

Supplementary information to the article

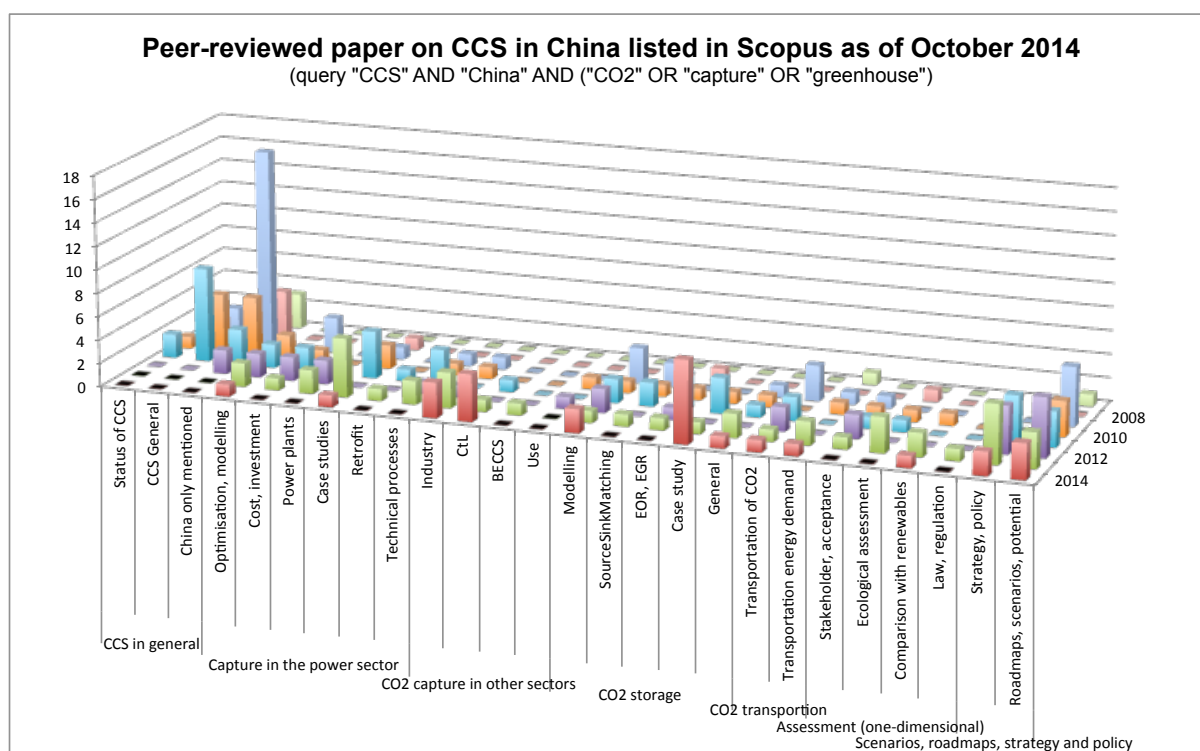
Prospects of Carbon Capture and Storage (CCS) in China's Power Sector – an Integrated Assessment

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For further information, reference is made to the project report on which this article is based: Viebahn P., Esken A., Höller S., Vallentin D.: CCS Global – Prospects of Carbon Capture and Storage Technologies (CCS) in Emerging Economies. Wuppertal: 2012.

Section 1: Introduction

Literature review



Section 3.2: Long-term usable CO₂ storage potential for China's power sector

Power plant analysis

Table 1: Overview of parameters assumed for future coal-fired power plants in China

