Carbon dioxide storage options for the COACH project in the Bohai Basin, China

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Abstract

The Cooperation Action Carbon Capture and Storage China-EU project (COACH) is a three-year EC Framework 6 co-funded collaborative project with Chinese and EU partners investigating geological storage options in the Bohai Basin, China. This paper discusses interim assessments of storage potential for the Dagang oilfield complex (Tianjin Municipality), deep saline aquifers in the Jiyang depression (Shandong province) and the Kailuan coalfield (Hebei Province). Source-sink matching options are also discussed using large 'point source' data collected for the Shandong Province.

Carbon capture and storage; China; Bohai; COACH; GeoCapacity; NZEC; Dagang; Jiyang; Kailuan; Shandong; Shengli

1. Introduction

In China, most industrial development and therefore the majority of large sources of carbon dioxide (CO_2), lie along the eastern coastline and consequently storage sites are being sought is this area. The COACH (Cooperative action within Carbon Capture and Storage China-EU) project considers storage in the Bohai Basin, a rift-subsidence basin located in north-eastern China, south-east of Beijing (Figure 1). The work on storage capacity in the COACH project is building on the earlier work in China of the EU GeoCapacity project (Bohai Basin, Hebei Province) and is complemented by investigation of the UK-NZEC (Near Zero Emissions from Coal) project (Jilin Province, Subei Basin and Songliao Basin).

The Bohai Basin was formed during the Cenozoic when frequent tectonic movements developed numerous fault blocks. During Cenozoic rifting, the basin divided into six sub-basins; Liaohe, Jizhong, Huanghua, Bozhong, Jiyang and Linqing [1]. Each of these sub-basins or depressions has been independently affected by tectonic activity and sedimentation.

From collation of large sources in the Shandong Province, average annual emissions for power stations larger than 100 mW (Megawatts) in the Shandong Province were 2.5 Mt; over a 25-year estimated lifespan of a power plant this would mean that a storage volume of 62.5 Mt would be required for a full-scale demonstration of carbon capture and storage (CCS).

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2. Dagang oilfield

The Dagang oilfield complex (operated by PetroChina) lies in the Huanghua depression and covers an area of circa 24 km^2 in Cang County, Hebei Province (Figure 1). Exploration in the area began in 1964 and production started in the Dagang oilfields in 1968. The oil-bearing area covers 640 km^2, with in total, 16 oil fields developed with an estimated reserve of nearly 1.1 billion tonnes of oil. The Dagang oil reservoirs lie at depths of 1000–2500 m and have a complex and highly compartmentalised stratigraphy and structure. The main reservoir rocks in the Dagang complex are fluvial facies of Cenozoic age, including the Dongying, Guantao and Minghuazhen groups (Figure 2).

The Research Institute of Petroleum Exploration and Development, PetroChina Co. Ltd studied the reservoirs of the Dagang field to assess potential for geological CO_2 storage. There are several types of reservoir-trap systems observed in the Dagang field; fault block condensate gas field, complex faulted block, bottom water reservoir, low permeability reservoir, limestone reservoir and volcanic reservoir. At the first-pass assessment for suitable storage sites, the limestone and volcanic reservoirs were discarded as less favourable than the clastic sedimentary reservoirs due to their smaller size and lower porosities and more complex chemical reactions with CO_2. The fault block condensate gas fields were discarded due to conflicts of interest as PetroChina is considering these for natural gas storage. The low permeability, bottom water and complex block fields were considered further. The sandstone-dominated Gangdong, Gangxi, Gangzhgong, Wangguantun and Shenvshi fields were studied in more detail, having average porosities in the range 19-31%, permeability 18-975 mD (milli Darcies), average net pay thickness 10-22m and oil API 33-34 and saturation 60-65% (in Table 1).

