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ScienceDirect
Energy Procedia 1 (2009) 2793–2800
Energy Procedia
www.elsevier.com/locate/procedia

GHGT-9

CO_2 Point Emission and Geological Storage Capacity in China

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Abstract

Carbon dioxide capture and geological storage (CCS) is regarded as an effective option to reduce CO_2 emissions from the use of fossil fuels. CCS is particularly important to China due to its large and rapidly rising emissions and high dependence on fossil fuel, and large remaining coal reserves. This paper presents the key results of the authors' study to evaluate opportunities for the deployment of CCS technologies within China. It focuses on the data, methodology, and results of basin-scale CO_2 storage capacity and CO_2 point emission estimation in China. There is a total estimated theoretical CO_2 geological storage capacity of 3088 gigatons in China's onshore and offshore basins, including a storage capacity of 3066 gigatons for deep saline formations accounting for 99% of total geological storage resource. China also has an annual emission about 3.9 billion tons of CO_2 from large point sources in 2007. In view of initial site-source matching analysis, Hehuai Basin, Bohai Bay Basin, Subei Basin and Sichuan Basin have the best potential for CCS deployment. There is significant potential for CCS technologies to deliver deep, sustained and cost-effective emissions reductions for China over the course of this century

Keywords: CO_2 geological storage; Storage capacity estimation; CO_2 point source; source-site matching

1. Introduction

Addressing climate change is a large-scale, global challenge to reduce and avoid the release of enormous amounts of greenhouse gas (GHGs) over the course of this century. China emitted approximately 5.4 gigatons of net carbon dioxide equivalent into the atmosphere in 2005, and is expected to become the leading country in releasing GHGs in the near future. Therefore China needs cost-effective technologies to provide large-scale mitigation of its CO_2 emissions. Many studies have demonstrated that carbon dioxide capture and storage (CCS) technologies are capable of delivering significant and sustained reduction in CO_2 emission over the course of this century. CCS technologies are believed as an effective option for China to mitigate CO_2 emission. The primary step of large-scale CCS technologies deployment is to understand the potential of CO_2 storage in geologic formations via examination and compilation of large anthropogenic CO_2 emission sources and potential CO_2 geological storage capacity. This paper presents results of recent research, providing preliminary insights on the potential for CCS technologies to deploy widely within China.

doi:10.1016/j.egypro.2009.02.051

2. CO_2 emission of Point sources in China

2.1. Methodology of CO_2 point emission sources

Industrial sectors examined within the scope of this study include power plants, cement, iron & steel, petroleum refineries, ammonia, ethylene, ethylene oxide, and hydrogen. The CO_2 emissions calculation methodology is based on IPCC Guidelines for national greenhouse gas inventories [1] and based on available plant capacities and productivities, as noted below:

$$(ECO_2)_{ji} = (EF)_{ji} \times (P_1)_{ji} \tag{1}$$

$$(ECO_2)_{ji} = (EF)_{ji} \times (P_2)_{ji} \times (A)_{ji} \times (T)_{ji} \tag{2}$$

$$(ECO_2)_{ji} = \sum_{j}^{N} \sum_{i}^{M} (ECO_2)_{ji} \tag{3}$$

Where, $(ECO_2)_{ji}$ - the estimated annual CO_2 emissions of i^{th} CO_2 emission source within j th industry sector; $(EF)_{ji}$ - emission factor of i^{th} CO_2 emission source within j^{th} industry sector; $(P_1)_{ji}$ –production yield of i^{th} CO_2 emission source within j^{th} industry sector; $(P_2)_{ji}$ -productive capacity of i^{th} CO_2 emission source within j^{th} industry sector; $(A)_{ji}$ -productive rate; $(T)_{ji}$ -full load time (hour). N is the number of industry sectors; M is the number of factories within sector i; CO_2 emission for cement, refineries, iron and steel, and ammonia is based on reported production, while productive capacity was applied for power plants, hydrogen plants , and a mixture of these for ethylene oxide and ethylene). Table 1 shows CO_2 emission factor applied to each of these sectors [1, 2].

