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Energy Procedia 63 (2014) 7307 – 7314

Energy Procedia

GHGT-12

Early opportunities of CO_2 geological storage deployment in coal chemical industry in China

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Abstract

Carbon dioxide capture and geological storage (CCS) is regarded as a promising option for climate change mitigation; however, the high capture cost is the major barrier to large-scale deployment of CCS technologies. High-purity CO_2 emission sources can reduce or even avoid the capture requirements and costs. Among these high-purity CO_2 sources, certain coal chemical industry processes are very important, especially in China. In this paper, the basic characteristics of coal chemical industries in China is investigated and analyzed. As of 2013 there were more than 100 coal chemical plants in operation. These emission sources together emit 430 million tons CO_2 per year, of which about 30% are emit high-purity and pure CO_2 (CO_2 concentration >80% and >98.5% respectively). Four typical source-sink pairs are chosen for techno-economic evaluation, including site screening and selection, source-sink matching, concept design, and economic evaluation. The technical-economic evaluation shows that the levelized cost of a CO_2 capture and aquifer storage project in the coal chemistry industry ranges from 14 USD/t to 17 USD/t CO_2. When a 15USD/t CO_2 tax and 20USD/t for CO_2 sold to EOR are considered, the levelized cost of CCS project are negative, which suggests a benefit from some of these CCS projects. This might provide China early opportunities to deploy and scale-up CCS projects in the near future.

Peer-review under responsibility of the Organizing Committee of GHGT-12
Keywords: Coal chemical industry; Techno-economic evaluation; Carbon capture and geological storage; Early opportunities;

1. Introduction

Carbon dioxide capture and geological storage (CCS) is regarded as a promising option to reduce CO_2 emissions. CCS may be particularly important to China given its massive coal reserves and fast growing economy with heavy

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Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.767

dependence on fossil fuels. However, the high cost of CO_2 capture is the major barrier to large-scale deployment of CCS technologies.

High-purity CO_2 emission sources can provide lower cost of capture for CCS projects and lead to nearer term deployment. Among these CO_2 sources, coal chemical industries are very important, especially for China. Based on the energy development strategy of the National Development and Reform Commission (NDRC), the coal-based industry is greatly supported and encouraged towards national energy security and energy independency. There are large streams of high-purity CO_2 (>80% concentration) or pure CO_2 (>98.5% concentration) available as a result of coal chemicals production and industry separation process [1, 2]. So the capture and purification process for this CO_2 is much cheaper than that from conventional CO_2 emission sources, and in some cases can avoid CO_2 capture processes altogether. Therefore, the coal chemical industries can provide an early low-cost opportunity for CCS deployment using low cost CO_2 from industrial separation processes [3]. The goal of this paper is to examine the techno-economic features of possible low-cost opportunities for CCS in China. Several representative source-sink pairs are chosen and evaluated by techno-economic study, which includes site suitability, source-sink matching, economic, and preliminary risk analysis.

2. CO_2 emission from coal chemical industry

The coal chemical industry in China uses coal as raw material to produce gases, liquids and solids of various chemicals and cleaner energy forms. Traditional coal chemical industry mainly includes coal to methanol, calcium carbide, synthetic ammonia and coke with mature technology. Modern coal chemical industries encompass coal to olefins, coal to oil, coal to synthetic gas, coal to ethylene glycol, and coal to other oil substitutes. The technology employed by the industry includes coal gasification and coal liquefaction which emit high-purity CO_2 and pure CO_2 (>80% or 98.5% respectively) [2]. With slight technology improvement or optimization for CCS, additional CO_2 can be high-purity or pure CO_2, which could further cut down the cost of CCS dramatically.

