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The cost of carbon capture and storage for coal-fired power plants in China

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ABSTRACT

This study takes a systematic approach to quantify variability and uncertainty in the cost of carbon capture and storage (CCS) for new pulverized coal-fired power plants in China under a common costing framework and examines the role of economic and policy strategies in facilitating CCS deployment. The CCS cost varies with key parameters including capacity factor, fixed charge factor, coal price, plant location, and CO_2 removal efficiency. Given the probability distribution assumptions for uncertain parameters, results from the probability analysis show that the addition of amine-based CCS for 90% CO_2 capture would increase the plant cost of electricity generation significantly by 58%–108% in comparison with the plant without CCS at 95-percent confidence and result in a CO_2 avoidance cost within the 95-percent confidence interval from $35/tonne to $67/tonne, which is much lower than in other countries. With the nominal assumptions made for the base case study, an emission tax policy to encourage CCS implementation for 90% CO_2 capture at the baseload coal-fired plants requires a CO_2 price of $41/tonne, while a CO_2 sale price of $24/tonne is needed for CO_2-enhanced oil recovery operations to offset the added cost for CCS.

1. Introduction and research objectives

The Paris Agreement on climate change was made in December 2015, with an aim to hold the increase in the global average temperature at or below 2 °C this century (United Nations, 2015). Emissions of carbon dioxide (CO_2), the major contributor to climate change, mainly come from burning fossil fuels. Carbon capture and storage (CCS) is the key technological option to achieve deep reductions in CO_2 emissions from fossil fuel-fired electricity generation systems. Without CCS, the cost of mitigation in meeting the global climate goal could increase by approximately 140% (Pachauri and Meyer, 2014).

China contributed about 28% of global carbon emissions in 2013, mainly from fossil fuel combustion (IEA, 2015a). In China, the energy sector accounts for 32% of the total CO_2 emissions (Li et al., 2015), in which coal-fired power plants provide 75% of the national electricity demand (IEA, 2013). It is unlikely that the heavy reliance on coal for electricity generation will change dramatically in the short term (Korsbakken et al., 2016; Wara, 2007). Therefore, CCS deployment appears important for low-carbon energy in China. In recent years, China has boosted efforts on CCS research, development, and demonstration, featured by 12 large-scale CCS pilot and demonstration projects (Global CCS Institute, 2014). The first industrial-scale CO_2 capture project in China has demonstrated its technical feasibility for coal-fired power plants (Huang et al., 2010).

Information on CCS costs is needed for various applications, such as climate and energy policy assessments, technology assessments and investments, energy system planning, and decision-making at various levels (Rubin et al., 2015). To date, numerous studies have been conducted to estimate the cost of CCS for Chinese coal-fired power plants through deterministic techno-economic estimation (ADB, 2015; Dave et al., 2011; IEA, 2015b; Li et al., 2011; Liang et al., 2009; Wu et al., 2013). However, as illustrated later in detail, there are large discrepancies in major economic metrics for CCS, mainly because of the differences in costing methods and parameter assumptions. Some studies may even directly use the U.S.-based CCS cost to assess the economics of Chinese coal-fired power plants with CCS, which overestimates the CO_2 capture cost because it ignores lower costs of labor, equipment, material, and manufacturing in China (Dave et al., 2011; Global CCS Institute, 2011). In addition, uncertainties in power plant and CCS designs and financial conditions have been widely ignored in the existing cost studies. The major objectives of this study, therefore, are to quantify variability and uncertainty in the cost of CCS for new pulverized coal-fired (PC) power plants in China and to offer rigorous assessments for policy strategies that facilitate large-scale CCS deployment in China. Similar to a previous study on U.S.-CCS (Rubin and Zhai, 2012), we perform a systematic analysis that characterizes variability and uncertainties in power plant and CCS systems and estimates the China-CCS cost under a common costing framework.

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Table 1
Summary of Assumptions and Results for Cost Studies on Chinese Coal-fired Plants.

Parameter[a]	IEA (2015b)	Liang et al. (2009)	Li et al. (2011)	Wu et al. (2013)	Zhao et al. (2008)	Dave et al. (2011)	ADB (2015)	Renner (2014)
Reference plant without CCS								
Gross power output (MWg)		600		600	1200	600	600	
Net power output (MW)	1000		1000		1126	570	570	
Net plant efficiency, HHV (%)[p]	42[b]	41[b]	41[b]	38[b]	39[b]	41	41	42[b]
Capacity factor (%)	85		75	100	64			85
Cost year	2013$	2006$	2010$	2010$	2006$	2010$[c]	2014$[d]	2011€[e]
Discount rate (before taxes) (fraction)	0.10[f]	0.06–0.10		0.06				
Fixed charge factor (fraction)	0.102	0.073–0.106	0.120	0.066				
Coal price ($/GJ)(HHV)[p]	4.2		4.9	4.6		3.6[b]	3.3[b,d]	3.5[b]
Construction time (years)	4	2			3	2		4
Plant TCR[p]								
(reported $/kWnet)	947[g]	611[g]	664[g]	1106	519[g]	688[g]	794[g]	
(2013$/kWnet)[q]	947	694	684	1139	589	709	782	
Plant VOM ($/MWh)[p]	63.6[h]					33.9		
Plant FOM ($/MWh)[p]	4.07	6.09	5.92	4.62			18 M$[i]	
Plant LCOE[p]								
(reported $/MWh)	81.6				34.6	42.8	52	
(2013$/MWh)[q]	81.6				39.3	44.1	51.2	
Same plant with CCS								
Total CO_2 removal efficiency (%)		83[j]	~84[k]	90		90	90	90
Capacity factor (%)				100				85
Net power output (MW)		567				412	389	
Net plant efficiency, HHV (%)[p]				27		30	28	33
CCS T & S cost ($/t$CO_2$)[p]		7.4–14.9					13% VOM	3.3 ($/MWh)
Plant TCR ($/kW-net)[p]				1780[l]		1275	1430	
Added plant TCR for CCS ($/kWnet)[p]			398–445[m]	674		587	636	
Plant VOM ($/MWh)[p]								
Plant FOM ($/MWh)[p]			3.1–3.5[m]	11.7			21 M$[i]	
Plant LCOE[p]								
(reported $/MWh)						63.5	99	
(2013$/MWh)[q]						65.4	97.5	
Added plant LCOE for CCS ($/MWh)[p]						21.3	46.3	
Cost of CO_2 avoided								
(reported $/tonne)			39–47	61[n], 40.7[o]		30	53	
(2013$/tonne)[q]			40–48	63[n], 41.9[o]		31	52	