Table 1.Emission factors of different CO_2 emission source

Sector	CO_2 Emissions Factors			
Cement (kt/kt)	0.882[a]	0.867[b]	1.111[c]	1.102[d]
Power plant (kt/Gw.h)	1.0[e]	0.5[f]	0.4[g]	
Steel & Iron (kt/kt)	1.270			
Refineries (kt/kt)	0.219			
Ethylene (kt/kt)	2.541			
Ammonia (kt/kt)	3.800			
Ethylene Oxide (kt/kt)	0.458			
Hydrogen (kt/kt)	6.150			

[a]dry process1; [b]dry process 2; [c]wet process 1; [d]wet process 2
[e]coal power plant; [f] gas power plant; [g] oil comb, turbine or internal combustion.

The process for all of these sectors involved locating available information from a variety of sources, including the economic & trade commission of China, IEA greenhouse gas inventory database, Ministry of Commerce of the People's Republic of China, major industries annual reports, annual statistic report of provinces, enterprise databases, inventories, and websites, and so on. Most data were published before 2005, so CO_2 emission source for most sectors is based on scenario before 2005, except for power plants which are from 2007.[1] Enterprise locations including city and province were taken from these databases as well as web searches, and latitude and longitude coordinates were assigned based on centre of corresponding city. Differential data sources, changes in operations and development of these power and industrial sectors, and calculation methods may cause some discrepancies among different statistics, which will be improved and optimized in the further investigation and research.

Results of this effort indicate that there are over 1,620 large stationary CO_2 point sources in China that each emits at least 100,000 metric tons of CO_2 per year. Combined annual CO_2 emissions from these sources are estimated at

[1] Data on power plants in China was compiled from the 2007 World Electric Power Plants Asia Database [3]. More recent data was sought for the power sector in this study due to its very large and fast-growing nature. However, because it was not possible to update all sectors to a similar data year, the proportion of power sector emissions in the totalcumulative emissions will appear slightly exaggerated.

over 3,890 million tons ($MtCO_2$). There are 629 power plants emitting 72% of the total emissions, with the remainder split amongst the 994 sources from other sectors.