		2010	2020	2030	2040	2050
Efficiencies for newly built coal-fired power plants						
Subcritical	%	37				
Supercritical	%	40	41	42	44	46
Ultra-supercritical	%	42	43	44	46	48
Integrated Gasification Combined Cycle	%	46	47	48	50	52
Efficiency losses through CCS						
Efficiency penalty post-combustion	% pt	12	8.5	7	6	5
Efficiency penalty pre-combustion	% pt	8	6.5	6	6	6
Additional efficiency penalty for retrofitting	% pt	1.5	1.5	1.5	1.5	1.5
Other parameters						
Origin of hard coal: import share	%	10				
Net calorif. value medium-quality Chinese coal	MJ/kg _{coal}	23.03				
Costs of hard coal mix (10% import)	\$ ₂₀₁₁ /kWh _{el}	3.44	3.47	3.89	4.16	4.63
Technical lifetime of newly built coal-fired plants	a			40		
Plant load factor (PLF)	% / h/a			80 / 7.000		
CO ₂ capture rate	%			90		
CO ₂ leakage of storage sites	%/a			0		
Cost parameter						
Coal-fired power plants without CCS						
Capital cost	\$ ₂₀₁₁ /kW _{el}	625	Further development depends on installed capacities within pathways E1–E3			
O&M cost (4% of capital cost)	\$ ₂₀₁₁ /kW _{el}	25				
Learning rate capital cost	%			1.7		
Learning rate O&M cost	%			3.9		
Interest rate	%			10		
Depreciation period	a			25		
Resulting annuity factor	%/a			11		
Coal-fired power plants with CCS						
Capital cost (175% of capital cost w/o CCS)	\$ ₂₀₁₁ /kW _{el}		Development depends on installed capacities within pathways E1–E3			
O&M cost (183% of O&M cost w/o CCS)	\$ ₂₀₁₁ /kW _{el}					
Learning rate capital cost	%			2.5		
Learning rate O&M cost	%			5.8		
Average/maximum CO ₂ transport distance	km			250		
CO ₂ transportation costs via pipeline. 250 km	\$ ₂₀₁₁ /t _{CO2}			3.3		
Other parameters						
CO ₂ costs	\$ ₂₀₁₁ /t _{CO2}		42	49	56	63

CCS Deployment

Table 2: Conventional and CCS-based coal-fired power plant capacity installed in China in the three pathways E1–E3 for the base case (CCS from 2030)

	2010	2020	2030	2040	2050
E1: high					
Currently installed	567	565	514	385	10
Newly built without CCS	60	338	658	548	548
Newly built with CCS	0	0	0	340	873
Retrofitted with CCS	0	0	15	126	126
CCS penalty load newly built	0	0	0	54	122
CCS penalty load retrofitted	0	0	3	20	18
Total CCS newly built + penalty	0	0	0	394	995
Total CCS retrofitted + penalty	0	0	18	146	143
Total CCS	0	0	18	539	1,138
Total	628	903	1,191	1,472	1,696
E2: middle					
Currently installed	523	565	514	385	10
Newly built without CCS	0	200	327	281	281
Newly built with CCS	0	0	0	255	620
Retrofitted with CCS	0	0	11	56	56
CCS penalty load newly built	0	0	0	40	85
CCS penalty load retrofitted	0	0	2	9	8
Total CCS newly built + penalty	0	0	0	295	706
Total CCS retrofitted + penalty	0	0	13	65	64
Total CCS	0	0	13	360	769
Total	523	765	854	1,026	1,061
E3: low					
Currently installed	567	565	514	385	10
Newly built without CCS	35	188	184	183	183
Newly built with CCS	0	0	0	0	143
Retrofitted with CCS	0	0	8	10	10
CCS penalty load newly built	0	0	0	2	18
CCS penalty load retrofitted	0	0	2	0	2
Total CCS newly built + penalty	0	0	0	2	161
Total CCS retrofitted + penalty	0	0	10	10	11
Total CCS	0	0	10	12	173
Total	603	753	708	579	366
All quantities are given in GW _{el}					

Source-sink matching

Table 3 shows the comparison of storage scenario S1 with coal development pathways E1–E3. The source-sink match starts with onshore basins because they are more easily accessible. For all basins, effective capacities in aquifers as well as in oil and gas fields are considered together. These basins are filled with the emissions calculated in pathways E1 to E3. Basins in China are very large and – in several cases – emissions from more than one administrative division could potentially be stored in one basin. Thus once emissions from the first closest division have already been stored, emissions from the next division are sequestered until either all emissions have been stored or the sink is full. After filling onshore basins, the same process is repeated for offshore basins. Finally, a total matched capacity is yielded for each combination of storage scenario and development pathway. If capacity exceeds the total emissions of neighbouring divisions, this storage site is not filled entirely. In a similar way, storage scenarios S2 and S3 are compared with coal development pathways E1–E3 (Table 4, Table 5).

Table 3: Source-sink match of effective storage scenario S1: high with coal development pathways E1–E3 in China

Basin	Effective storage capacity			Available for emissions from	E1: high	E2: middle	E3: low
	Saline aquifers	Oil and gas fields	Coal seams				
Onshore							
Bohai	116.7	1.3		Beijing	0.6	0.4	0.1
				Tianjin	4.2	2.9	0.6
				Hebei	13.0	8.9	2.0
				Shandong	17.0	11.6	2.7
				Liaoning	8.1	5.4	1.0
				Henan	17.3	11.8	2.7
Songliao	113.9	1.9		Jilin	3.6	2.4	0.4
				Heilongjiang	4.5	3.0	0.5
Subei	45.0	0.3		Jiangsu	21.3	14.6	3.3
Ordos	128.3	0.7	2.0	Inner Mongolia	18.3	12.5	2.8
				Shaanxi	6.3	4.4	1.0
				Shanxi	14.2	9.7	2.2
				Ningxia Hui	3.1	2.1	0.5
				Gansu	3.0	2.0	0.5
HeHuai	89.0			Anhui	10.1	6.9	1.6
Sichuan	38.8	0.1		Sichuan	4.0	2.7	0.6
JiangHan - Dongting	26.4	0.0		Hubei	5.8	3.9	0.9
Tarim	372.9	0.4	0.3	Xinjiang	1.3	0.9	0.2
Junggar	98.6	0.4	2.0	Xinjiang			

