



New potential carbon emission reduction enterprises in China: deep geological storage of CO₂ emitted through industrial usage of coal in China

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Abstract: Deep geological storage of carbon dioxide (CO₂) could offer an essential solution to mitigate greenhouse gas emissions from the continued use of fossil fuels. Currently, CO₂ capture is both costly and energy intensive; it represents about 60% of the cost of the total carbon capture and storage (CCS) chain which is causing a bottleneck in advancement of CCS in China. This paper proposes capturing CO₂ from coal chemical plants where the CO₂ is high purity and relatively cheap to collect, thus offering an early opportunity for industrial-scale full-chain CCS implementation. The total amount of high concentration CO₂ that will be emitted (or is being emitted) by the coal chemical factories approved by the National Development and Reform Commission described in this paper is 42 million tonnes. If all eight projects could utilize CCS, it would be of great significance for mitigating greenhouse gas emissions in China. Basins which may provide storage sites for captured CO₂ in North China are characterized by large sedimentary thicknesses and several sets of reservoir-caprock strata. Some oil fields are nearing depletion and a sub-set of these are potentially suitable for CO₂ enhanced oil recovery (EOR) and CCS demonstration but all these still require detailed geological characterization. The short distance between the high concentration CO₂ sources and potential storage sites should reduce transport costs and complications. The authors believe these high purity sources coupled with EOR or aquifer storage could offer China an opportunity to lead development in this globally beneficial CCS option.

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Keywords: capture; CCS; China; coal; CTL; storage

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Received June 28, 2012; revised and accepted September 29, 2012

Published online at Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ghg.1314





Introduction

China is the world's greatest energy consumer and also the world's largest coal producer.¹ Currently, coal is the main energy source, representing 77% of primary energy production and 70% of the total fuel consumed in China² and it is expected that coal will remain the main energy source for China for decades to come. For this reason, much of the CCS research in China has focused on coal-fired power generation and coal-based industries. However, previous research has not considered the rapid development of industrial-scale conversion of coal to liquid (CTL) products such as gas or olefin over the past few years in China. This rapid expansion occurred in response to shortages in the supply of oil and rapidly rising global oil prices. Coal-based synthetic natural gas, for example, has benefitted from growth in demand and rising prices in the Chinese natural gas market. These coal chemical industries emit large amounts of high concentration CO₂ which is currently disposed of into the atmosphere.

The authors believe that the high cost of post-combustion CO₂ capture from power plant flue and the high cost and lack of maturity in pre-combustion capture of CO₂ is causing a bottleneck in the deployment of CCS in China.^{3–5} The high purity-CO₂ produced from these coal chemical plants could be captured more cheaply than CO₂ from lower purity sources, thereby assisting the growth of CCS in China. If this relatively cheap CO₂ could offer further financial benefit such as for enhanced oil recovery (EOR), this would also support investment in CO₂ capture research in China. The authors suggest that these sources are therefore of great interest for CCS and so potential storage sites near these chemical plants should be sought.

In this paper, the authors first present the location and calculated emissions for coal chemical plants which have been approved by the National Development and Reform Commission (NDRC), China, some of which are already under construction. Then basins near these sources are screened in terms of suitability for CO₂ storage and storage potential is calculated. Finally, the authors discuss what this could mean for CCS in China and how CCS linked to coal chemical plants globally could reduce emissions.

Chemical coal industries in China

In recent years, the rate of demand for oil has outstripped national supply which has promoted rapid

development of the coal chemical industry. Hot spots of coal-based industrial development have focused on regions with abundant coal reserves such as the Xinjiang, Inner Mongolia, Shaanxi, Ningxia, and Shanxi provinces (and Autonomous Regions). The low price of coal and proximity to coal mining districts make coal to gas/liquid/olefin products economically viable. The coal to gas, liquid and olefin projects which have been approved by the NDRC are described in Table 1.