The distribution of coal chemistries in China was investigated using data from a variety of sources, including enterprise databases from the Chinese Academy of Sciences, industries annual reports, enterprise interview, websites, and so on. The investigation results show that there are more than 100 coal chemical factories in operation as of 2013. The CO_2 emissions calculation methodology is based on IPCC Guidelines for national greenhouse gas inventories and based on available plant capacities and productivities, as noted below:

$$ECO_2 = \sum_j^N \sum_i^M (ECO_2)_{ij} = \sum_j^N \sum_i^M \left(EF_{ij} \times P_{ij}\right) \quad (1)$$

Where, ECO_2 is the total annual CO_2 emissions of all coal chemical industries; $(ECO_2)_{ij}$ the estimated annual CO_2 emissions of i^{th} CO_2 emission source within j^{th} industry sector; EF_{ij} - emission factor of i^{th} CO_2 emission source within j^{th} industry sector; P_{ij} - production yield of i^{th} CO_2 emission source within j^{th} industry sector; N is the number of industry sectors; M is the number of factories within industry sector i. The coal chemical industries analysed include coal to oil, coal to gas, coal to olefins, coal to ethylene glycol and coal to dimethyl ether. CO_2 emission factors refers to the paper by Zhang Jian, Liang Qinfeng [4], CO_2 emission factors for different industries sectors are shown in Table 1.

Table 1 Emission factors for CO_2 emission sources evaluation

Coal chemicals	EFs (tons CO_2/ton)	Coal chemicals	EFs (tons CO_2/ton)
Direct liquefaction (coal to oil)	2.1	Coal to olefins	6.0
Indirect liquefaction (coal to oil)	3.3	Coal to ethylene glycol	8.0
Coal to gas	4.6	Coal to dimethyl ether	4.0

Distribution of the more than 100 coal chemical factories is shown in Fig 1. These CO_2 sources are primarily concentrated in the Ordos Basin, Bohai Bay Basin, Songliao Basin and Junggar Basin. The total CO_2 emitted from coal chemistry industries are 430 million tons CO_2/y. About 30% of the total CO_2 is high-purity or pure (CO_2

concentration >80% and >98.5% respectively) by current industry technologies suggested by experts. So there are about 130 million tons of high-purity or pure CO_2 emitted from coal chemical factories annually. According to the plan of the National Development and Reform Commission (NRDC) in 2006, from 2015 to 2020 coal chemical industries in China should focus on consolidating towards larger and more modern plants utilizing more advanced waste emission control. Such changes to the industry will provide more high-purity CO_2 sources amenable to CCS in the near future.

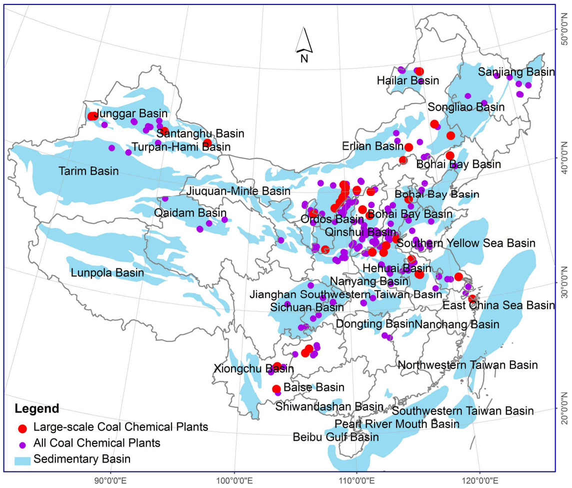

Fig 1 Distribution of coal chemical factories in China

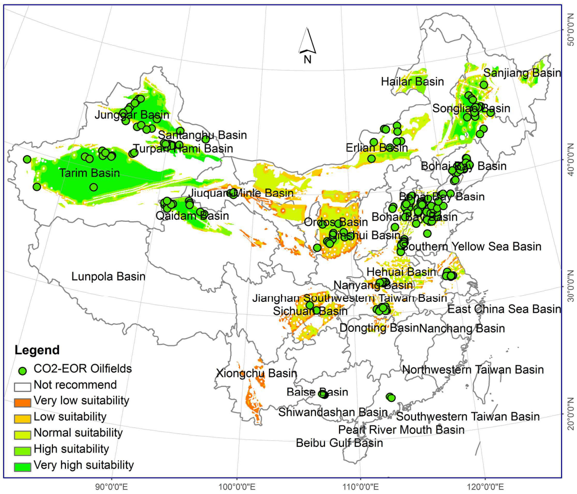

Fig 2 Relationship of candidate storage sites and coal chemical factories (deep saline aquifers and oil fields)