[a] The blank cells indicate that there are no data available from the reviewed papers.
[b] A 0.93 conversion factor provided by the U.S. National Research Council (2000) for coal in China was used to adjust the reported lower heating value to the higher heating value.
[c] The author indicated an exchange rate of August 2010 between CNY and AUS$ as "present". The exchange rate between CNY and USD (6.77 CNY/USD) at that period was applied.
[d] An exchange rate of 6.14 CNY/USD was applied to convert the reported data.
[e] Unless noted, a conversion factor of 0.719 (EUR/USD) was applied in this column to convert values on a 2011 USD basis.
[f] The IEA report presented three scenarios, only the scenario with a discount rate of 10% was included here.
[g] That was defined as investment cost by the IEA, including the overnight cost and interest during construction. That was defined by Liang et al. and Li et al. as initial capital outlay (fixed capital) plus working capital. Total plant investment capital was defined by Zhao et al. representing overnight cost plus other engineering cost, contingency and interest during construction. Capital investment cost as defined by Dave et al., including the interest during construction. Total overnight capital expenditure was defined by the ADB report.
[h] The estimated fuel cost was 35.7 $/MWh in the variable O & M costs.
[i] Only the total fixed O & M value on the absolute basis was given in the report.
[j] The removal efficiency was assumed in this study.
[k] The CO_2 emission rate was reported to change from 743 g/kWh to 122 g/kWh with CCS deployment.
[l] The value was assumed by the author.
[m] The two bounds stand for a 60% and 67% extra cost for reference plants with and without CCS ready hub respectively.
[n] This was phrased as "a carbon price required to justify the CCS investment for PC plants". The estimation was made based on the case of the 2010 investment.
[o] Projected value for 2030.
[p] HHV = Higher Heating Value, TCR = Total Capital Requirement, VOM = Variable Operation and Maintenance cost, FOM = Fixed Operation and Maintenance cost, LCOE = Levelized Cost of Electricity, T & S = Transport and Storage.
[q] The costs from different studies were converted to 2013 year US dollars using the Chemical Engineering Plant Cost Index. However, please note that the application of the index to non-US countries might bias estimates to some extent.

2. Review of cost studies on chinese coal-fired power plants

Numerous studies have reported cost estimates for Chinese coal-fired power plants (ADB, 2015; Dave et al., 2011; IEA, 2015b; Li et al., 2011; Liang et al., 2009; Wu et al., 2013; Zhao et al., 2008). Among the factors that affect the overall cost of a PC plant with CCS, plant type and size, capacity factor, and CO_2 removal efficiency are the major plant design parameters, while discount rate, fixed charge factor, and fuel price are the major financial and economic parameters (Rubin et al., 2007; Rubin and Zhai, 2012; Zhai and Rubin, 2013). The plant levelized cost of electricity (LCOE) generation and the cost of CO_2 avoided are the two most common cost metrics used for CCS assessments. Table 1 summarizes the major assumptions and results from recent cost studies of Chinese PC power plants by researchers from different agencies including the International Energy Agency (IEA), the Asian Development Bank (ADB), and Imperial College London. To make a comparison, the reported costs were adjusted to 2013 year dollars using the Chemical Engineering Plant Cost Index (CEPCI) ("Plant Cost Index – Chemical Engineering Magazine," 2016).

Among these existing studies, the reference plants are supercritical

(SC) or ultra-supercritical (USC) PC plants. For the cases with CCS, amine-based systems are widely selected for post-combustion CO_2 capture with a removal efficiency of about 80–90%. The differences in the major cost metrics shown in Table 1 mainly come from two sources: differences in costing methods and differences in parameter assumptions.

The existing studies used inconsistent nomenclature and different costing methods in terms of cost components and their estimation approaches, in particular for CCS capital cost. The term of total capital requirement (TCR) was used directly by Wu et al. (2013) and indirectly used by Zhao et al. (2008), who used the "total plant investment capital values" that includes overnight cost, other engineering cost, contingency cost and financial cost. IEA (2015b) and Dave et al. (2011) used the term of "capital investment cost" covering the overnight cost and interest during construction. Li et al. (2011) defined the "capital investment cost" as the sum of fixed capital and working capital, which are also the cost components of the "initial capital outlay" defined by Liang et al. (2009). The ADB report only presented a highly aggregated overnight capital cost (ADB, 2015). Among the existing studies, some of them were based on either highly aggregated capital and operating and maintenance (O & M) cost assumptions without detailed performance and cost modeling and analysis for CCS systems, or information from personal communications (Wu et al., 2013). Furthermore, most studies just reported the overall cost results without providing detailed cost breakdowns, such as process facilities cost, general facilities capital cost, contingencies, and interest charges. They did not or were not able to provide any details about the methods of estimating individual cost categories. As a result, it is hard or impossible to know if they have similar or identical cost components in their costing frameworks.

Among these existing studies, the assumed capacity factor falls within a range from 64% to 100%, while the coal price adopted for evaluation varies from \$3.3/GJ to \$4.9/GJ on the higher heating value (HHV) basis. For PC plants without CCS, the reported plant TCR, discounted rate or fixed charge factor, and LCOE vary significantly by a factor of about two. For plants with CCS, the total plant capital cost is reported to be increased by 48% to 85% with CCS deployment. The added LCOE for CCS is reported to fall within a wide range from \$21/MWh to \$46/MWh. As a result of the differences in these performance and financial parameters and cost estimates, the reported cost of CO_2 avoided by CCS varies by a factor of approximately two. We can conclude that there are substantial differences in model parameters and assumptions. However, few studies have coherently characterized variability and uncertainty and provided probabilistic cost estimates for CCS under a common framework, including the likelihood of their cost estimates. Therefore, it is likely biased to assess the cost of CCS in China simply by examining published estimates.