There are four coal-to-coal-based synthetic natural gas (SNG) Projects with the total amount of synthetic natural gas produced being 15.1 Billion m³ per year.^{6–8} The amount of CO₂ emitted during coal to SNG processing is dependent on coal rank and technology amongst other factors. Based on expected emission factors (such as those used by IEAGHG) it was estimated that 214 000 tonnes* CO₂ with about 90% concentration are emitted for every 100 Mm³ natural gas produced.⁹ These four SNG projects would be expected to emit around 32 Mt (million tonnes) of CO₂ per year in total.

There is one NDRC-approved coal to liquid (CTL) project, it was estimated that 3.5 tonnes of CO₂ with about 90% concentration would be emitted per tonne of oil produced. Therefore, the total amount of CO₂ emitted by this plant was estimated to be 3.78 Mt per year. Sales of CTL products are welcome on the market due to their premium quality; the Shenhua Ordos CTL Branch easily obtained its license from China's Ministry of Commerce as a wholesaler for oil products.

There are three approved coal to olefin (CTO) projects which would be expected to produce about four tonnes of CO₂ with a concentration of about 90% would be emitted per tonne of polypropylene produced. The total amount of CO₂ emitted from these projects was estimated to be 6.4 Mt per year.

Site screening of geological storage options

Research required to screen deep saline aquifers for CO₂ storage includes the geological setting (such as geological structure, tectonic activity, heterogeneity, lithology, sensitivity, etc), reservoir conditions (such as salinity, sweep efficiency, reservoir depth and

*The authors assumed 2.14kg CO₂ would be emitted when 1 cubic meter of SNG is produced, therefore, 214 000 t CO₂ will be emitted when 100 M cubic meters of SNG are produced.

**Table 1. Coal Chemical Projects and CO₂ emissions**

Location	Project and product amount		Type	CO ₂ emissions (Mt/Y)
Hexigten Qi, Inner Mongolia AR, under construction	Datang Group, Hexigten Qi (Keshiketeng)	Phase I – 1.34 Billion m ³ /y in 2011	CTG	Phase I – 2.86
		Phase II – 2.68 Billion m ³ /y in 2012	CTG	Phase II – 5.73
		Phase III – 4 Billion m ³ /y in 2014.	CTG	Phase III – 8.56
Duolun County Inner Mongolia AR (built and undergoing calibration)	Datang Group, Duolun County	0.5 Mt/y poly-propylene	CTO	2
Fuxin City, Liaoning Province, under construction	Datang Group, Fuxin City,	4 Billion m ³ /y	CTG	8.56
Baotou City, Inner Mongolia AR (in operation)	Shenhua Group (Baotou)	0.6 Mt/Y olefin	CTO	2.4
Lingwu City, Ningxia Ningxia Hui AR (built and undergoing calibration)	Ningdong factory Shenhua Ningmei Group	0.5 Mt/y propylene	CTO	2
Ejinhoro Qi, Erdos City, Inner Mongolia AR, under construction	Huineng Group, Ejinhoro Qi,	1.6 Billion m ³ /y	CTG	3.42
Ejinhoro Qi, Erdos City, Inner Mongolia AR (in operation)	Shenhua Group, Ejinhoro Qi,	1.08 Mt/Y (oil production)	CTL	3.78
Yining County, Xinjiang Uyghur AR, under construction	Qinghua Coal Chemical Engineering Group, Xinjiang	Phase I – 1.37 Billion/Y	CTG	
		Phase IV – 5.5 Billion m ³ /y	CTG	11.77

Note: AR – Autonomous Region, CTG – Coal to Gas, CTL – Coal to Liquid, CTO – Coal to Olefin.

