Front. Earth Sci. 2023, 17(3): 844–855
https://doi.org/10.1007/s11707-022-1030-1

RESEARCH ARTICLE

Assessing the cost reduction potential of CCUS cluster projects of coal-fired plants in Guangdong Province in China

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Abstract Carbon capture, utilization, 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. 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 the unit emission reduction cost for each plant with a capacity of 300 million tonnes per year is 392.34, 336.09, and 334.92 CNY/tCO_2. By building CCUS cluster project, it could save 56.43 CNY/tCO_2 over the average cost of individual projects (354.45 CNY/tCO_2) when the total capture capacity is 9 million tonnes per year (by 15.92%). Furthermore, we conducted a simulation for the scenario of a smaller designed capture capacity for each plant. We found that as the capture scale increases, the cost reduction potential is higher in the future.

Keywords cost reduction potential, CCUS cluster projects, coal-fired plant, carbon neutrality

1 Introduction

The 26th UN Climate Change Conference (COP26) concluded on 12 November 2021. 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, utilization, and storage (CCUS) was widely recognized 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).

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). 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 2000 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

Received September 21, 2022; accepted October 12, 2022

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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 emphasized 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's State Council, 2021a; Zhao et al., 2021). 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 must capture at least 1 billion tons of carbon dioxide (CO_2) per year in 2060 to guarantee a carbon neutrality target (Zhang, 2020). Therefore, CCUS plays a key role in China's low-carbon transition process (Xiao et al., 2021; Xu et al., 2021).

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 CO_2 was produced by 4931 individual facilities, each emitting under 200000 tons of CO_2 per year (GCCSI, 2021). Other parts of the world also have significant volumes of CO_2 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. It is important to understand that smaller industrial facilities around the world contribute significant cumulative CO_2 emissions that are unavoidable as long as the facilities continue to operate.

The international development of CCUS projects also shows a trend of 'transferring individual projects to 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 (2021) 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.

As presented in Table 1, the United States and the UK 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 CO_2, such as in enhanced oil recovery (EOR), and 50 US dollars per tonne of geologically stored CO_2 (US GOV, 2018). This has greatly increased the economic motivation to deploy large-scale CCUS projects. The Prime Minister of the UK outlined the UK'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 UK 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 CO_2 by 2030 (UK GOV, 2020; The European Commission, 2019).

An increasing number of industries are involved in CCUS cluster projects, and various ways of cooperation exist between enterprises. 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 specialized 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 (Faubert et al., 2020; World Bank, 2020).

Geological utilization or sequestration has become the primary method of CO_2 utilization in CCUS cluster projects (Zheng et al., 2018; Cheng et al., 2021; Zhao et al., 2021). All 22 projects with clearly planned CO_2 modes adopted geological utilization, including deep saline formation storage, depleted oil and gas reservoir storage, and CO_2-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 CO_2 emission reduction (Zheng et al., 2019). 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.

The initial demand for additional CO_2 transportation capacity is likely to occur in an incremental and geographically dispersed manner as new dedicated capture plants, storage, and EOR facilities are brought

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	UK	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	UK	Hydrogen Production, Natural Gas Power	8.0	Pipeline	Deep Saline Formations	2030
9	Hynet North West	UK	Hydrogen Production	1.0	Pipeline	Deep Saline Formations	2030
10	Net Zero Teesside	UK	Natural Gas Power, Iron and Steel Production, Chemical Production	1−6.0	Pipeline	Deep Saline Formations	2030
11	Zero Carbon Humber	UK	Hydrogen Production, Iron and Steel Production, Chemical Production, Cement Production, Ethanol Production	10	Pipeline	Deep Saline Formations	2030
12	South Wales Industrial Cluster	UK	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
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
26	Xinjiang Junggar Basin CCUS Hub	China	Coal Fired Power, Hydrogen Production, Chemical Production	3.0	Pipeline, Tank Truck	EOR	2030

* 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.

* The items in the table are only those with a clear implementation schedule, and some conceptual projects without substantive arrangement are not listed here.