3. Materials and methods

This study employs a techno-economic modeling tool to evaluate the cost of amine-based CCS for Chinese coal-fired power plants (IECM, 2016), which reflects the "next commercial offering" technology (NETL, 2013). To evaluate the economics of Chinese power plants, the default capital and O & M costs of a PC power plant and environmental control systems in the tool are then updated using China-specific cost information. Thus, the "tailored" tool is applied to assess CCS costs for different designs and assumptions. Details about the costing methods, assumptions, sources of various data, and power plant modeling are available in Sections S-1 to S-6 of the Supplementary material (SM).

3.1. Integrated environmental control model for technical and economic assessments

The newly enhanced Integrated Environmental Control Model (IECM) developed by Carnegie Mellon University is used for evaluation (IECM, 2016), which offers systematic estimates of the performance, emissions, and costs for an array of fossil fuel-fired power plant configurations that can employ CCS and a variety of environmental systems controlling emissions of traditional air pollutants (IECM, 2016). The costing method and nomenclature employed in the IECM are based on the Electric Power Research Institute's (EPRI) Technical Assessment Guide (EPRI, 1993). The performance models based on mass and energy balances are linked to engineering-economic models that estimate the capital cost, annual O & M costs, and LCOE for an overall power plant and environmental control systems. The engineering-economic models first determine the TCR for each of the subsystems and sum them up to obtain the overall plant capital cost, which includes the process facilities cost (PFC)—representing the cost of purchasing and installing all equipment—plus a number of indirect costs such as general facilities cost, engineering and home office fees, contingency costs, interest charges, royalty fees, and preproduction and inventory costs. As given in Section S-5 of the SM, the indirect costs are often estimated empirically as a percentage of PFC or total plant cost or total plant investment. In addition to the deterministic estimates, the IECM also allows uncertainties of performance and costs to be characterized for key designs and parameters and enables to provide probabilistic comparative assessments for different systems under uncertainty (Zhai et al., 2012). Additional details about the IECM's capital and O & M costing methods and major cost metrics calculations are available in Section S-1 of the SM.

3.2. Cost estimation for Chinese coal-fired power plants

The Electric Power Planning and Engineering Institute (EPPEI) in China has established a technical assessment guide (TAG) to help design and assess Chinese thermoelectric power plants (EPPEI, 2014). Referring to the EPPEI's TAG, the IECM is used to first configure and model a typical Chinese PC plant (without CCS) in terms of plant type and size, coal type, and environmental control systems as well as emission regulations and tax policies for major air pollutants including sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (Ministry of Environmental Protection of the People's Republic of China, 2012, 2003).

The EPPEI's TAG provides detailed estimates of capital costs for SC PC power plants and environmental control systems, which are different from the cost information provided in the IECM that is applicable to U.S. power plants. So, it is necessary to adjust the U.S.-based costs to China-based costs prior to any CCS evaluation. Similar to the IECM's costing method, the EPPEI's TAG also presents PFC for each subsystem (except SO_2 and NO_x control systems) but provides other indirect capital cost components aggregated on the basis of the overall plant, including construction site occupation and cleanup costs, large cargo transportation cost, project management and technical service fees, contingencies, and preproduction cost. For SO_2 and NO_x control systems, however, only the TCR is provided separately in the EPPEI's TAG. Thus, cost adjustment factors are derived from the comparisons of PFC between two cost models for subsystems (except SO_2 and NO_x control systems) of the typical Chinese power plant and then applied to the IECM's PFCs to ensure that the resulting direct capital costs agree with the reported values. Then, the overall indirect capital costs are disaggregated and allocated to each subsystem (except SO_2 and NO_x control systems) based on their PFC share in the overall plant. Finally, we adjust the TCRs of SO_2 and NO_x control systems similarly by using cost adjustment factors to agree with the Chinese TAG's data. Different from the IECM's costing method, the interest charge during construction is not included in the EPPEI's TAG. So, this cost item was zeroed out in the IECM before cost adjustment factors were derived. As there is no capital cost information available for CCS in the EPPEI's TAG, we applied an analogous approach to estimate the capital cost of a CO_2 capture system in China, making an assumption that it has a similar cost adjustment factor as other subsystems of a PC plant.

In addition to the capital costs for subsystems, various O & M costs such as fuel, labor, and chemical costs in the IECM were updated as much as possible based on Chinese prices. Additional details about the Chinese TAG's costing methods and the cost adjustment factor estimation are provided in Section S-2 of the SM, while additional details about the O & M cost estimation and coal properties are provided in Sections S-3 and S-4 of the SM. Details about the IECM modeling are provided in Sections S-5 and S-6 of the SM.

4. Base case results

The tailored IECM (v9.2) was applied to evaluate PC plants with and without CCS. This study reports all costs in 2013 U.S. dollars, assuming an exchange rate of 6.1 CNY per U.S. dollar (EPPEI, 2014).

4.1. Capital cost adjustment factors for Chinese versus US power plants

The 2 × 660 MWg SC PC plant described by the EPPEI's TAG was modeled in the IECM. Capital cost adjustment factors were then applied to the PFCs of individual subsystems in alignment with the corresponding estimates reported in the EPPEI's TAG, except for SCR and FGD systems that only have TCRs reported. Changes to the default values of indirect cost parameters were further made to ensure that the TCRs estimated by the IECM agree with the TCRs derived from the TAG for individual subsystems. Table S-7 of the SM shows the PFCs and TCRs for individual subsystems and the overall plant before and after various adjustment factors and parameter changes were made in the IECM, which represent the costs of U.S. and Chinese plants with common performance designs, respectively.