Turpan-Hami	27.2	0.3	1.6	Xinjiang			
Erlian	42.5	0.1		Inner Mongolia			
Sanjiang	22.5	0.1	0.1	Heilongjiang			
Qaidam	10.8	0.3	0.1	Qinghai			
Hailaer	8.1	0.1	1.2	Inner Mongolia			
Nanxiang	3.8	0.1		Henan			
Yuxi			0.1	Yunnan	0.1	0.1	0.1
Total onshore	1,144.1	6.0	7.5		155.6	106.1	23.7
Offshore							
East China Sea	170.9	0.2		Zhejiang	12.7	8.7	2.0
				Fujian	5.2	3.6	0.8
				Jiangsu			
Southern Yellow Sea	66.9			Jiangsu			
				Shandong			
Bohai Bay	54.6	0.1		Shandong			
				Beijing			
				Tianjin			
				Hebei			
				Liaoning			
Zhujiangkou (Pearl River Mouth)	34.9	0.3		Guangdong	13.6	9.3	2.1
				Hainan	1.0	0.7	0.2
Yinggehai	28.0	0.2		Hainan			
Northern Yellow Sea	15.8			Jiangsu			
				Shandong			
Beibu Gulf	11.9	0.1		Guangxi	3.6	2.5	0.6
				Guangdong			
Western Taiwan	5.5			Fujian			
Total offshore	388.4	1.0			36.1	24.6	5.7
Total matched capacity	1,532.5	7.0			191.7	130.8	29.4

All values are given in Gt CO₂

The maximum transport distance between sources and sinks is assumed to be 500 km.

Source: Authors' calculation

Table 4: Source-sink match of effective storage scenario S2: intermediate with coal development pathways E1–E3 in China

Basin	Effective storage capacity		Available for emissions from	E1: high	E2: middle	E3: low
	Saline aquifers	Oil and gas fields				
Onshore						
Bohai	30.3	1.2	Beijing	0.6	0.4	0.1
			Tianjin	4.2	2.9	0.6
			Hebei	13.0	8.9	2.0
			Shandong	13.7	11.6	2.7
			Liaoning		5.4	1.0
			Henan		2.4	2.7
Songliao	29.6	1.3	Jilin	3.6	2.4	0.4
			Heilongjiang	4.5	3.0	0.5
Sanjiang	5.8	0.0	Heilongjiang			
Subei	11.7	0.1	Jiangsu	11.8	11.8	3.3
Ordos	33.3	0.4	Inner Mongolia	18.3	12.5	2.8
			Shaanxi	6.3	4.4	1.0
			Shanxi	9.0	9.7	2.2
			Ningxia Hui		2.1	0.5
			Gansu		2.0	0.5
Erlian	11.1	0.0	Inner Mongolia			
HeHuai	23.1		Henan	17.3	9.5	
			Anhui	10.1	6.9	1.6
Nanxiang	1.0	0.1	Henan			
Tarim	97.0	0.1	Xinjiang	1.3	0.9	0.2
Turpan-Hami	7.1	0.1	Xinjiang			
Junggar	25.6	0.2	Xinjiang			
Sichuan	10.1	0.0	Sichuan	4.0	2.7	0.6
JiangHan - Dongting	6.9	0.0	Hubei	5.8	3.9	0.9
Qaidam	2.8	0.1	Qinghai	0.5	0.3	0.1
Hailaer	2.1	0.0	Inner Mongolia			
Total onshore	297.5	3.4		124.0	103.6	23.7
Offshore						
East China Sea	44.4	0.0	Zhejiang	12.7	8.7	2.0
			Fujian	5.2	3.6	0.8
			Jiangsu	9.6	2.8	
Southern Yellow Sea	17.4		Jiangsu			
			Shandong	3.3		
Bohai Bay	14.2	0.1	Shandong			
			Beijing			
			Tianjin			

			Hebei			
			Liaoning	8.1		
Zhujiangkou (Pearl River Mouth)	9.1	0.1	Guangdong	9.1	9.1	2.1
			Hainan			0.2
Yinggehai	7.3	0.0	Hainan	0.9	0.7	
Northern Yellow Sea	4.1		Jiangsu			
			Shandong			
Beibu Gulf	3.1	0.0	Guangxi	3.1	2.5	0.6
			Guangdong			
Western Taiwan	1.4		Fujian			
Total offshore	101.0	0.2		52.0	27.3	5.7
Total matched capacity	398.5	3.6		176.0	130.9	29.4

All values are given in Gt CO₂

The maximum transport distance between sources and sinks is assumed to be 500 km.