2.2. Location of Large CO_2 Point Sources in China

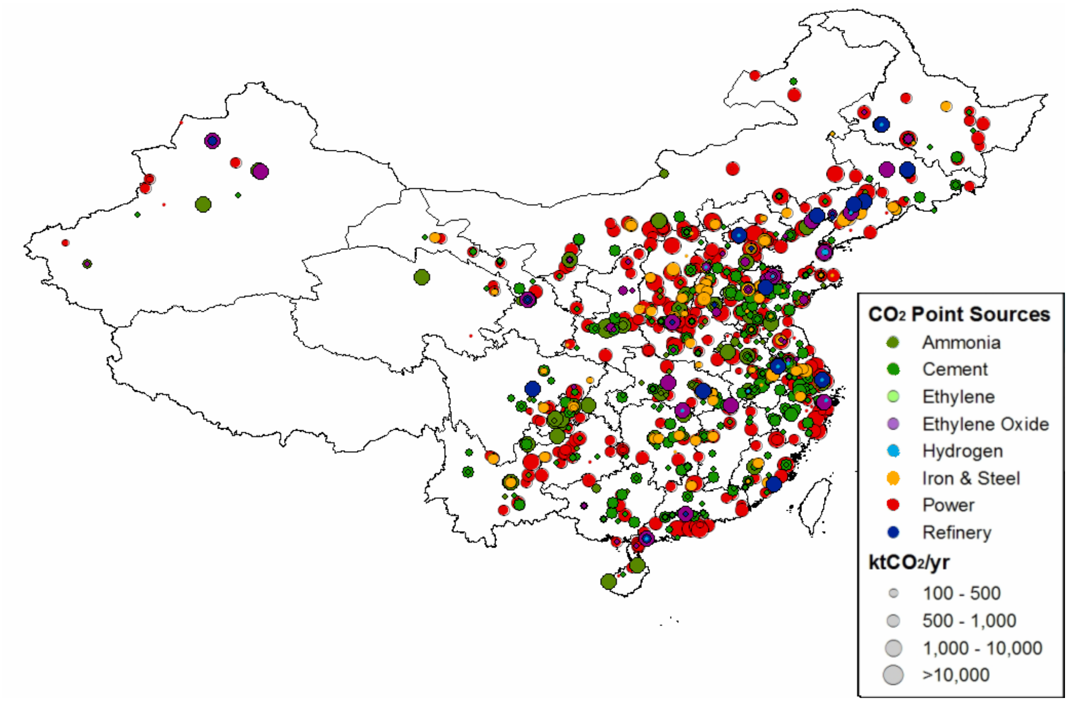

Figure 1. Map of large CO_2 point sources by type and annual emissions

Figure 1 presents the size and spatial distribution of these 1,620 large CO_2 point sources in China. The majority of these emission sources are concentrated along the more heavily industrialized North China plain and coastal zones of China.

3. CO_2 Geological Storage Methodology

The methodology applied to CO_2 storage capacity estimation, and the types and level of detail of the necessary data vary, depending on the scale and resolution of the assessment [4]. A basin-scaled capacity assessment methodology was used in this theoretical CCS capacity evaluation, based on data availability and evaluation stage.

3.1. Deep Saline Sedimentary Formations

Deep saline-filled sedimentary formations (DSFs) tend to be the largest, most widely distributed, and highest capacity potential geologic CO_2 storage formations. This assessment applied the following solubility method as a conservative means of estimating storage capacity for DSFs (from Brennan and Burruss [5]):

$$S_{CO2} = A.\ h.\ \varphi.\ S \tag{4}$$

Where, S_{CO2} is CO_2 storage capacity of deep saline formations; A is deep saline aquifer area; h is average depth of net sand in DSFs; φ is average porosity of sandstone in DSF; S is solubility of CO_2 in deep saline formations.

Total theoretical CO_2 storage capacities for each basin were estimated by applying the Brennan and Burruss specific storage capacity (conservatively assuming 100% residual water saturation and 4m NaCl equivalent total dissolved solids concentration) to the basin pore volumes. Figure 2 shows major sedimentary basins in China. Table 4 shows the individual values for thickness and porosity parameters assumed as the final estimated CO_2 storage capacity for each major sedimentary basin. CO_2 storage capacity in onshore deep sedimentary basins was estimated at as much as 2,288,000 $MtCO_2$; offshore capacity was estimated at 780,000 $MtCO_2$.