The cost ratios of PFC and TCR for Chinese versus U.S. power plants are also provided in Table S-7 of the SM for individual subsystems, falling within a range from 0.2 to 0.6. The cost ratios for the overall plant are about 0.4–0.5. To evaluate the plant with CCS, therefore, an adjustment factor of 0.4 was applied to the default PFC of the IECM's amine-based capture system to estimate the capital cost of "next-commercial" CO_2 capture systems in China, which is similar to the approach adopted by other studies (Global CCS Institute, 2011; Renner, 2014; Zheng et al., 2010).

4.2. Case study assumptions and results

IECM v9.2 was employed to configure a new 2 × 660 MWg PC power plant without CO_2 capture as the reference plant, which installs such environmental control systems as selective catalytic reduction (SCR), electrostatic precipitator (ESP), and flue gas desulfurization (FGD) to comply with Chinese emission standards (Ministry of Environmental Protection of the People's Republic of China, 2012). Emission taxes of SO_2 and NO_x ($99/tonne) are also applied (Ministry of Environmental Protection of the People's Republic of China, 2003). The bituminous coal produced in Shanxi Province is selected for evaluation since this province accounts for about 40% of the national coal reserves (National Bureau of Statistics of China, 2015). The coal properties are determined based on the laboratory data from the U.S. Geological Survey (USGS) (Tewalt et al., 2010). For the plant with CCS, a commercially-available Ecoamine CCS system in the IECM is deployed for CO_2 capture, in which the steam used for solvent regeneration is extracted from the plant steam cycle. Both the base plants with and without CCS have the same net power output in order to estimate the cost of CO_2 avoided. Table 2 summarizes the major parameters and assumptions for the base plants and CCS. In addition to updating the capital costs for individual subsystems and the overall plant in agreement with the Chinese TAG, the values assumed for O & M expenses come mainly from literature on Chinese power plants (Dahowski et al., 2009; Guo et al., 2010; Maoming Petro-Chemical Shihua Co. Ltd., 2016; Meng et al., 2007; National Bureau of Statistics of China, 2014; National Research Council, 2000; Wang et al., 2007). In particular, the coal price is estimated based on the recent average national price reported by the National Development and Reform Commission (NDRC) (2015). The information of coal properties is available in Section S-4 of the SM. The major performance and cost parameters and assumptions of the amine-based CCS are provided in Table 4 and Section S-6 of the SM.

Table 3 summarizes the major results for the base plants with and without CCS, in which the estimated TCR includes the interest during construction. The CCS implementation would significantly decrease the net plant efficiency by eleven percentage points and increase the plant TCR and LCOE by 81% and 73%, respectively. As a result, the cost of CO_2 avoided for 90% CO_2 capture is about $41 per tonne of CO_2 (in

Table 2
Major Parameters and Assumptions for Coal-fired Power Plants and CCS.

Parameter	Assumption	Reference
Plant type	Pulverized coal	EPPEI (2014)
Coal rank	Bituminous	USGS (Tewalt et al., 2010)
Air pollution control systems		
NO_x control	Hot-side SCR	EPPEI (2014)
TSP control	Cold-side ESP	EPPEI (2014)
SO_2 control	Wet FGD	EPPEI (2014)
CCS system	Econamine	IECM (2016)
Cooling system	Wet tower	EPPEI (2014)
Capacity factor (%)	85	IEA (2015b)
Construction time (years)	3	EPPEI (2014)
Cost basis	Constant 2013$	
Discount rate (before taxes) (fraction)	0.07	IECM (2016)
Fixed charge factor (fraction)	0.102	IEA (2015b)
Coal price		
($/GJ)(LHV)	3.1	NDRC (2015)
($/GJ)(HHV)	2.9	NDRC (2015), NRC (2000)
Ammonia cost ($/tonne)	456	Guo et al. (2010)
Lime cost ($/tonne)	54	Wang et al. (2007)
Limestone cost ($/tonne)	23	Wang et al. (2007)
Amine cost ($/tonne)	1910	Maoming Petro-Chemical Shihua Co. Ltd. (2016)
SCR catalyst cost ($/m^3)	7610	Guo et al. (2010)
Urea cost ($/tonne)	335	Guo et al. (2010)
Water cost ($/kL)	0.46	Wang et al. (2007)
Labor rate ($/hr)	5.25	NBS (National Bureau of Statistics of China, 2015)
Total number of operating jobs (jobs per shift)		
without CCS	82	EPPEI (2014)
with CCS	92	
CCS system (when applicable)		
CO_2 removal efficiency (%)	90	
Capital cost adjustment factor (fraction)	0.4	IECM (2016), EPPEI (2014)
CO_2 T & S cost ($/tonne CO_2)	8	Dahowski et al. (2009), Meng et al. (2007)

Table 3
Performance and Cost Results for Base Coal-fired Plants with and without CCS.

Variable	Case 1: no CCS	Case 2: with CCS
Gross electrical output (MWg)	1320	1497
Net power output (MWnet)	1238	1238
Net plant efficiency (HHV, %)	42.8	31.5
Coal flow rate (tonne/hr)	378	514
CO_2 emission rate (kg/kWh)	0.778	0.106
Plant TCR (2013$/kWnet)	635	1160
Plant VOM (2013$/MWh)	27.1	45.9
Plant FOM (2013$/MWh)	1.9	3.5
Plant LCOE (2013$/MWh)	37.6	65.1
Added plant TCR for CCS (2013$/kWnet)		517
TCR of CO_2 capture system alone (2013$/kWnet)		353
Cost of CO_2 avoided (2013$/tonne)		41.0
Increase in plant LCOE for CCS		
(2013$/MWh)		27.5
(%)		73

Table 4
Probability Distribution Functions and Assumptions.