Source: Authors' calculation

Table 5: Source-sink match of effective storage scenario S3: low with coal development pathways E1–E3 in China

Basin	Effective storage capacity		Available for emissions from	E1: high	E2: middle	E3: low
	Saline aquifer	Oil and gas				
Onshore						
Bohai	4.7	1.2	Beijing	0.6	0.4	0.1
			Tianjin	4.2	2.9	0.6
			Hebei	1.0	2.5	2.0
			Shandong			2.7
Songliao	4.6	1.3	Jilin	3.6	2.4	0.4
			Heilongjiang	2.2	3.0	0.5
Sanjiang	0.9	0.0	Heilongjiang	0.9		
Subei	1.8	0.1	Jiangsu	1.9	1.9	1.9
Ordos	5.1	0.4	Inner Mongolia	5.5	5.5	2.8
			Shaanxi			1.0
			Shanxi			1.7
Erlian	1.7	0.0	Inner Mongolia	1.7	1.7	
HeHuai	3.6		Henan	3.6	3.6	2.7
			Anhui			0.8
Nanxiang	0.2	0.1	Henan	0.2	0.2	
Tarim	14.9	0.1	Xinjiang	1.3	0.9	0.2
Junggar	3.9	0.2	Xinjiang			
Turpan-Hami	1.1	0.1	Xinjiang			
Sichuan	1.6	0.0	Sichuan	1.6	1.6	0.6

JiangHan - Dongting	1.1	0.0	Hubei	1.1	1.1	0.9
Qaidam	0.4	0.1	Qinghai			
Hailaer	0.3	0.0	Inner Mongolia			
Total onshore	45.8	3.5		29.4	27.6	19.0
Offshore						
East China Sea	6.8	0.0	Zhejiang	6.8	6.8	2.0
			Fujian			0.8
			Jiangsu			1.5
Southern Yellow Sea	2.7		Jiangsu	2.7	2.7	
			Shandong			2.7
Bohai Bay	2.2	0.1	Shandong	2.3	2.3	
			Liaoning			1.0
Zhujiangkou (Pearl River Mouth)	1.4	0.1	Guangdong	1.5	1.5	1.5
Yinggehai	1.1		Hainan	0.9	0.7	0.2
Northern Yellow Sea	0.6		Jiangsu	0.6	0.6	
Beibu Gulf	0.5	0.0	Guangxi	0.5	0.5	0.5
Western Taiwan	0.2		Fujian	0.2	0.2	
Total offshore	15.6	0.2		15.5	15.3	10.0
Total matched capacity	61.3	3.6		44.9	42.8	29.1

All values are given in Gt CO₂. The maximum transport distance between sources and sinks is assumed to be 500 km.

Source: Authors' calculation

Section 3.4: Environmental impacts of CCS-based power plants from a life cycle assessment perspective

Table 6: Parameters used in the life cycle assessment (LCA) of future coal-fired power plants in China

		PC power plant	IGCC power plant
Coal-fired power plants without CCS			
Installed capacity	MW _{el}	300	451
Net efficiency	%	43	48
Plant load factor (PLF)	% / h/a	85 / 7.500	
Plant lifetime	a	25	
Type of cooling		Wet	
Net calorific value of coal	MJ _{th} /kg _{coal}	23.03	
Methane emissions from coal mining	kg CH ₄ /kg _{coal}	0.0169	
CO ₂ emissions from coal	kg/MJ _{th}	0.0974	
CO ₂ capture			
Type of capture process		Post-comb.	Pre-comb.
Concentration of solvent	kg/t of CO ₂	1.958	0.011
Energy required for capture	kWh _{el} /t of CO ₂	178	119
Energy required for compression	kWh _{el} /t of CO ₂	92.84	
CO ₂ capture rate	%	90	
CO ₂ transportation and storage			
Average CO ₂ transport distance	km	250	
Energy required for recompressor	kWh/tkm	0.011	
Energy required for CO ₂ injection into 800 metre deep saline aquifer	kWh/kg CO ₂	0.00668	