thickness, porosity, and permeability), source-sink matching and assessment of the cost and the geological risks. Previous research in the EU-funded COACH and NZEC China-EU collaborative projects has also indicated that there is potential for storage in the Bohai,¹⁰ Songliao, Subei, and Qinshui Basins in north-east China.^{11–15} A similar approach to the initial screening undertaken in those studies was applied here. Basins near the coal chemical plants described earlier in this paper were screened for suitability based on proximity to the sources and the presence of porous and permeable sandstone-rich formations with large areal extent at depth, capped by impermeable layers. Basins identified by this screening process included Bohai Bay Basin, Eren Basin, Ordos Basin (including Hetao Basin) and Junggar Basin. These basins include potential reservoir and caprock sedimentary sequences, which could make the basins possible sites for CO₂ storage (Fig. 1). A summary of the stratigraphical successions in the Bohai Bay, Ordos, Hetao and Junggar basins is given in Figs 2–5 and selected geological data relevant to CO₂ storage are given in Table 2. More detail on results of the basin screening is given below.

Storage potential in the central Bohai Basin was identified by the COACH project. For this paper, the Western sub-basin in the Xialiaohe Depression of the Bohai Bay Basin was also considered as it contains porous sandstone and conglomerate rich formations with thickness varying from tens to several hundreds of meters (Fig. 2). These are sealed by mudstones and lithological and structural traps could also potentially store CO₂ from the Datang Group Fuxin City CTG plant which is currently under construction. Fuxin City is also close to the Shuguang and Huanxiling oil fields (80 km) and Damintun Oil field (100 km). Initial exploitation of these oilfields began in the 1970s.¹⁶ There are three sets of caprock – storage pairs developed in Liaohe Oil Field complex. From the oldest to youngest these are:

- Caprock in the third member of Shahejie Formation and storage in the fourth member of the Shahejie Formation plus the Kongdian Formation.
- Caprock in the first member of Shahejie Formation and storage in the second member of Shahejie Formation.
- Caprock in the Minghuazhen Formation and storage in the Guantao Formation.