3. Framework of techno-economic evaluation

The techno-economic evaluation is a crucial step for the feasibility study of CCS projects. Based on literature review and expert consultation, a preliminary framework of techno-economic study has been developed. The framework includes site screening and selection, source-sink matching, technology selection, empirical economic evaluation and risk analysis. Due to a lack of detailed site characterization data, such as, 2D/3D seismic data, well drilling & logging, core study and other site-scale characterization, the techno-economic evaluation in this study considers large-scale properties and representative statistical data to evaluate the suitability and techno-economic feasibility of potential CCS projects. This techno-economic evaluation can provide a solid indication of the relative potential for specific source-sink pairs, and provide a foundation for further feasibility and FEED studies.

3.1 Site suitability evaluation

Site suitability of CO_2 saline aquifer storage and CO_2-EOR for the chosen source-sink pairs are evaluated in four important sedimentary basins in China, including Ordos Basin, Bohai Bay Basin, Junggar Basin, and Songliao Basin.

Site suitability evaluation of CO_2 aquifer storage was performed using a process based on multi-criteria methods considering storage optimization, risk minimization, economics, and social criteria [5]. Available geographic information system (GIS) data and spatial analysis tools were applied to assess the multi-criteria sub-basin scale suitability of onshore aquifer sites as shown in Fig 2.

After reviewing existing screening criteria for CO_2-EOR [6, 7], the methodology recommended by Bachu [6] was chosen for screening priority oil fields for further techno-economic assessment. Reservoir properties, including reservoir depth, oil gravity, pressure, temperature, oil viscosity, and residual oil saturation are included in site suitability evaluation of oil fields. The suitable oil fields for CO_2-EOR are also shown in Fig 2.

3.2 Source-sink matching

With preliminary site suitability of oil fields and aquifer sites, the source-sink matching can be performed. Preliminary analysis suggests that there are lots of promising source-sink options within the Ordos Basin, Bohai Bay Basin, Songliao Basin, and Junggar Basin. Fig 3 shows that the most of large-scale coal chemical plants in these four basins can find suitable aquifer sites and oil fields to deploy CCS projects. Surrounding each CO_2 point source are zones with radii of 50, 100 and 150 km, indicating the straight-line distance to areas of suitable storage. Among the 36 large-scale CO_2 emission sources located within these basins, 25% of emission sources have a possible storage site within a range of 50 kilometers, 33% of sources may find storage sites within a distance of 100 km, and 11% of sources have no apparent suitable storage options within 150 km. Four of these actual source-sink pairs (one from each of these sedimentary basins) are identified for further techno-economic analysis as representative examples to highlight the characteristics of different basins, and for convenient routes to build CO_2 pipeline along the roads and landform.

