion of the capture scale (Fig. 3).

In both scenarios I and II, the Haifeng plant has the maximum cost reduction potential compared to the other two power plants. This is mainly because the Haifeng Plant is furthest away from the LF-2A structure. Therefore, emission sources which are far away from potential storage sites will benefit more from the construction of the CCUS cluster project. The capture capacity of Scenario II is three times that in Scenario I, and the unit CO₂ reduction cost dropped from 475.81 to 298.02 CNY/t, reducing by 37.37%. Consequently, the scale of CCUS cluster projects has a significant impact on the unit emission reduction cost.

From a comprehensive perspective, the CCUS cluster project saves 118.49 CNY/tCO₂ over the average cost of individual projects (594.30 CNY/tCO₂) in Scenario I (by 19.94%). The CCUS cluster project saves 56.43 CNY/tCO₂ over the average cost of individual projects (354.45 CNY/tCO₂) in Scenario I (by 15.92%).

6. Discussion

Carbon peak and carbon neutrality climate targets put forward higher requirements for low-carbon transformation for all industrial sectors in China. As most industrial sectors cannot replace fossil fuels in the short term, CCUS will play a key role in the progress of China's low-carbon transformation. By summarising the development trend of international CCUS projects, this study suggests that industrial sectors should consider the cluster construction of CCUS projects in the future. CCUS cluster projects can significantly reduce project costs by sharing CO₂ transportation networks and storage facilities.

This study considers three coal-fired plants in Shanwei City as research targets, assuming two scenarios with differently designed capture capacities, to assess the cost reduction potential of a CCUS cluster project. Through comparative analysis, we found that a CCUS cluster project can greatly reduce the unit CO₂ reduction cost. In the assumed case, the CCUS cluster project could reduce at least 15% of the cost in scenarios I and II. Moreover, the designed capture capacity and transportation distance are key factors affecting the cost of CCUS cluster projects.

Theoretically, the CCUS cluster project has further cost reduction potential for Shanwei, with only three enterprises included in the emission trading system. If more adjacent emission sources in other adjacent cities jointly participate in this CCUS cluster project, or if the capture capacity of the three coal-fired plants increases to larger scales, there is more room for cost reduction. Meanwhile, this study selected offshore saline formation as a storage mode, which led to higher transportation and storage costs compared to onshore saline formation storage methods. It may be more economical to conduct CCUS cluster projects in areas with great potential for onshore storage in the future.

Economical utilisation of CO₂ is not considered in this study as most innovative CO₂ utilisation technologies cannot handle the specified amounts of captured CO₂. Even though China launched the National Emission Trading System on 16 July 2021 with a carbon price of 50 CNY/tCO₂, this study aims to provide a reference for CCUS stakeholders from the perspective of emission reduction cost, instead of potential benefits. With the increasing carbon price in the China National Emission Trading System and the rapid development of large-scale CO₂ utilisation technologies, the cost of CCUS cluster projects will certainly continue to reduce.

As low-carbon transformation has become the main direction of all industries in China, CCUS has been recognised as a necessary technology to achieve carbon neutrality by the government. If more enterprises participate in the cluster construction of CCUS projects, it will not only greatly reduce the unit CO₂ reduction cost, but also enrich the business models of CCUS projects and improve the anti-risk capability of the projects. CCUS cluster projects also have a potential talent gathering effect, which is conducive to knowledge sharing, technical breakthroughs, and innovation. By accelerating the cluster construction of CCUS projects, it will facilitate low-carbon transformation of the industrial sectors and successfully help China achieve carbon neutrality.

During the China 14th Five-Year Plan Period (2021–2025), the China government should start to formulate special plans and binding development goals related to CCUS cluster construction. At this stage, through systematic research, detailed specifications for several regional CCUS clusters should be completed, including industrial level CCUS cluster projects source-sink matching. Meanwhile, the government should develop and implement effective CCUS incentive policies, including but not limited to finance and taxation, the inclusion of CCUS in the national carbon market, CCUS certificate trading, and setting emission intensity targets for new projects and other mechanisms. This will help form a financial guarantee for high-concentration emission sources to achieve emission reductions by use of a CCUS cluster.

Declarations

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Author contributions

Muxin Liu contributed to the conception of the study, data analysis and manuscript preparation;

Yueze Zhang performed the numerical simulation;

Xi Liang helped perform the analysis with constructive discussions.

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Figures

Figure 1

***Suggested CCUS cluster regions in China** (This figure only displays the CO₂ sources with annual emissions of more than 300,000 tonnes per year)*

Figure 2

Geographical location of the CCUS cluster projects

Figure 3

Comparative analysis of Scenarios I and II