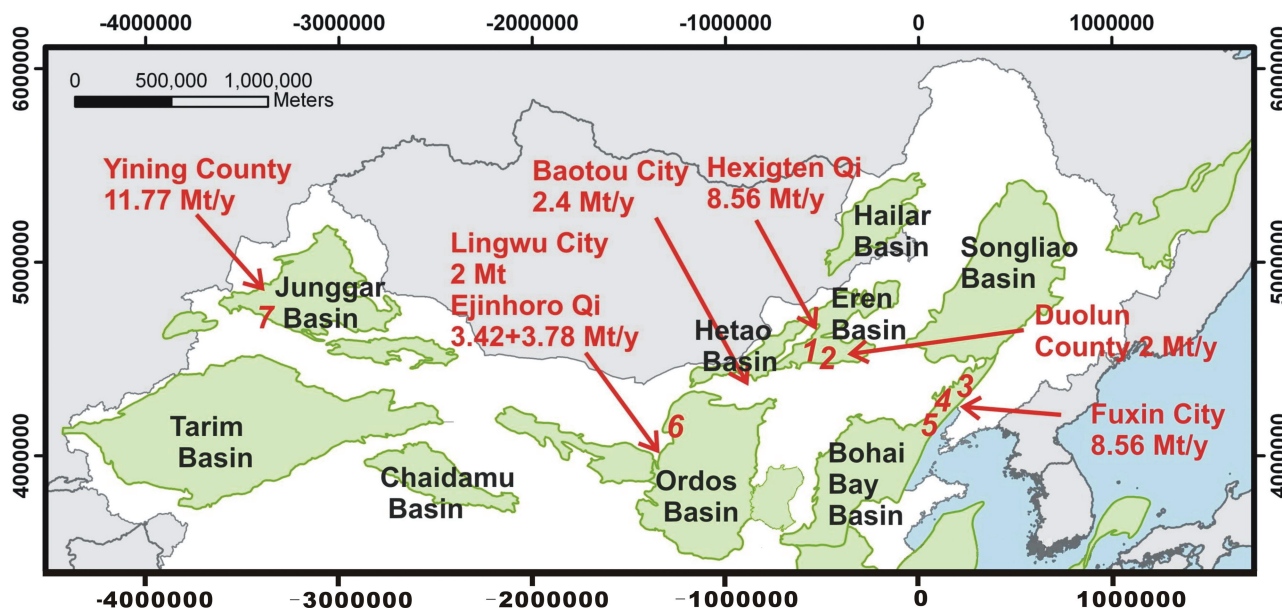


Figure 1. Sources of CO₂ (red) and main sedimentary basins (green) in the northern sedimentary basins of China. Basemap data taken from the Digital Chart of the World (1:1 million data) provided by ESRI, State province and basin outline reproduced with the kind permission of the USGS. 1 - Manite sub-basin, 2 - Tengger sub-basin, 3 - Xialiaohu Depression, 4 - Shuguang Oil field, 5 - Huanxing Oil field, 6 - Wulanmulun Zhen, 7 - Yining County.

Therefore, there are three sets of regional storage-seal pairs potentially available for CO₂ storage: the upper is the Guantao Formation – Minghuazhen Formation; the middle is combined sub-reservoir-caprock

pair of Eocene age; the deepest is the Buried Hill carbonate Formation (the Wumishan Formation in Jixian system of middle-upper Proterozoic age).

Eren basin is a strongly heterogeneous continental basin with generally low porosity and low permeability. There are two sub-basins however, which could have some storage potential: the Manite and Tengger sub-basins where there are sandstone rich formations that are hundreds of meters thick. The Datang Group Hexigten Qi coal to gas factory is located less than 100 km from the Tengger sub-basin.^{17,18} In these sub-basins, the sandstone reservoir formations are buried at depths of 1–3km and potential storage sites are formed by structural and fault traps.

A pilot project storing 100 000 tonnes of CO₂ emitted by Shenhua DCL plant was launched in January 2011. The CO₂ is injected into a saline aquifer formation in Wulanmulun Zhen, Ejinhoru Qi (county) in the Ordos Basin. This project is being carried out by the Shenhua Group and is not

discussed further in this paper as it is already undertaking CO₂ storage.²⁰ However, another coal to olefin plant, Ningdong factory located in Lingwu City, lies 40 km from Majiatan Oil Field and 38 km from Lizhuangzi Oil Field. It could also be considered as a potential capture target for storage of CO₂ in oilfields and surrounding aquifers in the same basin where there are sandstones around 200 m thick at suitable depth and potential structural and lithological traps (Fig. 4).

The coal to olefin factory in Baotou City is located in the Hetao Basin (Figure 1, Figure 3). In the Hetao Basin, mudstone interbedded with fine-grained sandstone of the Pliocene Wulantuke Formation and mudstone intercalated with fine-grained sandstone and marlite of the Miocene Wuyuan Formation form the caprock and silt to medium-grained sandstone of the Oligocene Linhe Formation (thickness 260–340 m) offer a potential storage site in the Huhe Depression of the basin with structural and lithological trapping potential.¹⁹

The coal to gas factory under Qinghua Coal Chemical Engineering Corporation located in Yining County, Xinjiang lies about 250 km from the Yining and Dushanzi Oil Fields in the Junggar Basin



Geological Age			Formation	Member	Seal / Reservoir
Neogene	Pliocene	Nm	Minghuazhen	1	[Pattern]
				2	
	Miocene	Ng	Guantao	1	[Pattern]
				2	
Eocene	Oligocene	Ed	Dongying	1	[Pattern]
				2	
				3	
	Eocene	Es	Shahejie	1	[Pattern]
				2	
				3	
				4	
	Palaeocene	Ek	Kongdian	1	[Pattern]
				2	
				3	
Cretaceous	Upper	K2	Wangshi		
Jixian Series		Jxw	Wumishan		

Figure 2. Simplified stratigraphy of Bohai Bay Basin.