Uncertainty Source	Parameter	Unit	Nominal value	Distribution function	References
Ambient air	annual air temperature	°C	11.2	Uniform(10.7, 11.8)	NBS (2005–2014)
	annual relative humidity	%	56	Uniform(51, 58)	NBS (2005–2014)
Power plant capital cost	total plant capital requirement of power plant	% of base	100	Uniform(95, 145)	IEA (2015b), Zhao et al. (2008)
Financing	fixed charge factor	fraction	0.102	Uniform(0.066, 0.150)	Zheng et al. (2010), Wu et al. (2013)
Utilization	capacity factor	%	85	Uniform(57, 90)	Zheng et al. (2010), China Electric Power Yearbook 2014 (2015)
Power plant O & M cost	coal price	$/GJ	2.85	Uniform(1.3, 4.9)	Li et al. (2011), NDRC (2015)
	labor rate	$/h	5.3	Uniform(3.9, 6.6)	EPPEI (2014)
CO_2 capture system	ID fan efficiency	%	75	Uniform(70, 75)	Rao and Rubin (2002)
	pump efficiency	%	75	Uniform(70, 75)	Rao and Rubin (2002)
	regeneration heat requirement	kJ/kg CO_2	3600	Triangular(3290, 3600, 3890)	Abu-Zahra et al. (2007)
	cooling duty	tH_2O/tCO_2	91	Triangular(67, 91, 162)	Zhai et al. (2011)
	nominal sorbent loss	kg/tCO_2	0.3	Triangular(0.25, 0.3, 1.55)	Rao and Rubin (2002)
	solvent pumping head	MPa	0.21	Triangular(0.03, 0.21, 0.25)	Rao and Rubin (2002)
	CO_2 product pressure	MPa	13.8	Uniform(12.4, 15.2)	Rao and Rubin (2002)
	CO_2 compressor efficiency	%	80	Uniform(75, 85)	Rao and Rubin (2002)
	process contingency	%PFC	10	Uniform(10, 20)	EPRI (1993)
	project contingency	%(PFC + E + C)	20	Uniform(15, 30)	EPRI (1993)
	capital cost adjustment factor	fraction	0.4	Triangular(0.2, 0.4, 0.8)	IECM v9.2 (2016), Global CCS Institute (2011), Zheng et al. (2010)
CO_2 T & S	transport and storage cost	ratio of base	1	Triangular(0.25, 1, 1.75)	Meng et al. (2007), Dahowski et al. (2009)

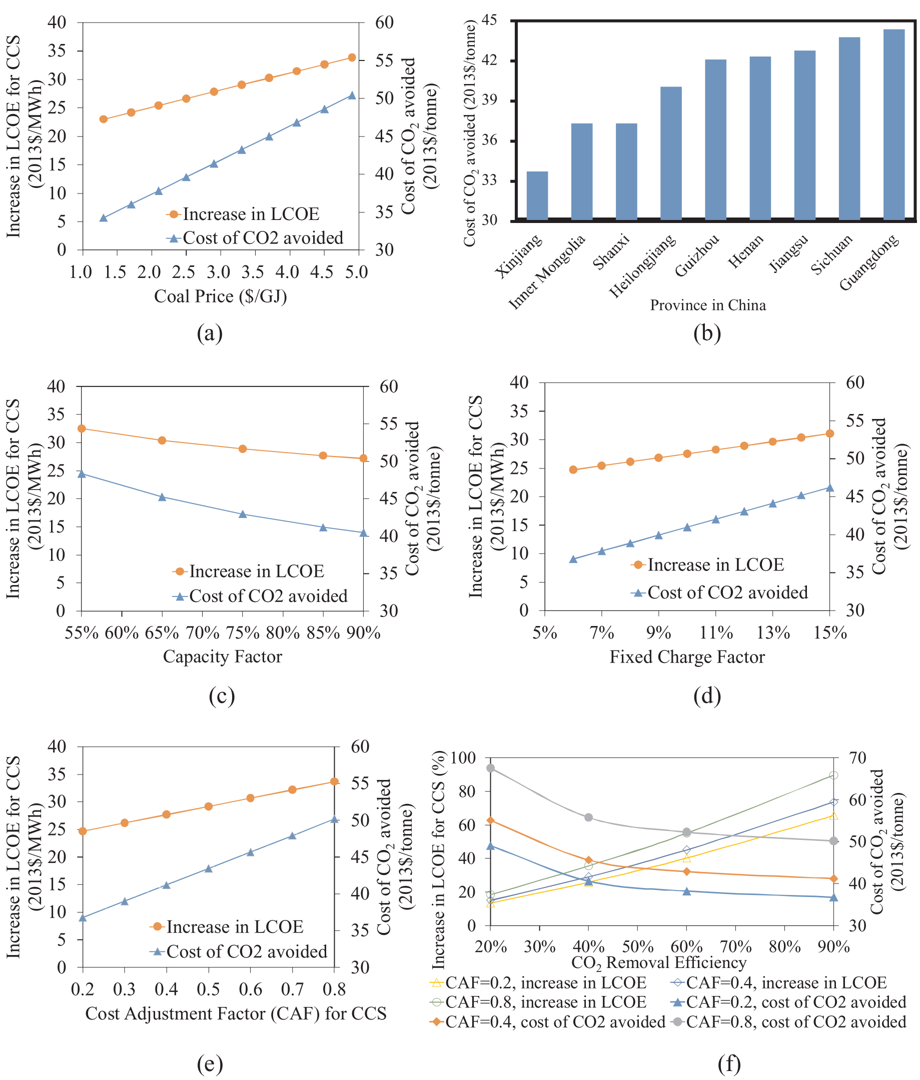

Fig. 1. Effects of key parameters on added cost for CCS and CO_2 avoidance cost.

2013 constant dollars), which is significantly lower than that (about \$60/tonne) for U.S. coal-fired plants (Zhai and Rubin, 2013).

Compared to those studies given in Table 1, our base plant without CCS has a larger net plant efficiency; the coal price assumed in our study is lower, mainly because coal prices in China have been continuously decreasing over the recent years from \$80/tonne to \$54/tonne (NDRC, 2015); our plant LCOE estimate for the case without CCS is similar to that by Zhao et al. (2008) and Dave et al. (2011), while the estimate for the case with CCS is similar to that by Dave et al. (2011); the estimated cost of CO_2 avoided basically falls within the ranges reported by Li et al. (2011) and Wu et al. (2013), but is larger than that by Dave et al. (2011), mainly because their study excluded CO_2 transport and storage costs; our plant TCR estimates for both the cases with and without CCS are 23% lower than those reported by the ADB (2015), whereas our plant LCOE and avoidance cost estimates are about 85% and 45% lower, respectively. The differences in the assumed coal price, fixed charge factor (FCF) and capacity factor (CF) can collectively lead to the significant differences in the LCOE and avoidance cost. Unfortunately, the FCF and CF assumptions are not explicitly provided in the ADB report, making it difficult to identify all the sources of the differences. Because numerous parameters affect the reported cost metrics, we next conduct a sensitivity analysis to examine their effects on CCS cost estimates.