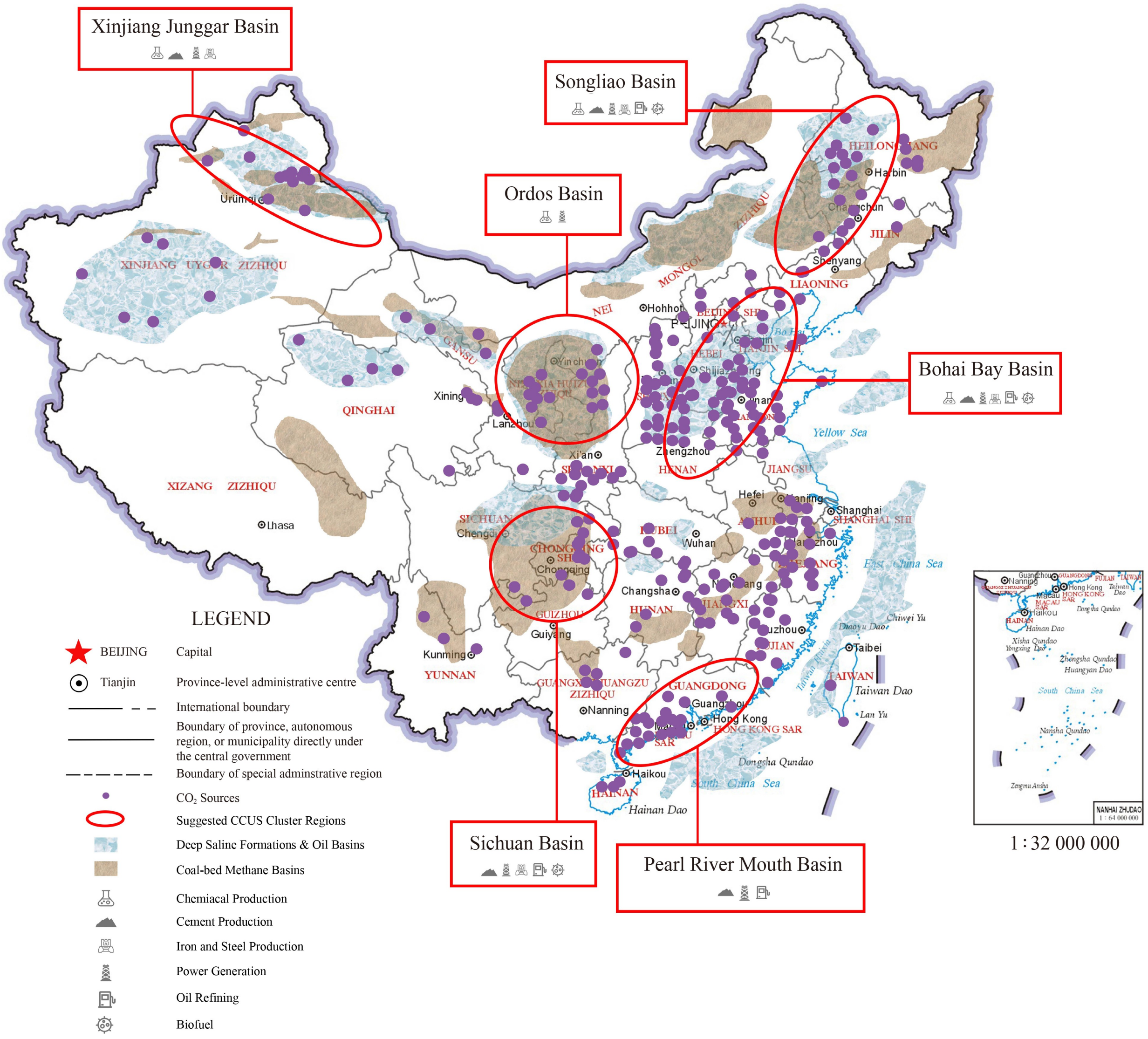

Fig. 1 Suggested CCUS cluster regions in China (this figure only displays the CO_2 sources with annual emissions of more than 300000 tonnes per year. This figure was created by using ArcGIS 6.0 software).

online. The incentives for CCS projects to be developed as part of a cluster, hub, or network linking proximate CO_2 sources, through a hub, to clusters of sinks, either by ship or so-called 'back bone' pipelines - include economies of scale. Development of large-scale and strategically located infrastructure solutions will enable the lower cost and full-scale deployment of CCS in industrial clusters, reducing cost and risk to industrial and power emitters.