Geological Age			Formation (Central)	Member	Seal / Reservoir
Cretaceous	Lower	K1	Zhidan Fm		
Jurassic	Upper	J3f	Fenfanghe Fm		
	Middle	J2a	Anding Fm		[Pattern]
		J2z	Zhiluo Fm		[Pattern]
	Lower	J1y	Yanan Fm	4	[Pattern]
				3	[Pattern]
2				[Pattern]	
1				[Pattern]	
	J1f	Fuxian Fm		[Pattern]	
Triassic	Upper	T3y	Yanchang Fm	5	[Pattern]
				4	[Pattern]
				3	[Pattern]
				2	[Pattern]
		1	[Pattern]		
	Middle	T2z	Zhifang Fm		
	Lower	T1h	Heshanggou Fm		
T1l		Liujiagou Fm			
Permian	Upper	P3s	Shiqianfeng Fm		

Figure 3. Simplified stratigraphy of Ordos Basin.

Geological Age			Group / Formation	Seal / Reservoir
Quaternary		Q		
Neogene	Pliocene	N2	Wulantuke Fm	
	Miocene	N1	Wuyuan Fm	[Pattern]
Eogene	Oligocen	E3l	Linhe Fm	[Pattern]
	Eocene	E2w	Wulate Fm	[Pattern]
Cretaceous	Lower	K1	Guyang Fm	[Pattern]

Figure 4. Simplified stratigraphy of Hetao Basin.

where there is potential for CO₂ storage in sandstones in structural anti-formal closures and lithological trapping²¹ (Fig. 5), however the sandstones here are only 17 m thick, so this may not be a promising site.

Geological storage calculations

CO₂ storage during CO₂-EOR

During carbon dioxide enhanced oil recovery (CO₂-EOR) operations, some CO₂ is stored in the oil reservoir. The additional oil recovered is calculated as

Geological Age			Group/Formation (West)	Seal / Reservoir	
Quaternary	Pleistocene	Q1x	Xiyu Fm		
Upper Tertiary	Pliocene	N1-2d	Dushanzi Fm		
		N1t	Taxihe Fm		
	Miocene	E3-N1s	Shawan Fm	[Pattern]	
Eogene	Oligocene	E2-3a	Anjihai Fm	[Pattern]	
	Eocene				
	Palaeocene	E1-2z	Ziniquanzi Fm	[Pattern]	
Cretaceous	Upper	K2d	Donggou Fm	[Pattern]	
	Lower	K1tg	Tugulu Group	[Pattern]	
Jurassic	Upper	J3q	Qigu Fm	[Pattern]	
		J2t	Toutunhe Fm	[Pattern]	
	Middle	J2x	Xishanyao Fm	[Pattern]	
		Lower	J1s	Sangonghe Fm	[Pattern]
			J1b	Badaowan Fm	[Pattern]
Triassic	Upper	T2-3xq	Xiaoquangou Group	[Pattern]	
	Middle				
	Lower	T1cn ^b	Shangcangfang-gou Group	[Pattern]	
Permian	Upper	P2cn ^a	Xiacangfanggou Group	[Pattern]	

Figure 5. Simplified stratigraphy of Junggar Basin.