5. Senstivity analysis

A range of parametric analyses were conducted to examine the effects of major factors and parameters on the key cost metrics for CCS. The major factors and parameters affecting power plant costs include coal quality and price, capacity factor, fixed charge factor, and CO_2 removal efficiency and capture system capital cost (Rubin et al., 2007; Rubin and Zhai, 2012; Zhai and Rubin, 2013). When a parameter was analyzed, other parameters were held at the base case values given in Table 2, unless otherwise noted.

5.1. Effects of coal quality and price

Coal quality affects both the power plant performance and cost (Rubin et al., 2007), while coal price directly affects the cost of electricity generation. The range used in this assessment covered provincial coal prices reported in the past two years (2014–2015) (NDRC, 2015) and was extended to include those adopted in recent studies given in Table 1. Fig. 1a and b shows that their economic impacts are substantial. For the given coal, the added LCOE for CCS and the cost of CO_2 avoided increase from \$23/MWh to \$34/MWh and from \$34/tonne to \$50/tonne when the coal price varies from \$1.3/GJ to \$4.9/GJ, respectively.

We further examined the effect on the avoidance cost of various coals from different provinces. The assessment was based on province-specific coal properties and prices. As mentioned earlier, the coal properties given in Section S-4 of the SM for different provinces are also based on the laboratory data from the USGS (Tewalt et al., 2010), which fall within the 90% confidence interval presented by Liu et al. (2015). The coal prices are also based on the recent average province prices reported by the NDRC (2015). The HHV values of these selected coals range from 19,500 kJ/kg to 28,900 kJ/kg, while the coal prices range from \$32/tonne to \$100/tonne. As shown in Fig. 1b, there is pronounced variability by location in the cost of CO_2 avoided, mainly driven by the coal price.

5.2. Effects of plant capacity factor (CF) and fixed charge factor (FCF)

Given that CCS systems are still in early stages of commercialization, there are some uncertainties in their operation and financing (Rubin et al., 2007). To account for the effects of both factors, further parametric analysis was conducted for CF and FCF. The ranges of CF and FCF were determined based on several existing studies (China Electric Power Yearbook Editorial Committee, 2015; Wu et al., 2013; Zheng et al., 2010). Fig. 1c and d shows their economic impacts. For the given FCF of 10.2%, the cost of CO_2 avoided rises from \$40/tonne to \$48/tonne if the CF adopted in the base case is decreased from 85% to the current national average capacity factor of 55% (China Electric Power Yearbook Editorial Committee, 2015). As shown in Fig. 1c, an improvement in plant utilization over life of the plant can significantly lower both the increase in LCOE and the cost of CO_2 avoided. For the given CF of 85%, when the FCF value varies from 6% to 15%, both the added LCOE for CCS and the cost of CO_2 avoided increase remarkably by 26%.

5.3. Effects of CCS capital cost and CO_2 removal efficiency

This study used an analogous approach to estimate the capital cost for CCS in China. As discussed earlier, the capital cost adjustment factor (CAF) varies with subsystem type, ranging from 0.2 to 0.6. Different from what we present in Table S-7 of the SM for individual subsystems, the Global CCS Institute (2011) reports that the cost conversion factors from U.S. to China are 0.81 for equipment and materials and 0.05 for labor. Given the uncertainty in the CAF, we further examine the effects of carbon capture system capital cost by varying the CAF from 0.2 to 0.8. It turns out that the resulting cost of CO_2 avoided increases by 36% from \$37/tonne to \$50/tonne when the CAF rises in this range, shown in Fig. 1e.

CO_2 removal efficiency is a key parameter that determines the system size and cost and the effects of CCS on the overall plant performance and cost. The bypass design is adopted for partial CO_2 capture (Rao and Rubin, 2006). A portion of the flue gas enters the amine-based capture system for 90% CO_2 removal, while the rest of that is bypassed without CO_2 capture. Fig. 1f shows its effects over the range from 20% to 90% with different CAFs assumed for CCS. It turns out that an increase in CO_2 removal efficiency elevates the added LCOE for CCS but lowers the cost of CO_2 avoided; for a given CO_2 removal efficiency, both the cost measure estimates increase remarkably when the capital cost of CCS increases.

6. Probabilistic analysis

To account for interactions among multiple uncertain or variable parameters and their collective impacts and to estimate the likelihood of a specific outcome, the IECM's probabilistic capability is employed to characterize the effects on plant LCOE and CO_2 avoidance cost of uncertainties or variability in major parameters. For example, such uncertain parameters as fan efficiency, pump efficiency, regeneration heat requirement, and CO_2 product pressure that affect the capture system's energy penalty are taken into account. Parameters like water and limestone price that have minor effects on the overall plant LCOE are not included in the probabilistic assessment. In the analysis, distribution functions are first assigned to independent variables under uncertainty and then are sampled repeatedly using Monte Carlo or related methods to yield a distribution function that quantifies the probability of a specific outcome (Rubin and Zhai, 2012).