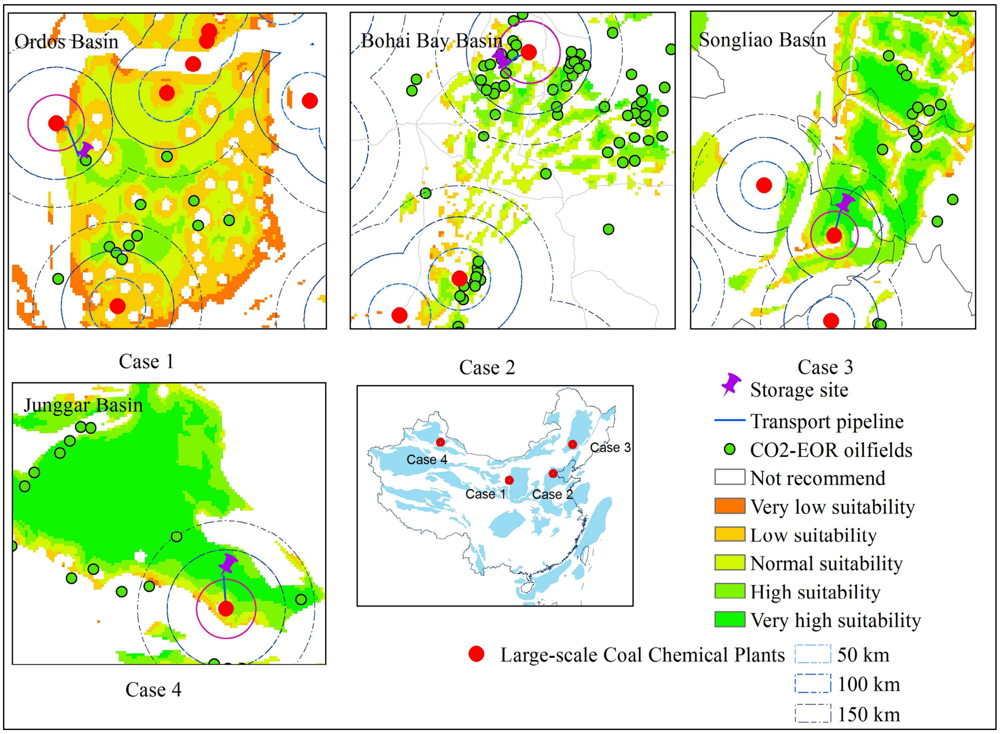

Fig 3 Concept design of identified CCS projects

3.3 Techno-economic evaluation

3.3.1 Conceptual design of CCS system

The conceptual design of each identified CCS project is that the CO_2 is taken from a high-purity source, purified and compressed, then transported by pipeline to the selected storage site, and injected in aquifer formations and sold to EOR. The CO_2 is of sufficient purity from a coal chemical plant that significant capture and purification processes are not required.

The inlet pressure for pipeline transportation is set as 15 MPa. The compression process uses five-stage compressor from 0.1 MPa to 7.38 MPa and one-stage pump from 7.38 MPa to 15 MPa. The routes of pipeline transportation of different CCS projects are shown in Fig 3.

The operating strategy of CO_2 aquifer storage is critical to the safety and economics. Multiple injection wells with pressure control wells (water production wells) are chosen for this large-scale CO_2 injection process. The ratio between injection wells and pressure control wells is set as 1:0.5 in the techno-economic study.

CO_2 aquifer storage coupled with CO_2-EOR could be an attractive CO_2 geological storage option where viable, as aquifer storage can provide a buffering effect for the dynamic need of CO_2-EOR and CO_2-EOR can provide additional revenue for the overall CCS project[8]. Because the CO_2-EOR project is owned by petroleum industries, a sale price of 20USD/t CO_2 is recommended at the terminal of pipeline without any further CO_2 processing. 20 USD/t is well recognized currently in China. Under this approach the strategy applied in this analysis is that 60% of the CO_2 is stored in an aquifer and 40% is sold for use in EOR, without considering the dynamic need for EOR and buffer effect of aquifer storage. This enables the owner of the CCS project to balance high CO_2 storage with reducing overall costs. The basic information and technology types of identified CCS projects are shown in Table 2.

Table 2 Basic information and technology types of identified CCS projects.