Section 3.5: Analysis of stakeholder positions

Table 7: List of stakeholders interviewed in China (face-to-face interviews)

Organisation	Date of interview
<i>Government bodies</i>	
Administrative Centre for China's Agenda 21	22/09/2010
<i>Industry</i>	
Siemens Ltd., China Fossil Power Generation Division	18/04/2011
China Shenhua Coal Liquefaction Co. Ltd.	26/04/2011
China United Coalbed Methane	27/04/2011
<i>Civil society</i>	
Natural Resources Defense Council, China Office	05/07/2010
Greenpeace China	05/07/2010
World Resources Institute	20/04/2011
The Climate Group	21/04/2011
WWF China	26/04/2011
<i>Science and advisory bodies</i>	
Institute of Energy, Environment and Economy, Tsinghua University	08/07/2010
Clean Air Task Force	20/04/2011
Centre for Climate and Environmental Policy in the Chinese Academy of Environmental Planning	20/04/2011
Institute of Geology and Geophysics, Chinese Academy of Science	21/04/2011
State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology	22/04/2011
Centre for Energy and Environmental Policy (CEEP), Beijing Institute of Technology	22/04/2011
Department of Thermal Engineering, Key Laboratory for Thermal Science and Power Engineering of the Ministry of Education, Tsinghua University	25/04/2011
EOR Research Center, China University of Petroleum	26/04/2011
Research Center for International Environmental Policy (RCIEP), Tsinghua University	26/04/2011
Tsinghua-BP Clean Energy & Research Education Center	27/04/2011

Source: Authors' compilation

Questionnaire (research interviews)

Your General Position on CCS

1. Please describe your function and how you are involved in the debate on CCS in China.
2. What do you think about carbon capture and storage (CCS) in general and its potential in China?
3. In which way are you and your organisation dealing with CCS technologies?

CCS Stakeholders in China

4. Which stakeholders are most important with regard to the prospects of CCS in China, both within the government and industry?
5. Is there a public opinion on CCS and CO₂ storage in China in particular? Is public acceptance an important determinant for the deployment of CCS?

CCS in China's Energy Sector

6. Which technological and economic parameters are of crucial importance for a possible market introduction and diffusion of CO₂ capture technologies in China?
7. What are the most important CO₂ capture activities (demonstration projects, policy initiatives, etc.) being undertaken in China at present?
8. Which technology path is most relevant for China and the world as a whole (post-combustion, pre-combustion, oxyfuel)?
9. Is CCS primarily considered for the power sector or also for other industrial CO₂ large-point sources?
10. What share of China's power plant fleet could be equipped with CCS by 2030 or 2050?
11. To which degree do you expect the cost of CCS plants in China to differ from that at the international level? Why?
12. Does the proximity of China's CO₂ sources or storage sites inhibit or support CCS?
13. Is there a problem regarding increased water needs for CO₂ capture in water-scarce regions?

Energy Scenarios

14. What are the most relevant scenario projections (until 2050) for energy and power demand in China?
15. Which of these scenario projections could be used as a basis for a conservative, moderate and ambitious development of CCS in China?
16. How far can CO₂ be transported in China for geological storage in a feasible manner? Is there a maximum value (e.g. 500 km)?

CO₂ storage

17. What are the most important CO₂ storage activities (demonstration projects, policy initiatives, etc.) being undertaken in China at present?
18. Which storage estimates seem to be more realistic for China: Dahowski et al: >3,000 Gt CO₂ or the Chinese Academy of Science/APEC 2005: 1,500 Gt CO₂?
19. Do you know of any other estimates or research projects on China's underground storage capacity?
20. Which formations seem most promising in China for CO₂ storage: coal fields (ECBM), depleted oil or gas fields, deep saline aquifers or basalt formations?

21. Regarding CO₂ sequestration in aquifers: would water be produced to increase the amount of space? If this is the case, what should be done with the water produced to avoid an environmental hazard?
22. Do you see a potential conflict of interest between groundwater supply, geothermal energy production and CO₂ storage projects?
23. Could CO₂-EOR help to boost CCS in China and increase oil production? Are any new EOR operations being planned?
24. Is there a limit to the amount of CO₂ that can be injected safely into the subsurface per year and site (injection rate)?
25. Does seismic activity exclude formations and regions from being potential CO₂ storage sites? Which regions?

Political Aspects of CCS

26. Which political developments are decisive for CCS deployment in China?
27. In which way are China's governments supporting the development and deployment of CCS?
28. Are regulatory frameworks and incentives existent or being developed?
29. Would the integration of CCS into the CDM foster CCS development and deployment?