We first identified uncertain parameters for power plants and CCS. Probability distribution functions (PDFs) were assigned to the uncertain parameters based on the range of assumptions made in those cost studies given in Table 1, other CCS studies (Abu-Zahra et al., 2007; Dahowski et al., 2009; EPRI, 1993; Meng et al., 2007; Rao and Rubin, 2002; Zhai et al., 2011; Zheng et al., 2010), and our own judgment. Table 4 summarizes the assumed PDFs for uncertain parameters. Fig. 2 shows the probability distributions of cost estimates for the PC plants with and without CCS. As shown in Fig. 2a, the plant LCOE results are characterized as a cumulative distribution function (CDF) that provides confidence intervals (CIs) and the probability of various outcomes. The resulting LCOE distribution has a 95-percent CI (from the 2.5th to

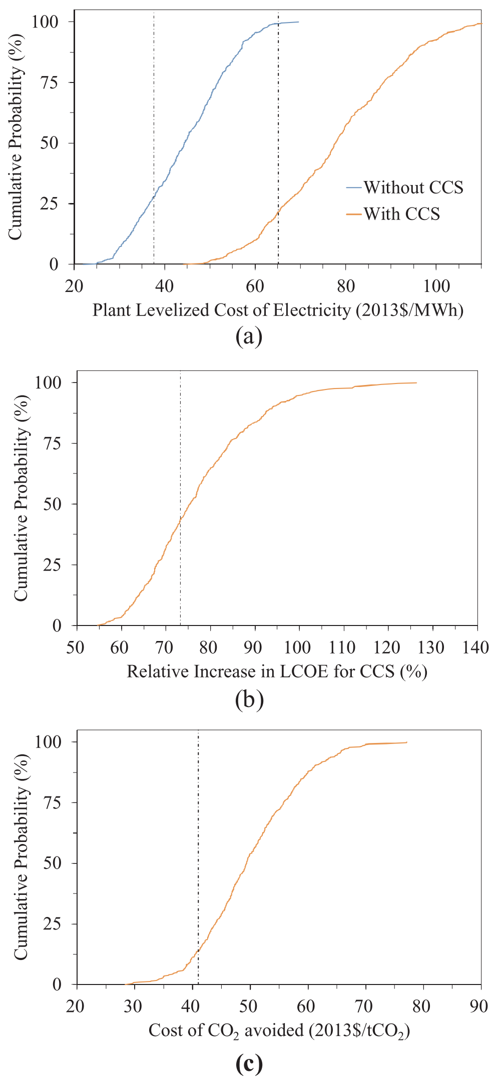

Fig. 2. Probability distributions of cost estimates for PC plants with and without CCS (a) plant LCOE (b) relative increase in plant LCOE for CCS (c) cost of CO_2 avoided. Note: the vertical dash line indicates the deterministic estimate.

97.5th percentiles) from $29/MWh to $62/MWh for the PC plant without CCS, while the 95-percent CI ranges from $52/MWh to $106/MWh for the PC plant with CCS. Because the assumed distributions for key parameters like FCF, TCR, and CAF are non-symmetric relative to the nominal deterministic value, the probability that the plant LCOE is higher than the deterministic estimate is more than 70% for the no-capture case and about 75% for the capture case. Please note that a different choice of PDFs for uncertain parameters might affect the CDF of the results.

We further estimate the *relative increase* in plant LCOE for CCS and its *likelihood*, employing the IECM's probabilistic comparative assessment procedure (Zhai et al., 2012). To compare two plants under uncertainty, we first identified their common and uncommon variables. To generate a probabilistic difference, the identical set and sequence of random samples was assigned to the variables common to both plants, while uncommon variables for the CCS system were sampled randomly. Results for each iteration were then paired to obtain a relative LCOE increase for each pair (Rubin and Zhai, 2012). The resulting set of sample increases was then used to construct a CDF for the *relative increase* in plant LCOE for CCS, as shown in Fig. 2b. The resulting 95-percent CI of the relative LCOE increase ranges from 58% to 108%, compared to the plant without CCS. We applied the same procedure to obtain the probabilistic estimates of CO_2 avoidance cost. Fig. 2c shows its 95-percent CI ranging from $35/tonne to $67/tonne.

7. Policy and economic incentives for CCS deployment in China

Results from the systems analyses presented above reveal that although the cost of CO_2 avoided by CCS in China is most likely to be lower than that in the U.S. or other countries, CCS deployment would still lead to significant increases in the cost of electricity generation. Policy and economic incentives are strongly needed to facilitate large-scale CCS deployment in China. Emission tax or price and CO_2 use for enhanced oil recovery (EOR) are two options considered widely for promoting CCS deployment (Zhai et al., 2015; Zhai and Rubin, 2013). This study contributes to the discussion about these two policy options based on the newly updated CCS cost information. In particular, this study estimates the breakeven emission tax and CO_2 sale price that would promote CCS deployment. Here we evaluate the two options in the context of Chinese power plants based on the nominal assumptions given in Table 2, unless otherwise noted. For illustrative purposes, the cost results are presented in the deterministic form. To obtain their probabilistic distributions, however, a thorough uncertainty analysis similar to Section 6 can be performed.

Fig. 3a and b shows the effects of CO_2 emission tax or price on plant LCOE and CO_2 avoidance cost for two levels of CO_2 removal at the base plants, respectively. Obviously, the plant LCOE increases with increasing CO_2 emission tax. The breakeven CO_2 emission tax or price at which the LCOE of both non-capture and capture plants is the same is $41/tonne for the 90% capture case and $55/tonne for the 20% capture case. In contrast, the cost of CO_2 avoided decreases with increasing emission tax and reaches zero at the breakeven value shown in Fig. 3a for each capture case.

Currently, there are seven pilot carbon trading markets under the emission trading scheme (ETS), including China Certified Emission Reduction (CCER) and Emission Allowance (EA) (Zhang et al., 2014). As reported by the Shanghai Environment and Energy Exchange in China, the most recent average transaction price of emission allowance varies from about $1.8/tonne (11.5 CNY/tonne) in Shanghai to $5.9/tonne (38.1 CNY/tonne) in Beijing (Shanghai Environment and Energy Exchange, 2016). A recent China Carbon Market Confidence Index reports that the transaction price of emission allowance is estimated to be around $3.1/tonne to $4.6/tonne (20–30 CNY/tonne), while that of CCER is estimated to be about $1.2/tonne to $2.3/tonne (8–15 CNY/tonne) in 2017 (Research Center for Climate Change and Energy Finance, 2016). Compared to the breakeven prices shown in Fig. 3a for promoting CCS deployment, the current emission trading prices in China are much lower. So, additional economic incentives for CCS are needed.