A simplified calculation (Equation 1), using the models presented by Bachu et al. [2] in the Carbon Sequestration Leadership Forum (CSLF) 2007 paper, gives an effective storage capacity of approximately 77 million tonnes (Mt) of carbon dioxide (CO_2) for the seven selected oilfields in the Dagang complex.

$$\text{Effective } CO_2 \text{ storage} = UR_p \,.\, FVF \,.\, \rho_{CO2r} \qquad (1)$$

Where: UR_p = proven ultimate recoverable oil

FVF = formation volume factor

ρ_{CO2r} = CO_2 density at reservoir conditions

The results of storage potential calculations are given in Table 1. The Gangdong field was believed to show the most potential of the selected fields, however, after calculating the storage capacity, the storage volume was only 27.5 Mt. A fluvial environment of deposition and faulting mean the reservoirs are highly compartmentalised, conditions not favourable to CO_2 storage. The number of wells drilled in the Dagang complex is also very large (spacing between boreholes is around 200m), presenting many potential leakage pathways. This also makes the Dagang complex unfavourable for CO_2 storage. There may be some opportunity to recover additional oil through enhanced oil recovery (EOR), however, the Dagang field is not considered suitable for large-scale storage of CO_2.

3. Kailuan coalfield

The Kailuan coalfield lies in the north Bohai Basin and has been in operation for over 100 years. The coals of the Kailuan field are of Carboniferous and Permian age (360-248 Ma old) and coal reserves are estimated to be 3753 million tonnes. Carbon dioxide is preferentially adsorbed by the coal, displacing coalbed methane. The effectiveness of this process varies with pressure (and therefore with depth). The macerals and the vitrinite reflectance of the coals from the Kailuan Coalfield which could significantly influence the CO_2 adsorption were examined.

The experimental adsorption capability of the coals with varying pressure and composition of injected CO_2-CH_4 (carbon dioxide and methane) gas was examined by the China University of Mining and Technology. Two coals of different rank and from different depths were selected for isothermal adsorption experiments and proximate analysis; the No.11 seam Coal from the Linnancang Mine and the No.9 seam Coal from the Majiagou Mine. Proximate analyses of the coals (moisture, ash and volatile matter) sulphur content and vitrinite reflectance were determined according to ASTM standards. Characteristics for isothermal adsorption of pure CO_2, pure CH_4 (methane) and CH_4/CO_2 mixed (binary) gas were analyzed using an IS 100 isotherm instrument. Results indicated the coals of the Kailuan Coalfield were of medium volatile bituminous rank. The maceral compositions and depth of the two coal seams (greater than 800 m) were determined to be favourable for CO_2 adsorption.

Experimental adsorption isotherms of pure CH_4, pure CO_2 and a mixture of the two gases (binary gas) were delineated for the No.11 coal from Linnancang Mine and for the No.9 coal from Majiagou Mine. As the level of CO_2 concentration was increased in the feed gas composition, the total adsorbed gas increased for both coal samples. The adsorption of CH_4/CO_2 binary gas is a competitive process rather than an independent adsorption of pure CH_4 and pure CO_2, thus the optimum binary gas mixture was tested experimentally. The adsorption curves of the CH_4/CO_2 binary gas lie above that for pure methane and below that for pure carbon dioxide. With the increase of CO_2 concentration for feed gas compositions, the adsorbed amounts of the total gas increased for the two coals. The adsorption capacity of the No.9 coal from Majiagou Mine is higher than that of the No.11 coal from Linnancang Mine. The Langmuir constant, necessary for calculation of CO_2 capacity using CSLF methodology [2] was determined. The maximum adsorption of CO_2 for both coal samples was 10-16 g/cm^3. Thus, for these coals, the vitrinite-dominated maceral composition was determined to be favourable for CO_2 adsorption.

Three different methods of predicting adsorption behaviour of the binary gas mixture were applied; the extended Langmuir equation, ideal adsorbtion theory and numerical analysis. It was determined that for the No.11 coal from Linnancang Mine, the numerical analysis method theoretical results were closest to those obtained experimentally. However, for the No.9 coal from Maijiagou Mine, the results from the extended Langmuir equations more accurately modelled the experimental results. Comparison of these theoretical and measured figures demonstrates the importance of experimental results for calculating absorption properties and estimating CO_2 storage capacity for the coals of the Kailuan Coalfield. However, mining continues in the Kailuan field, and potential storage sites would have to be selected with care to avoid potential leakage issues or contamination of mineable coals.