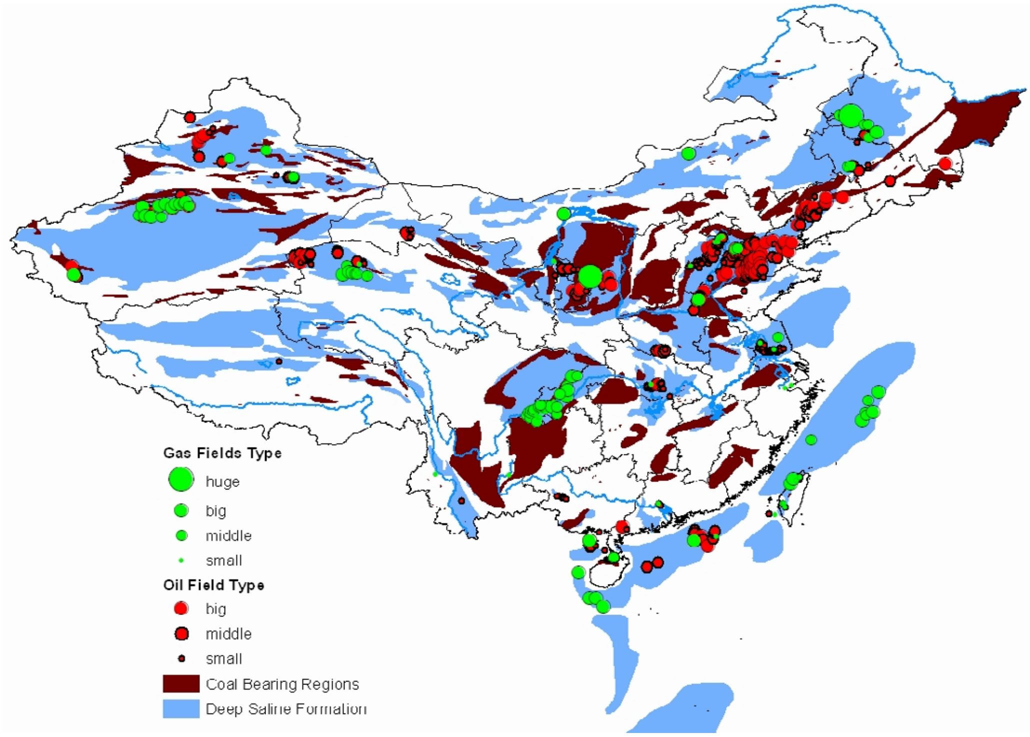

Figure 2. Map of potential storage Site in China (From G Li and M Lv, 2002, J Ren, 2000, Y Zhou, 2004, USGS, 2000)

3.2. Depleted Oil Basins and Enhanced Oil Recovery

The approach used to estimate CO_2 storage capacity for China was taken from Dahowski, et al. [6], and modified to accommodate available data. Data on individual oil fields for China were obtained from the second Atlas of Oil and Gas Basins in China [7]. Figure 2 shows the location of the oil fields and Sedimentary basin examined here as having potential for storing CO_2. Data for the oil basins, including original oil in place (OOIP), were obtained from the second and third national oil and gas resource assessments. Using this data, the amount of oil that could be produced via CO_2-flood EOR was estimated using the following method, as presented by IEA GHG [8]:

$$OOIP_c = OOIP \cdot C \tag{5}$$

Where, C represents the amount of the OOIP able to be contacted by the CO_2 within the formation, assumed to be 75%; OOIP is original oil resource in place.

The storage capacity methodology of oil field is as following (from [6]):

$$EOR = EXTRA.OOIP.C \tag{6}$$

$$M_{CO2} = EOR.\ (P_{LCO2}.R_{LCO2} + P_{HCO2}.R_{HCO2}) \tag{7}$$

Where, R_{HCO2}=3.522t/m^3 R_{LCO2}=2.113t/m^3; *EXTRA* is the proportion of extra recovery to *OOIP*.

$$\begin{cases} EXTRA = 5.3 & API < 31 \\ EXTRA = 1.3\left(API - 31\right) + 5.3 & 31 \le API \le 41 \\ EXTRA = 18.3 & API > 41 \end{cases} \quad (8)$$

API gravity is calculated as:

$$API = (141.5 / S_g) - 131.5 \quad (9)$$

Where S_g is specific gravity.

Table 2. Four EOR cases with different depth/pressure and API gravity conditions ([8])

Depth	API Gravity	% low -CO_2 oil /$P_{LCO2/\%}$	% high-CO_2 oil /$P_{HCO2/\%}$
<2000	>35	100	0
	≤35	66	33
>2000	>35	33	66
	≤35	0	100

3.3. Depleted Gas Basins

Capacity of CO_2 storage in gas fields is calculated as following.

$$SCO_2 = \sum_{j=1}^{N}\sum_{i=1}^{M} 0.75 \times R_{OGIPij} \times R_{CO_2/CH_4ij} \times \rho_{CO_2} \quad (10)$$

$$R_{OGIP} = a \times OGIP \times R_s \quad (11)$$

Where, SCO_2- the storage capacity in gas fields [mass]; N is the number of sedimentary basin; M is the number of gas fields within j^{th} sedimentary basin; R_{OGIPij}-is the natural gas resource left in i^{th} gas field within j^{th} sedimentary basin. In order to get reasonable capacity which can be compared with other countries in the world, natural gas resource data and calculation method provided by Zhang K. [11] is used here. *OGIP*- original gas resource in place; a is the correct coefficient; R_s -recovery coefficient. Correct coefficient and recovery coefficient for OGIP is as shown in Table 3. ρ_{CO2} is the CO_2 density on the surface (under standard condition, 1.98kg/m^3); $R_{CO2/CH4}$ is molar replacement ratio of CO_2/ CH_4, as a function of depth ; 0.75 is reduction coefficient with conservative capacity, 75% of void space created by exploiting natural gas may be replaced with CO_2 [12].