Selling and using the captured CO_2 for EOR operations can decrease CCS cost by providing income in lieu of a CO_2 storage cost (Zhai et al., 2015; Zhai and Rubin, 2013). With assumptions of a CO_2 transport cost at $3/tonne and permanent CO_2 storage via EOR (Zhai and Rubin, 2013), Fig. 3 presents the plant LCOE and CO_2 avoidance cost as a function of CO_2 sale price for two levels of CO_2 removal efficiency. As shown in Fig. 3c and d, the added LCOE for CCS or the cost of CO_2 avoided would be fully offset by the income stream from EOR operations at the CO_2 sale price of $24/tonne for the 90% capture case and $28/tonne for the 20% capture case. In contrast, the aforementioned ADB study assumed that the CO_2 sale price for EOR would be about $20/tonne (120 CNY/tonne) (ADB, 2015). Wei et al. (2015) reported a CO_2 sale price of about $18/tonne in China. These results imply that CO_2-EOR could be an economically feasible option as a short-term solution to facilitate CCS deployment and technological learning, though there is a concern about the net increase in life cycle CO_2 emissions via CO_2-EOR operations (Jaramillo et al., 2009). Based on the probabilistic analysis, the deterministic results presented in Fig. 3 are more likely to be underestimated than to be overestimated. The combination of multiple economic incentives for CCS is needed.

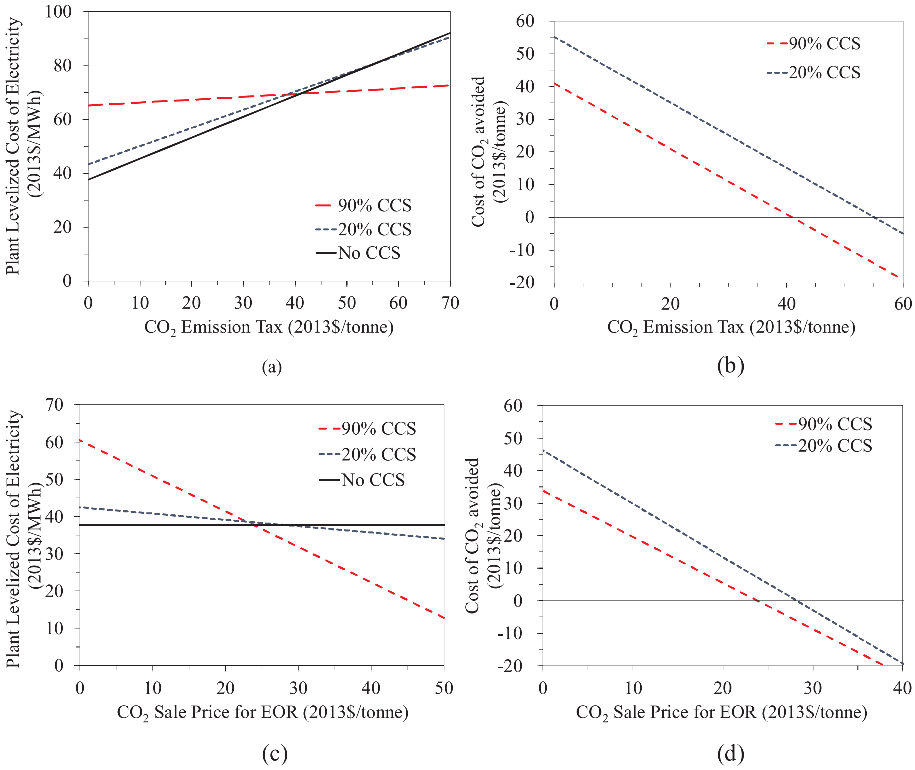

Fig. 3. Effects of CO_2 emission tax and CO_2 use for enhanced oil recovery.

8. Conclusions

This study performs a systematic assessment of how the addition of amine-based CCS to coal-fired power plants in China would affect the cost of electricity generation and determines the CO_2 avoidance cost in both deterministic and probabilistic forms. The magnitude of both the added LCOE for CCS and the cost of CO_2 avoided is affected remarkably by a range of power plant designs and parameters as well as amine-based CCS system designs, such as capacity factor, fixed charge factor, coal price, plant location, and CO_2 removal efficiency. The results from our systems analysis emphasize that it is biased or incorrect to assess variability or uncertainty in CCS costs in China simply by comparing cost information from various sources because of the differences in their costing methods and parameter assumptions.

The addition of amine-based CCS to new coal-fired power plants in China would increase the cost of electricity generation, but result in a lower CO_2 avoidance cost than in other countries, mainly because of the lower capital cost in China. Emission tax or price and CO_2-EOR are two options to facilitate CCS deployment. However, current CO_2 emission trading prices or CO_2 sale prices for EOR in China are not more than the expected breakeven prices. Thus, a combination of emission trading and CO_2 use along with financial support from government and other agencies is recommended to reinforce economic incentives and market demands for CCS deployment in China (Zhai et al., 2015). Subsidies and tax credits can also be considered for CO_2 capture and EOR operators before emission trading markets become mature in China (ADB, 2015).

In comparison between China and other countries, China would have substantially less capital and CO_2 avoidance costs for CCS at coal-fired plants. We can draw a similar conclusion from a further look that examines investments of existing large-scale post-combustion pilot or demonstration plus commercial-scale CCS projects around the world (European Industrial Initiative on CCS, 2013; IEA Clean Coal Centre, 2012; MIT, 2016; NETL, 2015). Details about the selected CCS projects are available in Section S-7 of the SM. As shown in SM Fig. S-3, there is substantial variation in investment among pilot or demonstration CCS projects around the world, and the capital costs of Chinese pilot or demonstration CCS projects are lower roughly by a factor of up to 10 than those of the selected pilot or demonstration projects in other countries. Given its heavy reliance on coal resources for electricity generation and unique cost advantage, China can be one of the global drivers in accelerating large-scale CCS deployment. Given that most CCS technology patent owners are in developed countries (ADB, 2015), international collaboration on CCS also appears particularly important to help expedite commercial-scale deployment in China and other countries.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijggc.2017.08.009.

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