	CO_2 emission sources	Storage site	Source-sink distance (km)	Annual emission of pure CO_2 (Mt/a)	Technology types of CCS projects		
					Compression Process	Transport	Storage options
Case 1	Shenhua Ningxia Coal industry Group: 500kt/a olefins	Ordos Basin	77	3	Five-stage compression Two steps From CO_2 gas to supercritical state	Supercritical CO_2 pipeline Pipeline laying along secondary roads	CO_2 aquifer storage (60%) + sale to CO_2-EOR (40%)
Case 2	Hebei Kaiyue Chemical Group: 1Mt/a dimethyl ether	Bohai Bay Basin	45	4			
Case 3	Tongliao Jin Chemical Ltd.: 400kt/a ethylene glycol	Songliao Basin	50	3.2			
Case 4	Baotailong Coal industry Ltd.: 200kt/a ethylene glycol	Junggar Basin	60	1.6			

3.3.2 Economic model

There are many economic models for CCS cost evaluation, such as, IEA model, the Battelle-Pacific Northwest National Laboratory model, Carnegie Mellon University model, ICEM, and other model. The economic evaluation follows are mainly based on the economic model of McCoy [9], and Dahowski, Davidson [10]. The model includes site performance and cost model. The cost coefficients and parameters are based on the annual budget report from petroleum industries in China [11]. All costs are shown in 2005 U.S. dollars.

The cost of a full-chain CCS project for each identified case includes CO_2 dehydration and compression cost, CO_2 pipeline transport cost, and CO_2 aquifer storage cost. The cost evaluation for each technical component includes Capital Expenditures (CAPEX) and Operation and Maintenance (O&M) costs. The CAPEX of CO_2 compression mainly considers the cost of CO_2 compressors and pumps, while O&M is mainly by equipment maintenance and power consumption. The total pipeline investment cost is affected by the location factor and landform factors, in addition to the transportation scale and length of pipeline. The location factor for China is recommended as 0.8 and the topographic factor is determined based on the different topographical conditions of pipeline construction for each project. O&M of CO_2 transport is calculated at 2.5% of the total investment cost [12]. The CAPEX of CO_2 aquifer storage includes the costs of site characterization and evaluation, well drilling & completion, CO_2 flow-line and connections, injection equipment, water production equipment, and water desalination equipment[12].

CCS costs are very sensitive to technical and cost parameters, such as system service lifetime, project scale, discount rate, CO_2 tax rate, electricity prices, CO_2 sale price, EOR scale, pipeline length, geographic features, reservoir properties, and so on. Among these parameters, variation in reservoir properties has significant impact on the storage cost for the well fields which is further impacted by the size of the storage project. Reservoir properties, including reservoir and fracture pressure, thickness and depth, horizontal and vertical permeability, are highly site specific and very significantly between basins and sub-basins. Without suitable scale site characterization, such as, well drilling & logging, 2D/3D seismic investigation, core testing, and other characterization tools; the reservoir properties evaluated in this analysis are based on the statistical properties of major target formations in the basins. A ±30% variation of average value is chosen as variation range for sensitivity study on *the techno-economic evaluation*.

3.4 Cost analysis

On the basis of the above techno-economic model for identified CCS projects, the cost of full-chain CCS can be obtained. The major coefficients for deterministic study are shown in Table 3. The results of the deterministic cost analysis of identified CCS projects are show in Fig 4.

Table 3 Major coefficients of identified CCS project cases

Coefficients	Case 1	Case 2	Case 3	Case 4
Total CO_2 Processed (Mt/a)	3.0	4.0	3.2	1.6
CO_2 to Aquifer Storage (Mt/a)	1.8	2.4	1.92	0.96
CO_2 Sale for EOR (Mt/a)	1.2	1.6	1.28	0.64
Depth(km)	2	2.2	1.5	1.8
Gross Thickness(m)	200	250	100	150
Horizontal permeability (mD)	12	60	40	100
Length of pipeline(km)	77	45	50	60
Ratio of production wells to injection wells	0.5	0.5	0.5	0.5
Electricity price(USD/kwh)	0.087	0.087	0.087	0.087
Life cycle(year)	20	20	20	20
Carbon tax (USD/t CO_2)	15	15	15	15
CO_2 sales price to EOR (USD/t CO_2)	20	20	20	20
Discount rate	0.12	0.12	0.12	0.12