Table 2. CO₂ sources and geological parameters of potential storage sites

CO ₂ project and quantity (Mt/y)	Basin	Area Km ²	Reservoir age and Type	Thickness m	Depth m	Reservoir Physical properties		Caprock Lithology and thickness m	Hydrological conditions		
						Porosity %	Permeability MD		Salinity mg/L	Storage type	
Hexigten Qi 2.86 – 8.56 Mt/y, Duolun County, 2Mt/y	Manite and Tengger sub-basins, Eren Basin	22170	K1 Sandstone	Several hundreds of m	1000~3000	10–30	8–3922	Mudstone 100–356	NaHCO ₃	1756–5797	CO ₂ -EOR
Fuxin City 8.56 Mt/y,	Bohai Bay Basin; Western sub-basin in the Xialiaohe Depression	427.6	Es Sand stone and conglomerate	Tens to several hundreds of m	700–3780	16–30	100–3000	Mudstone S1 0–945 S3 0-1861	NaHCO ₃	281–58107	CO ₂ -EOR
Baotou City 2.4 Mt/y	Hetao Basin, Huhe sub-basin	1500–2500	E K1 Sandstone	260–340 260–310	1800–3500	10–25 4.9–11.7	274–302 1.4–47.7	Mudstone 400–800			Saline aquifer
Lingwu City 2Mt/y, Eijnhoro Qi Huineng Group 3.42 Mt/y and Eijnhoro Qi Shenhua Group 3.78 Mt/y	Lizhuangzi, Mafang, Hongjingzi Oil Fields and other sandstone formations	150	J1y J1y2z Sand stone	200	870–2000	17.5–19	41.5–213.3	Mudstone 100–150	CaCl ₂ MgCl ₂ NaHCO ₃ Na ₂ SO ₄	3900–80000	CO ₂ -EOR
Yining County 11.77 Mt/y	Dushanzi Oil Field	1.2	N1s Sand stone	17	800–1800	17.6	0.8–46	Mudstone 200	CaCl ₂ NaHCO ₃	2000–37000	CO ₂ -EOR



a percentage of the original oil in place (OOIP) which comes into contact with the injected CO_2 . Stevens²² estimated that about 75% of the OOIP would be in contact with the CO_2 during miscible or immiscible flooding. The method used by Stevens²² was modified by the authors and used to calculate the potential for EOR²³ in the Liaohe Oil Field complex of the Bohai Bay Basin (Fig. 6).

The authors calculated the incremental oil production through CO_2 -EOR assuming that the oil recovery rate was 8%, 10%, and 15% of the OOIP. The potential CO_2 storage capacity in other oil fields during CO_2 -EOR operations in China could also be estimated for other fields using this method where data are available.

CO_2 storage potential in deep saline aquifers

All the sites selected through the basin-screening have suitable geological characteristics and initial volumetric estimates suggest they could store CO_2 emissions

from the nearby coal chemical plants for many decades. The next step is further site characterization and full assessment of the storage capacity by obtaining detailed geological data from new seismic data or borehole records.

Globally, a number of methods to calculate the CO_2 storage capacity in deep saline aquifers have been put forward, including the CSLF (Carbon Sequestration Leadership Forum), USDOE (United States Department of Energy) and others,²⁴⁻²⁶ but there is no single agreed methodology. Additionally, most of these methodologies include a 'storage factor' of some description which includes a number of factors (such as irreducible water saturation or sweep efficiency), the values of which are not generally known for aquifer storage sites since they are generally less well studied than oil fields. A more detailed site characterization is now required which may include 2D and 3D seismic data acquisition and further drilling of exploration wells to suit the nature of different regions and different storage sites in China where these data