CCUS cluster project also reduce the commercial risks, especially for the CO_2 storage. As the development of storage and transport infrastructure progresses, storage availability as a technical risk becomes increasingly more manageable by the storage developer, but at this stage commercial risks relating to CO_2 supply become important. CO_2 supply risk can be reduced if a storage provider is able to develop a portfolio of interlinked emitters that would ensure a continued supply regardless of the fate of individual industrial emitters.

While CCUS clustering will reduce costs, without government support these savings are currently insufficient to fill the cost-revenue gap. However, there is potentially large value in pre-investment in pipelines and storage facilities in order to generate the confidence needed for investment decisions on capture facilities. This suggests a possible role for government in facilitating such pre-investment, which otherwise may not occur due to the dispersed nature of the benefits. Therefore, it is more important for scholars to research on the tech-economic assessment of cluster project at current stage (Fan et al., 2022).

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 in China as a case study. This area is 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 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 organization 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 USD 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 CO_2 by 2030, and most of the captured CO_2 will be used to enhance oil recovery. The long-term plan of this project is to capture 10 million tons of CO_2 by 2060 to help Xinjiang 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.

As evident from Table 2 and Fig. 1, the six suggested regions have a large number of CO_2 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’s 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 emphasize 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.

3 Assessing the cost reduction potential of CCUS cluster project in China

A CCUS cluster project provides the opportunity for CO_2 emitters located in relatively close proximity to each other to join together to reduce large amounts of carbon

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

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 (Xian et al., 2022). 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 (Luo 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 CO_2 capture unit and a compatible designed membrane separation CO_2 capture unit. The designed capture capability of GCCT is 20000 tons per year; this project also reserves the test interface and space for other innovative carbon capture technologies, such as physical adsorption CO_2 capture technology.

According to research by Zhou et al. (2018), Guangdong province lacks onshore storage conditions, with only 20 million tons of storage potential in the central part. The potential of CO_2 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 (PRMB). 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. Guangdong has more than 240 large emission sources, but only 13 is proper to deploy offshore CCUS project in short-term for most of the large emission sources are too far away from the PRMB. To reveal the cost reduction potential of CCUS cluster projects and provide practical significance for CCUS project decision makers, it is more convincing to selected research target from 13 proper plants. 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.

3.1 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 CO_2/yr. 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 north-west Lufeng Sag, controlled by NW-trending faults, and forms three depressional uplifts with an average trap area of 151.55 km^2. 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 CO_2 storage capacity, with a total storage potential of more than 500 million tons. The LF-2A structure is the best candidate for deploying CO_2 saline formation storage for the three coal-fired power plants.

To reduce the transportation distance, a CO_2 treatment center was set up at the seaside 5 km away from Honghaiwan Plant; the distance between the CO_2 treatment center and the LF-21 structure is 113.56 km. The compressed and purified CO_2 from three coal-fired power plants is initially transported to the treatment center and then transported together to LF-2A in the Lufeng Depression for saline formation storage.

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 center/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 center and LF-2A structure is 113.56 km.

Transportation from the Honghaiwan Plant to the treatment center 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 center.

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 analyze the cost reduction potential of the CCUS cluster project. We assumed that three coal-fired power plants capture 1 and 3 million tonnes of CO_2 per year for scenarios I and II, respectively.