Further investigation into the storage potential for the coals is being carried out. Initial results for injectivity of the coals indicate that properties may be unfavourably low for large-scale storage. The Early Permian Taiyuan Formation coal is the most promising with porosity 3.7% and permeability 3.62mD.

4. Jiyang Depression

The Jiyang Depression (figure 1) lies in the central Bohai Basin near the Shengli oilfield complex. It covers an area of around 20000 km^2 and is divided into six sags; Huimin, Chezhen, Zhuandong, Dongying, Qingdong and Zhanhua. This is an oil producing region and the Shengli and Gudong oilfields lie within the Jiyang super depression, thus deep geological information is available in some areas. Aquifer sediments in the Jiyang Depression fall into five groups; Palaeozoic, Mesozoic, Eocene, Neogene (Guantao Group and Minghuazhen Group) and Quaternary. The Neogene aquifers are believed to have the best potential; they lie at suitable depth (greater than 1000 m) and have a broad areal distribution and good connectivity between fault blocks. From east to west, the environment of deposition grades from flood plain to lacustrine.

The Institute of Geology and Geophysics, Chinese Academy of Sciences studied the potential for storage in the Jiyang Depression. Here, the Guantao Group comprises partially cemented and fractured gravel rocks. The pore water chemistry is stable; the majority contain $CaCl_2$. On the southern and northern margins, pore water has composition $NaHCO_3$. Overall, the general total dissolved solid (TDS) is 10-20mg/l. The ratio of Na/Cl in most areas is less than 1. The hydrochemical characteristics indicate that the groundwater flows from the margin to the centre of the depression.

The Minghuazhen Group can be divided into the upper and lower deposits; the lower comprising thick mudstone and the upper comprising fluvial sandstones and mudstones. The Lower Minghuazhen Group could provide a regional cap rock for the underlying Guantao Group. The upper portion is a regional potable water source.

Most of the oil produced is from the east Jiyang Depression. There are 50 oilfields in Zhanhua and Dongying sags where oil is extracted mainly from the Guantao and Shahejie formations. Thus efforts to find aquifer storage are being focussed on the Huimin Sag, where there are only four oilfields (Linpan, Shanghe, Yuhuangmiao and Linfanjia) in operation and therefore it is less likely storage would be subject to be a conflict of interest with hydrocarbon production and associated risks of leakage from exploration wells.

There is more uncertainty in estimation of aquifer storage potential as a result of limited data availability due to general lack of commercial interest in deep saline aquifers. However, the Jiyang depression is a petroliferous area and oil and gas field data have been used to infer geological properties across this region and a crude storage estimate has been calculated. For the Linfanjia oilfield, the average porosity is 31% and the permeability is 392 mD (milliDarcies). Effective storage capacity is calculated to be 448 Mt for CO_2 storage based on the agreed CSLF-derived calculation (Equation 3) [2].

$$\text{Effective aquifer storage} = A \,.\, h \,.\, \varphi \,.\, \rho_{CO2r} \,.\, S_{cff} \quad (3)$$

Where A = area of regional aquifer

h = average height of aquifer multiplied by average net:gross ratio

φ = average reservoir porosity

ρ_{CO2r} = CO_2 density at reservoir conditions

S_{cff} = storage coefficient, here 0.02 is used based on results from the EU-GeoCapacity project

5. Large sources of carbon dioxide

Large sources of CO_2 (emissions greater than 100 kT/year) were mapped in the Shandong Province to allow some preliminary recommendations for source-storage matching. A GIS (Geographic Information System) comprising the large point sources, infrastructure and relevant information for assessment of the geological storage capacity has been created by the British Geological Survey, with the intention of aiding all project partners in making preliminary recommendations for matching geological storage options for CO_2 with large sources of CO_2.