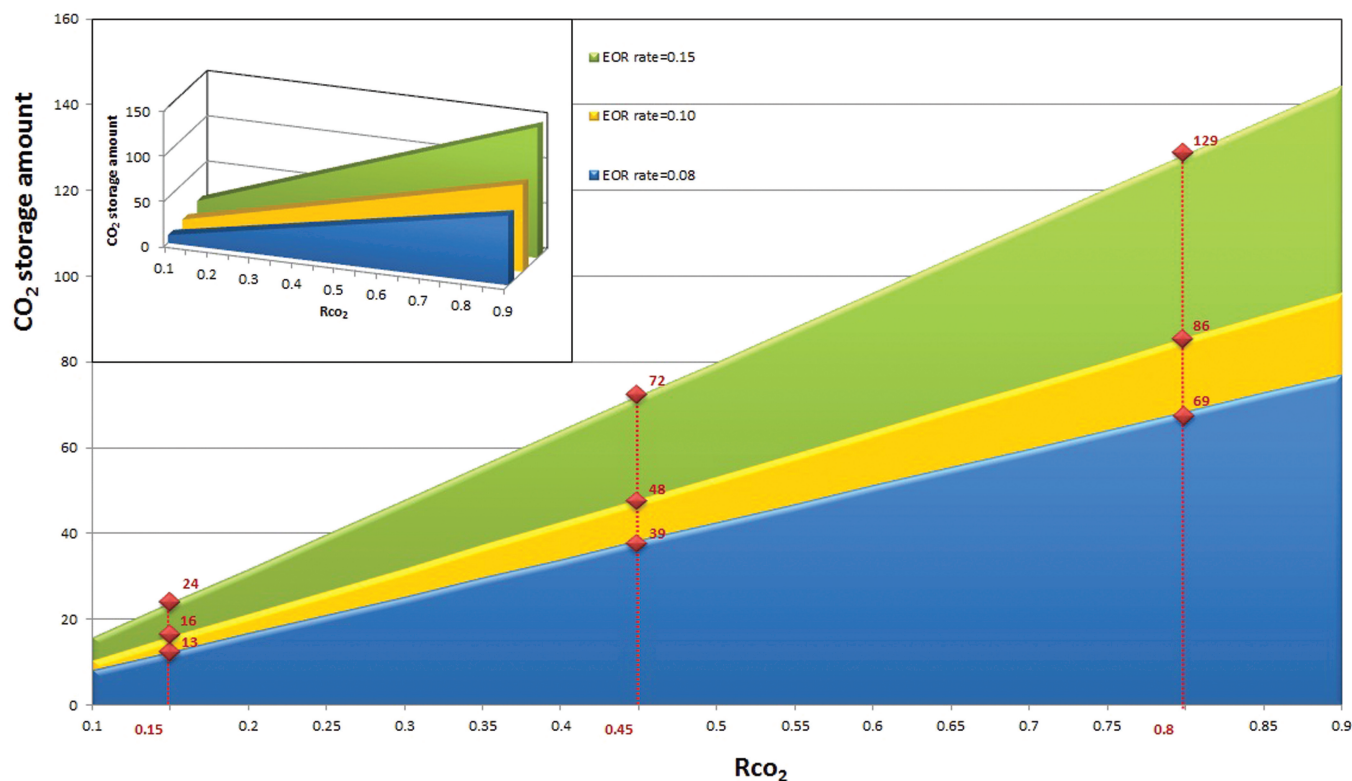


Figure 6. Total calculated potential stored CO_2 (figures on the graph in red in Mt) for the Damintun, Shuguang, Huanxiling and Gaosheng oilfields of the Liaohe Oil Field complex which have a combined Original Oil in Place of 1071 Mt. EOR rate is extra oil recovered during EOR expressed in terms of a percentage of the OOIP. R_{CO_2} is the ratio of CO_2 injected to additional oil recovered.



are not available. As identified from the COACH and NZEC projects, the basin lithology and structure is often complex and will be challenging to characterize and to utilize for CO₂ storage.

Some of the oilfields have undergone extensive water flooding, for example, the Buried Hill oil fields[†] have been exploited on a large-scale since the 1970s and are in the late stages of development; most of the oil in place has been extracted and the injected/native water has intruded into the oil fields to such an extent that it could be considered appropriate to estimate storage capacity of deep reservoirs in the Huabei oil field complex of the Bohai Bay Basin using the saline aquifer calculation. The average total effective thickness of the 13 Buried Hill reservoirs could be considered as the total thickness of saline aquifer formations (i.e. about 65 m) to estimate the storage capacity. In the Buried Hill reservoirs, porosity comprises intergranular pores and dissolution features in the dolomite and limestone seams. In the original assessment of hydrocarbon reserves, the average porosity was calculated to be 6%. This figure was used for calculating storage capacity. Irreducible water saturation was estimated to vary from 10–50%. The storage capacity was 573 to 953 million tonnes CO₂ in the Buried Hill reservoirs and more than 1 billion tonnes in the sandstone-rich Guantao Group.²⁷