3.2 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. Generally, economic feasibility of CCUS project is evaluated based on the EBITDA (Earnings before interest, taxes, depreciation and amortization) approach through calculating zero net present value (NPV) by the end of the lifetime for most CCUS economic research (Kourkoumpas et al., 2016; Szabolcs and Calin, 2018; Judit et al., 2020). EBITDA is a useful metric for the evaluation of large investments. However, EBITDA can only assess the feasibility of the project at a macro level. To evaluate the cost reduction potential of CCUS cluster project, we put forward a unit emission reduction cost equation which is based on our previous economic evaluation research method (Liang et al., 2019). The revised emission reduction cost analysis model was established for this study:

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

where C is the unit emission reduction cost (CNY/tCO_2); I_c is the capital investment of carbon capture facilities; I_t

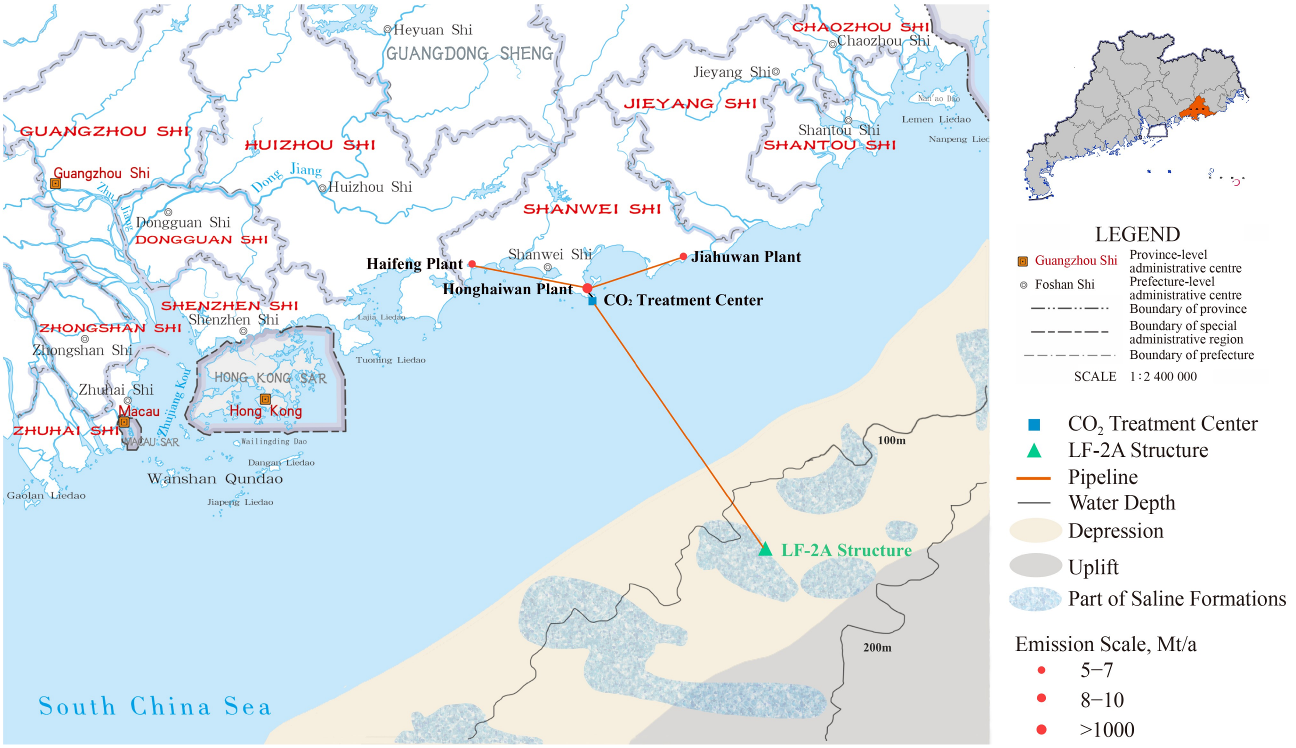

Fig. 2 Geographical location of the CCUS cluster projects (this figure was created by using ArcGIS 6.0 software).

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 CO_2 captured from the project in year n; A_n is the total amount of CO_2 generated from an auxiliary power plant for supplying steam and electricity for capturing, compressing, and storing CO_2 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.