To date, Tsinghua University have catalogued 49 power stations of over 100 MW generating capacity, with combined annual emissions of 121 Mt; one gas-fired plant, one oil-fired plant and 47 coal-fired plants. In addition, 66 power plants over 50MW were catalogued with total emissions of 125 Mt/a; one gas fired, one oil fired and 64 coal-fired. The average gross coal consumption rate for these power plants was 330 gce/kWh (grams coal equivalent per kW.hour).

Chinese Government policy is to close older, smaller thermal power stations and replace them with larger, more efficient power stations as part of a national scheme to save energy and reduce pollution. In 2007, 553 small power stations with a total capacity of 14.38 GigaWatts (GW) were closed across China. China intends to oversee the decommissioning of small thermal power plants (with total capacity 50 GW) with replacement by larger more efficient plants during the period 2005 - 2010. Shandong is the leading provincial region in this shut-down drive, having closed 1 GW thermal power capacity in 2007. Shandong has over 800 coal-fired power generating units with a capacity under 100 MW. By the end of 2010, it is planned that a further 4 GW of these small power plants will be decommissioned in the Shandong Province.

6. Source-storage site matching

Based on storage site potential evaluated by the COACH partners, it is considered that the Dagang oilfield is not suitable for large-scale storage, though could be considered for EOR pilots. The aquifers in the Jiyang Depression have a large storage potential; one option could be to route pipelines from the planned TRPI (Thermal Power Research Institute) at Tianjin (south-east of Beijing) via Dagang oilfield complex for an EOR pilot, then on to the Huimin Depression for storage. Alternatively, the potential for enhanced coalbed methane recovery from the Kailuan coalfield accompanied by large-scale aquifer storage in the Jiyang Depression could be considered.

7. Conclusions

Emissions in the Shandong Province are increasing as China’s economy grows. The greatest capacity for storage appears to lie in deep saline aquifer formations. However, the potential for ‘value-added’ options through enhanced oil recovery in the Dagang oilfield complex or enhanced coal-bed methane recovery at Kailuan coalfield should not be ignored when designing potential storage scenarios as these may offer a way to offset some of the initial outlay for CCS. Unfortunately, where deep boreholes have not been drilled, aquifer properties must be inferred from nearby hydrocarbon fields. This results in significant uncertainty in the storage estimates for the Jiyang Depression. However, of the sites considered for the COACH project, based on the potential storage volume, this region appears to be the most promising for storage and worthy of further investigation.

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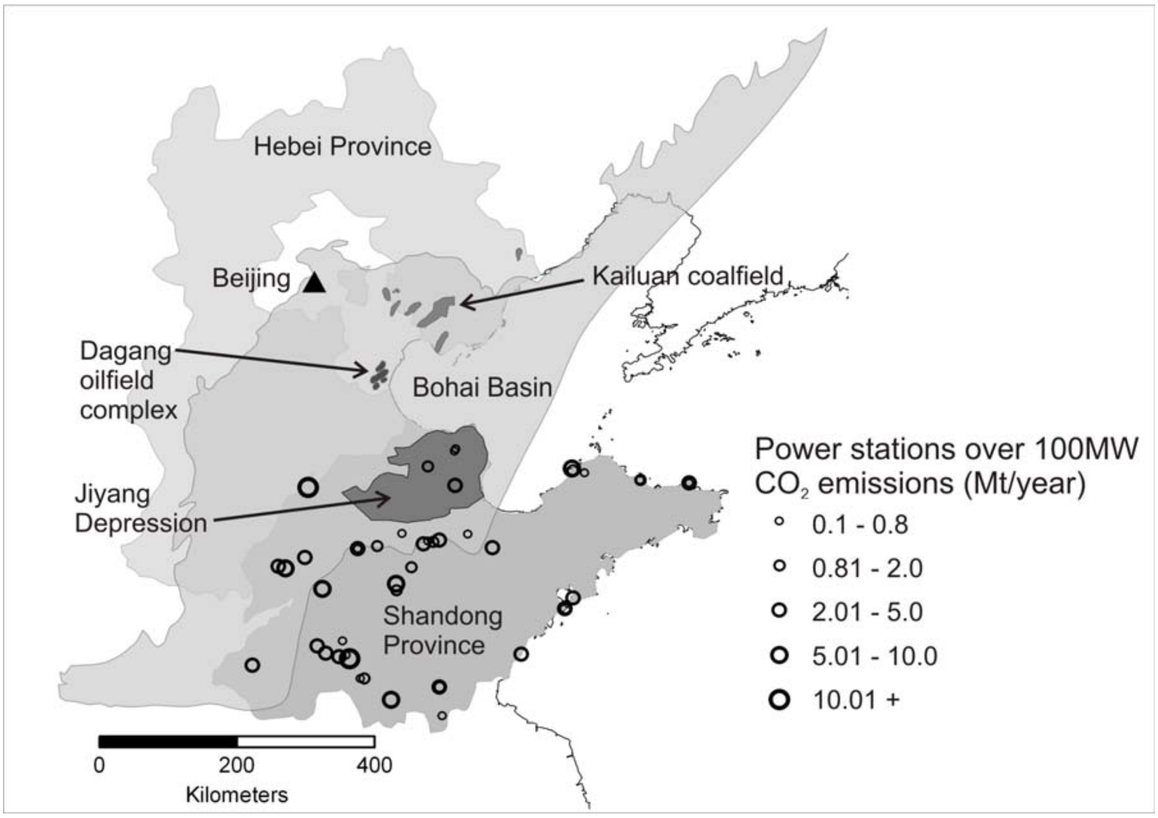