Table 3.Correct coefficient for different sedimentary basins

Zone	Sedimentary basin	Recovery Coefficient for Proved OGIP
East	North of China, Huabei, Nanxiang, Jianghan, and Subei Basin	0.42
Middle	Ordos, Sichuan, Chuxiong Basin	0.63
Northwest	Basins in Xinjiang,qinhai, Gansu province	0.55
Southeast	Sanshui Basin, Shiwandashan,	0.66
continental shelf	Off shore sedimentary basin	0.60

$$R_{CO2/CH4}=2\times10^{-7}D^2-0.0015D+4.1707 \quad (12)$$

Where: $R_{CO2/CH4}$ is molar ratio of CO_2/ CH_4 in the gas field condition; D is the depth of gas field [13, 14].

According to the natural gas resources information derived from the third national oil and gas resources survey, the original natural gas in place is about 48.39Tm^3 in China. If all natural gas fields are depleted, they can store about 5.18 gigatons of supercritical CO_2, with results by basin shown in Table 4 (along with estimated capacities in deep saline formations and oil fields). The best depleted gas fields for CO_2 storage are mainly located in Sichuan Basin, North China plain (including Dagang Oil Area of Huanghua Depression and Jizhong Depression), Songliao Basin and the southeast of Zhunggar Basin.

Table 4 Onshore and offshore sedimentary basins in China, with estimated CO_2 storage capacities

	Average Net Sand Thickness (m)	Average Porosity (%)	Estimated Capacity by solubility ($MtCO_2$)	Estimated Capacity in Oilfields by proved OOIP($MtCO_2$)	Estimated Capacity in Gasfields by proved OGIP($MtCO_2$)
Onshore Basins					
Tarim Basin	300	0.15	745,800	69	620
Ordos Basin	300	0.15	256,500	360	1110
Bohai Bay Basin	200	0.2	233,300	1,930	280
Songliao Basin	200	0.15	227,800	1570	590
Zhunggar Basin	300	0.15	197,100	200	100
HeHuai Basin	300	0.2	178,000		
Subei Basin	300	0.2	89,900	100	8
Erlian Basin	200	0.15	85,000		
Sichuan Basin	300	0.05	77,600	20	1050
Turpan-Hami Basin	300	0.15	54,300		
JiangHan-Dongting basin	150	0.2	52,800	24	
Sanjiang Basin	200	0.15	44,900		
Qinshui Basin	300	0.15	29,000		
Qaidam Basin	50	0.15	21,500	81	350
Hailaer Basin	100	0.15	16,100		
Nanxiang Basin	100	0.15	7,500	65	
Turpan-Hami Basin				120	36
Jiuxi-Jiudong -Huahai Basin				15	120
Erlian Basin				31	
Yilanyitong Basin				14	
Yanqi Basin				7	15
Total Onshore Basin			2,288,000	4,600	4,280
Offshore Basins					
East China Sea Basin	300	0.15	341,800		160
Southern Yellow Sea Basin	300	0.15	133,800		
Bohai Wan Basin	300	0.2	109,200	130	46
Zhujiangkou(Perl River Mouth)Basin	200	0.15	68,700	41	12
Yinggehai Basin	300	0.15	56,000		680
Northern Yellow Sea Basin	300	0.2	31,500		
Beibu Gulf Basin	300	0.15	23,800	18	
Western Taiwan Basin	100	0.1	10,000		
Luzhoudao Basin	100	0.15	1,900		
TOTAL			**3,066,000**	**4,800**	**5,180**

3.4. Unmineable Coalbeds

The methodology used to estimate CO_2 storage potential for unmineable coal seams is as follows:

$$SCO_2 = a \times \rho_{CO2} \times \sum_{i=1}^{n} \sum_{j=1}^{10} (G_i . C_{ij} / C_i \times RF_{ij} \times ER_{ij}) \tag{13}$$

Where: SCO_2 is resulting estimated CO_2 storage capacity; a is the fraction of a coal basin that contains recoverable coalbed methane [2]; G_i is Coalbed methane resource within reservoir i; C_{ij} is the coalbed methane resource in coal type j within reservoir i; C_i is the total coalbed methane resource within reservoir I; RF_{ij} is the assumed coalbed methane recovery rate of coal type j within reservoir i; ER_{ij} is the volumetric replacement ratio of CO_2 to CH_4 of coal type j within reservoir i; ρ_{CO2} is the density of CO_2 in standard condition.