3.3 Analysis of results

To assess the cost reduction potential of CCUS cluster projects, Scenario I analyzed the emission reduction costs of CCUS projects capturing 1 million tons of CO_2 per year in each coal-fired power plant. Scenario II analyzed the emission reduction costs of CCUS projects capturing 3 million tons of CO_2 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 shows that when three coal-fired plants

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 Zhu's research on modeling the investment of coal-fired power plant retrofit with CCS (Zhu et al., 2015)
4	I_t	<50 km: 400 million, CNY 50−100 km: 700 million, CNY 100−200 km: 1 billion, CNY	Reference to Wei'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 Liang's research on the economic analysis of CCUS project (Liang et al., 2019)
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 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 Liang's research (Liang et al., 2019)
9	Q_n	1 million t for Scenario I 3 million t for Scenario II	/
10	A_n	0.20 million t	Reference to Liang's research (Liang et al., 2019)

Table 5 Cost comparative analysis of individual CCUS projects and CCUS cluster projects: Scenario I, wherein

Item	Capture capacity/ million tonnes	Pipeline length/ km	Capital cost/ (million CNY)			Fixed operating and maintenance cost/(million CNY)			NPV (Absolute Value)/ CNY	Cost of CO_2 avoidance/ (CNY· tCO_2^{-1})	Percentage of cost Reduction in the cost of CO_2 avoidance
			Capture facilities	Transportation facilities	Storage facilities	Capture	Transportation	Storage			
Haifeng Plant	1	164.96	1290	1000	431	51.6	41.24	60	3863	646.41	26.39%
Jiahuwan Plant	1	122.3	1290	1000	431	51.6	30.58	60	3400	568.82	16.35%
Honghaiwan Plant	1	118.56	1290	1000	431	51.6	29.64	60	3392	567.66	16.18%
CCUS Cluster Project: Scenario I	3	228.23	3870	1500	862	1548	171	120	9240	475.81	/

Note: the total emission reduction is 3 million tonnes.

Table 6 Cost comparative analysis of individual CCUS projects and CCUS cluster projects: Scenario II, wherein the total emission reduction is 9 million tonnes

Item	Capture capacity/ (million tonnes)	Pipeline length/ km	Capital cost/million CNY			Fixed operating and maintenance cost/million CNY			NPV (absolute value)/ (million CNY)	Cost of CO_2 avoidance/ (CNY/ tCO_2^{-1})	Percentage of cost reduction in the cost of CO_2 avoidance
			Capture facilities	Transportation facilities	Storage facilities	Capture	Transportation	Storage			
Haifeng Plant	3	164.96	2580	1000	862	103.2	123.72	120	7033.3	392.34	24.04%
Jiahuwan Plant	3	122.3	2580	1000	862	103.2	91.73	120	6024.96	336.09	11.33%
Honghaiwan Plant	3	118.56	2580	1000	862	103.2	88.92	120	6004.01	334.92	10.93%
CCUS Cluster Project: Scenario II	9	228.23	3870	1500	862	1548	171	240	173632.2	298.02	/

separately deployed 1 million tonnes of CO_2 in the CCUS project, the unit emission reduction costs were 646.41, 568.82, and 567.66 CNY/tCO_2. 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 threefold. This study assumes that this cost increases only twofold according to Liang's research, but it may be lower in practice. The distance between the Honghaiwan Power Plant and the CO_2 treatment center is 5 km, and the cost of onshore pipeline transportation is relatively low, which is ignored to simplify the calculation. CO_2 captured by each power plant has been compressed and purified before being transported to the treatment center; thus, the CO_2 treatment center 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 CO_2) using formula E1. Compared with individual CCUS projects, the unit CO_2 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 5 presents that when three coal-fired plants deployed 3 million tonnes of CO_2 in the CCUS project, the CO_2 of avoidance is 392.34, 336.09, and 334.92 CNY/t, respectively. For the CCUS cluster project, the unit CO_2 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 CO_2 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 CO_2 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/tCO_2 over the average cost of individual projects (594.30 CNY/tCO_2) in Scenario I (by 19.94%). The CCUS cluster project saves 56.43 CNY/tCO_2 over the average cost of individual projects (354.45 CNY/tCO_2) in Scenario II (by 15.92%). Even taking the learning effect (which means CCUS project could benefits from experience gathered in different CCUS application and reduce the emission reduction cost) into account, it will take at least 35 years to reduce 20% cost for individual CCUS project in power plant (IEA, 2020). As a comparison, only 3 power plants in the case study form a CCUS cluster project could contribute around 15%–20% cost reduce at current stage. It is obvious for the stakeholders to concern building CCUS project cluster will be a robust pathway to achieve carbon neutrality.