Conclusions: New enterprises and new vista

The trend of high oil prices on international markets has strongly supported development of coal chemical industries in China. CTL, gas and olefin processes produce highly concentrated CO₂ streams. Capturing these waste gases would help to reduce greenhouse gas emissions to realize more environmentally sustainable development. Capturing CO₂ emitted from coal-based chemical industries for CO₂-EOR or for storage could be an effective approach for reducing greenhouse gas emissions in China and could help overcome the current developmental bottleneck of high costs for CCS when and where these high concentration streams of CO₂ are readily available. Following the example set by the pilot scale in the Ordos Basin project, the coal chemical

industry could offer an early opportunity for industrial-scale full-chain CCS implementation in China.

Carbon dioxide captured from these coal chemical processes could be stored in adjacent sedimentary basins where they have suitable geological characteristics. The basins identified in this paper in Northern and Eastern China are characterized by large sedimentary thicknesses, tectonic stability and several sets of reservoir-caprock pairs, they also include some oil fields that are nearing depletion and a sub-set of these are potentially suitable for CO₂-EOR and CCS demonstration but require detailed geological characterization. The short distance between the high concentration CO₂ sources represented by the coal-based chemical industries and storage sites should reduce transport costs and complications. Geographical relief is generally gentle, the wide grasslands and low relief hills are favorable for construction of the coal chemical plants as well as pipelines or roads for transport of raw materials and products. A CCS with EOR pilot using a coal chemical plant in North Shaanxi Province is being undertaken by Shaanxi Yanchang Petroleum (Group) Co., Ltd. and was supported by MOST in 2012.²⁸ This pilot, if successful, will prove the concept for future coal to liquid with CCS projects in China.

There is still the question of how much an energy company utilizing the CO₂ would pay as the CO₂ is currently disposed of as waste, and there are further questions about who would pay other costs such as capture and pipeline costs. The required investment capital, raw materials, energy, and water consumption in coal-based industries are very high and their comprehensive utilization and environmental control requirements are rather strict. Project investment must be carefully considered based on coal resources, water resources, capital investment, transportation, sustainability and optimization of other factors (e.g. proximity to markets, coal source, water sources). Nonetheless, the authors believe there is still a good opportunity here as the CO₂ streams are high purity and therefore the costs of CO₂ capture, purification and compression will be low compared with those from flue gas in conventional coal-fired power plants.

The total amount of high concentration CO₂ that will be emitted by the coal chemical factories approved by the NDRC that have been described in this paper is 42 million tonnes. If all eight projects could utilize CCS, it would be of great significance for

[†]Buried Hill oilfields describes a common structural form for oilfields in China – i.e. hydrocarbons are trapped against an erosional surface which used to be a hilly palaeo-geographical surface



mitigating greenhouse gas emissions for China and globally. The authors hope that utilizing these high purity sources in China for carbon capture, utilization, and storage (CCUS) in China could offer a good example for other countries rich in coal such as the USA, India, Germany, and Poland. The IEA technology roadmap²⁹ estimates that 7% of the CO₂ emissions from primary energy supply in 2012 came from high purity sources such as natural gas processing and syngas generation and this is expected to grow to 23% by 2050 according to the ETP Baseline scenario. This expected increase in high purity sources could be highly significant for reducing greenhouse gas emissions if these are combined with CCS wherever practicable. If all the CO₂ from these sources could be captured and stored, based on the ETP Baseline scenario, global CO₂ emissions in 2050 could potentially be reduced by 3.7 GtCO₂.

Acknowledgements

This work has been supported by the MOST, China. Project No: 2006CB705802 and 2011CB707303. Also, ADB and NDRC, China Project No: ADB TA-7286 (PRC) People's Republic of China. The authors also thank Global Carbon Capture and Storage Institute (GCCSI) for their encouragement and support. The authors also wish to thank the reviewers for their constructive comments on this paper. CJ Vincent and MH Stephenson publish with the permission of the Director, British Geological Survey (NERC).

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