[2] Based on experience of the IRSM team, this value was assumed to be 10%

Replacement ratios and recovery rates, shown in Table 5, were estimated for the ten coal type categories identified for China's coal basins (based on [14,15]). Table 6 lists the coal basins analyzed, along with their estimated CO_2 storage capacity. Total capacity in deep, unmineable coal seams via ECBM in China is estimated at approximately 12,000 $MtCO_2$ within these 45 major coal basins.

Table 5.The displacement ratio and recovery rate of CO_2/CH_4 in different coal

Coal class	Replacement Ratio($CO_2:CH_4$)	Recovery Rate
Lignite	10	1.00
Non-cakingcoal	10	0.67
Weakly caking coal	10	1.00
Long flame coal	6	1.00
Gas coal	3	0.61
Fat coal	1	0.55
Coking coal	1	0.50
Lean coal	1	0.50
Meager coal	1	0.50
Anthracite	1	0.50

Table 6. Estimated CBM-based storage capacities for 45 major coal-bearing regions in China

Coal-Bearing Region	Estimated Capacity/Mt	Coal-Bearing Region	Estimated Capacity/Mt
Ordos Basin & Hedong-Weibei	4450	Northern Tarim	36
Turpan-Hami Basin	2200	Northern Qaitam	30
Santang Lake	990	South Songliao	28
Eastern Junggar	650	Daqin-Wula Mountains	27
Qinshui Basin	610	Youerdusi	26
Ili Basin	560	Middle Qilian coal-bearing region	25
Northern Junggar	530	Dacheng	25
Southern Junggar	340	Jingyuan-Jingtai coal-bearing region	14
Sanjiang-Mulinhe	240	Northern Qilian coal-bearing region	11
Datong-Ningwu	160	Chengde	11
Yanqi Basin	120	Dunhua-Fushun coal-bearing region	11
Huainan	120	Huayinshan-Yongrong	11
Liupanshui	110	Kunming-Kaiyuan	10
Eastern Tarim	100	Beipiao Coal-bearing region	8
South Sichuan &North Guizhou	79	Jinan	7
Xuzhou-Huaibei	78	Fuxin-Zhangwu	7
Zhangjiakou	72	Yilan-Yitong	6
Western Shandong	68	Yanbian coal-bearing region	5
Western Henan	56	Baise Basin	5
Beijing-Tangshan	55	Eastern Henan	4
Eastern Piedmont of Taihang Mountains	51	Middle Shandong	4
Xuanhua-Weixian	44	Lianyuan-Shaoyang	4
Zhuozi-Helan Mountains	38	Total storage capacity	1200

4. Results and Conclusion

From the analysis above, **Error! Reference source not found.** summarizes the resulting total estimated storage capacities for China. Key findings from this analysis include:

1. The majority of emission sources are concentrated along the more heavily industrialized coastal zones of China, with half of all of the sources being located within the Huabei plane and coastal zones of China.
2. The total storage cap acities of CO_2 of the four geological storage options reach 3 088 gigatons that is about 600 times as the total CO_2 emission of China in 2005. The deep saline formations have the offer the largest potential storage capacity accounting for 99% of total geological storage resource.
3. In view of initial site-source matching analysis, Bohai Bay Basin, HeHuai Basin, Subei Basin and Sichuan Basin appear to offer the best opportunities for CCS deployment.
4. This analysis represents a primary assessment of the potential for CCS technologies to deploy in C hina and provides a solid foundation on which to build additional understanding in this new and complex area of research.

Table 7 Total estimated CO_2 geological storage capacity

	Estimated capacity ($MtCO_2$)	Estimated capacity in oilfields by proved OOIP($MtCO_2$)	Estimated capacity in gas fields by proved OGIP($MtCO_2$)	Estimated Capacity in Unmineable coalbed ($MtCO_2$)
Onshore	2,380,000	4,600	4,280	12,000
Total	3,160,000	4,800	5,180	12,000

The results presented here indicate that there is significant potential for CCS technologies to deploy in China and therefore there is significant potential for these technologies to deliver deep, sustained and cost-effective emissions reductions for China over the course of this century.

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