Figure 1: Location of potential storage sites and large point sources being catalogued in north-east China for the COACH project

Age		Formation	Member	Thickness (m)	Lithology	CO_2 storage potential
Quaternary		Pingyuan		200-400	Uncemented loess	
Neogene	Pliocene	Minhuazhen	Nm (O,G)	800-900	mudstone with siltstone intercalactions	potential for CO_2 storage (mainly structural traps) and some potential sealing horizons
	Eocene	Guantao	Ng1 (O,G)	300-900	conglomeritic sandstone and sandstone with mudstone intercalations	
			Ng2			
Oligocene		Donying	Ed1	700-1000	interbedded mudstone and sandstone and conglomeritic sandstone	
			Ed2			
			Ed3			
		Shaejie (Hydrocarbon source rocks Es1, Es3, Es4)	Es1	>2000	mudstone and sandstone with carbonatite and shale intercalations	potential seal
Eocene			Es2 (O)			potential CO_2 storage and sealing horizons
			Es3 (O)			
			Es4			
Palaeocene		Kongdian	Ek1	>1000	sandstone and mudstone	
			Ek2			
			Ek3			
U-Cretaceous						

(O) Oil bearing (G) Gas bearing

Figure 2: Summary of stratigraphic succession in the Bohai Basin

Table 1: Estimated storage capacity of seven oilfields in the Dagang complex

Field	**Formation**	**Ultimately recoverable reserves (tonnes)**	**Recovery factor**	**Conversion to cubic metres (37° API)**	**Ultimately recoverable reserves (m^3)**	**Formation volume factor**	**Density of CO_2 in reservoir**	**Storage capacity (million tonnes CO_2)**
Gangzhong	Dongying	350000	0.200688	1.19	416500	1.2	0.620	0.31
Gangzhong	Shahejie	4770000	0.190794	1.19	5676300	1.2	0.620	4.22
Shenvshi	Shahejie	1600000	0.203095	1.19	1904000	1.2	0.620	1.42
Shenvshi	Kongdian	928000	0.10602	1.19	1104320	1.2	0.620	0.82
Shenvshi		160000	0.052452	1.19	190400	1.2	0.620	0.14
Gangdong	Minghuazhen-Guantao	31071400	0.356387	1.19	36974966	1.2	0.620	27.51
Gangxi	Minghuazhen-Guantao-Shahejie	26545700	0.341756	1.19	31589383	1.2	0.620	23.50
Wnagguantun	Shahejie-Kongdian	21691600	0.217432	1.19	25813004	1.2	0.620	19.20
Total								**77.13**