4 Discussion and conclusions

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 summarizing 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

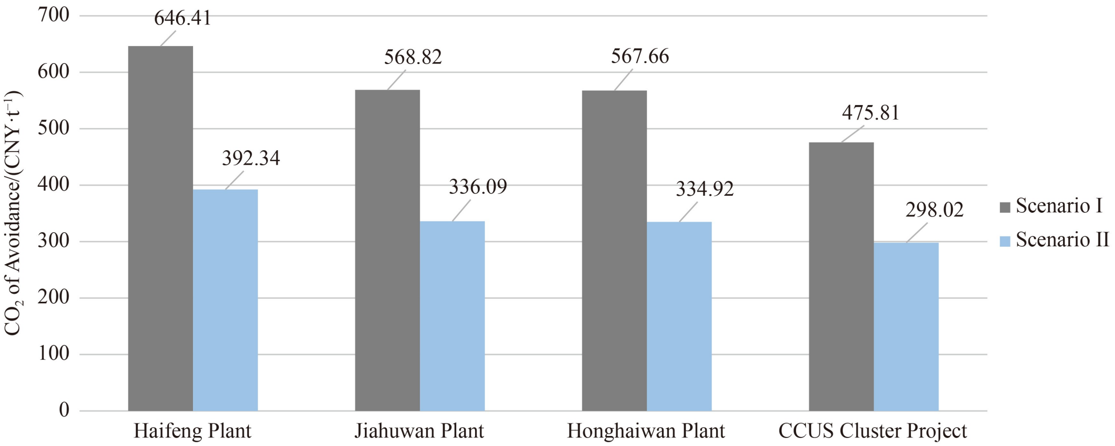

Fig. 3 Comparative analysis of Scenarios I and II.

cluster projects can significantly reduce project costs by sharing CO_2 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 CO_2 reduction cost. CCUS cluster project could saves 118.49 CNY/tCO_2 over the average cost of individual projects (594.30 CNY/tCO_2) when the total capture capacity is 3 million tonnes per year (by 19.94%). It saves 56.43 CNY/tCO_2 over the average cost of individual projects (354.45 CNY/tCO_2) when the total capture capacity is 9 million tonnes per year (by 15.92%). 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 project, or the capture capacity of the three coal-fired plants increases to larger scales, there will be more cost reduction space. 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 utilization of CO_2 is not considered in this study as most innovative CO_2 utilization technologies cannot handle the specified amounts of captured CO_2. Even though China launched the National Emission Trading System on 16 July 2021 with a carbon price of 50 CNY/tCO_2, 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 CO_2 utilization technologies, the cost of CCUS cluster projects will certainly continue to reduce.

Policy has a significant influence on CCUS cluster project development. China has not clearly issued national relevant polices for CCUS cluster project, so further research on how the policy quantitively influenced CCUS cluster project is still needed. Policy support for the proactive development of strategic CO_2 transport and storage infrastructure solutions is important to enable the low cost and full-scale deployment of CCUS in industrial clusters. This support should also link to existing and future opportunities for cross-border cooperation.

As low-carbon transformation has become the main direction of all industries in China, CCUS has been recognized 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 CO_2 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 provide a financial guarantee for high-concentration emission sources to achieve emission reductions by use of a CCUS cluster.

Even if the policy uncertainty remains in a high level, the cluster construction for CCUS project at current stage still will contribute 15%–20% cost reduce for small scale cluster project (less than 5 plants participate), it is obvious that CCUS cluster construction is the only way to promote the development of CCUS technological innovation.

Acknowledgments This research is supported by funds from the Department of Education of Guangdong Province (No. 2021KQNCX143), the National Social Science Foundation of China (Grant No. 21AGJ009) and the Research Base of Carbon Neutral Finance for Guangdong-Hong Kong-Macao (No. 22ATJR03).

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