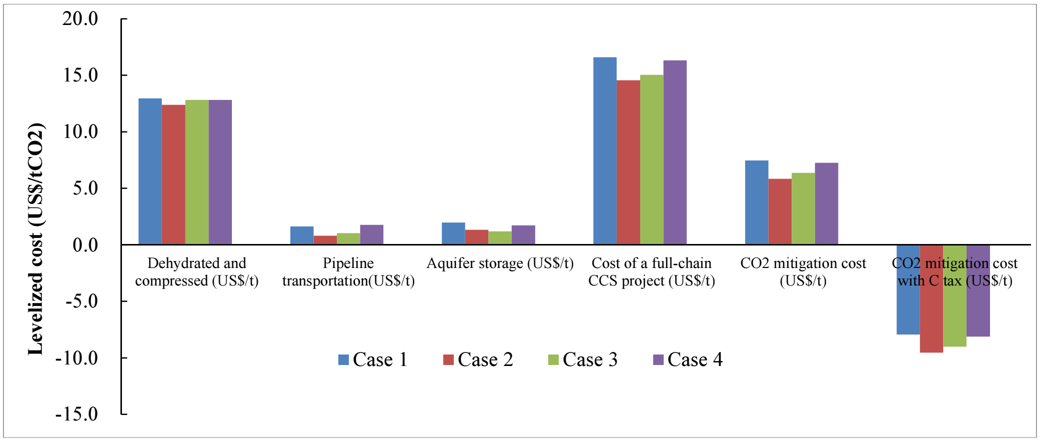

Fig 4 Cost components of the typical CCS project cases

Fig 4 shows the resulting component costs for the studied cases. Because of coal chemical industry with relatively pure CO_2 streams as the point sources, dehydration and compression cost is from 12 to 13 USD/t CO_2. The levelized cost of pipeline transportation ranges from 1 to 2 USD/t CO_2 based on project distance and scale, and storage cost ranges from 1 to 3 USD/t CO_2 based primarily on reservoir properties. Total cost of a CO_2 capture and aquifer storage project ranges from 14 to 17 USD/t CO_2 across these four selected scenarios. The CCS project can obtain benefit from CO_2-EOR projects when a buyer is available for some of the plant's CO_2 output. When 40% the CO_2 output is sold for EOR and thus is further not stored in the aquifer, the total net levelized cost for CCS decreases to between 5.7 and 7.5USD/t CO_2. When a carbon tax is set as 15 USD/t CO_2, which may be possible in China in 2020, the levelized costs of these selected CCS projects ranges from -8 to -10 USD/t CO_2; highlighting the economic benefit to CCS projects from a possible carbon tax.

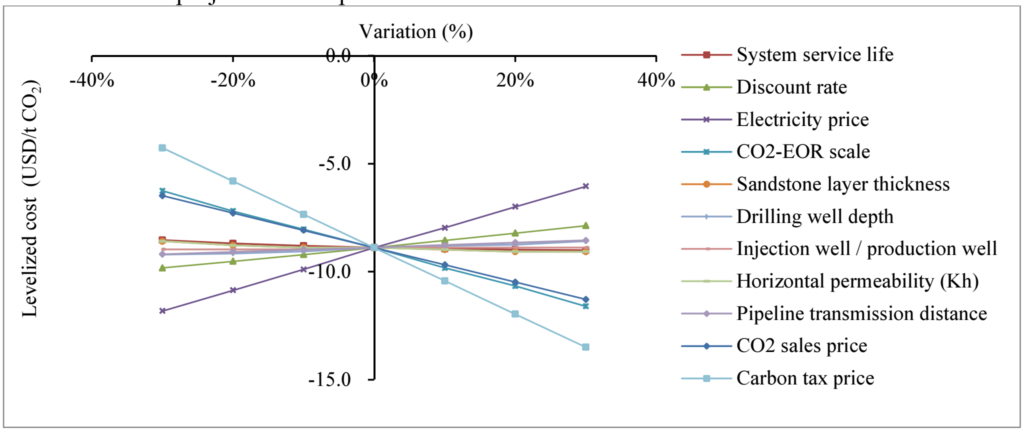

Fig 5 Relationship of parameters variation and levelized cost of a full-chain CCS project

A sensitivity study was carried on the CCS project in Ordos basin (Case 1) to show how the variation in coefficients affect the levelized cost of the CCS project. The relationship between parameter variation and levelized cost is shown in Fig 5. The results show that deeper the reservoir depth, lower horizontal permeability, thinner sandstone thickness, and higher ratio of production / injection wells all increase the levelized cost of storage; whereas higher CO_2 tax, CO_2 sales price, longer project lifetime, lower discount rate, lower electricity price, shorter pipeline transport distance, and larger CO_2-EOR allocation will reduce the CCS project cost, especially the influence of carbon tax. The sensitivity study shows that the total cost of CCS project are very sensitive to these major coefficients, highlighting that a deterministic study based on uncertain values should be viewed to best represent the magnitude and relative nature of costs as opposed to absolute values. Further techno-economic evaluation must base on more detailed work, such as, higher resolution site characterization, site performance evaluation, clarified coefficients and budget evaluation.

The preliminary cost results suggest that these four CCS cases may be viable candidates for a CCS demonstration project, though significant uncertainty remains. This preliminary study shows that the costs of CCS (CO_2 aquifer storage coupled with CO_2-EOR) projects in coal chemical industries is much cheaper than that of CCS projects in conventional industries, and there are some opportunities to deploy these project with low cost in coal chemistry industries.

3.5 Limitation of this study

With the limited geological data, concept design, and empirical techno-economic evaluation, the study in this paper cannot satisfy the minimum requirements of a feasibility study. Therefore the potential CCS projects in this study need further and more detailed evaluation and even FEED study, including further site characterization, site performance evaluation and selection, project design, budget assessment, and environmental and safety evaluation.

4. Conclusion

In this paper, the basic characteristics and distribution of the coal chemical industries in China were investigated and analyzed, the site suitability of aquifer sites and oil fields were evaluated for source-sink matching, four pairs of coal chemical factory and storage sites were chosen for techno-economic evaluation, which includes concept design and economic evaluation. Through this techno-economic study, the key founding of this study are as follows:

1) There are more than 100 coal chemical plants in operation across China as of 2013.These emission sources together emit 430 million tons CO_2/y, of which about 130 million tons per year are high-purity and pure CO_2emissions which can greatly reduce or eliminate prohibitive costs of capture.

2) The technical-economic evaluation shows that the levelized cost of CO_2 capture and aquifer storage over the 4 case study projects involving pure CO_2 from coal chemistry industry sources range from 14 to 17 USD/t CO_2. When 15USD/t carbon dioxide tax and 20USD/t CO_2 sale to EOR is considered, the levelized cost of CCS project are negative, this suggests a net economic benefit for these CCS projects.

3) The total costs of CCS projects are very sensitive to these major coefficients, so the results presented contain high uncertainty. Further techno-economic evaluation must be carried out to refine this work.

4) Yet, it appears that the coal chemical industries may provide attractive early opportunities to deploy and accelerate the scaling-up of CCS projects within China in the near future.

Acknowledgements

The authors gratefully acknowledge the financial support of the Chinese Academy of Sciences, Strategic Priority Research Program-Demonstration of Key Technologies for Clean and Efficient Utilization of Low-Rank Coal, CO_2 geological storage, and Demonstration project (Grant no. XDA07040300) and the projects of the International Cooperation of the Ministry of Science and Technology of China, Joint Research on Key Technologies of Oxy-fuel Combustion Based on CO_2 Capture and Storage System (Grant no. 2012DFB60100).

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