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Prospects of Carbon Capture and Storage (CCS) in China's Power Sector

An Integrated Assessment

Wuppertal Institut

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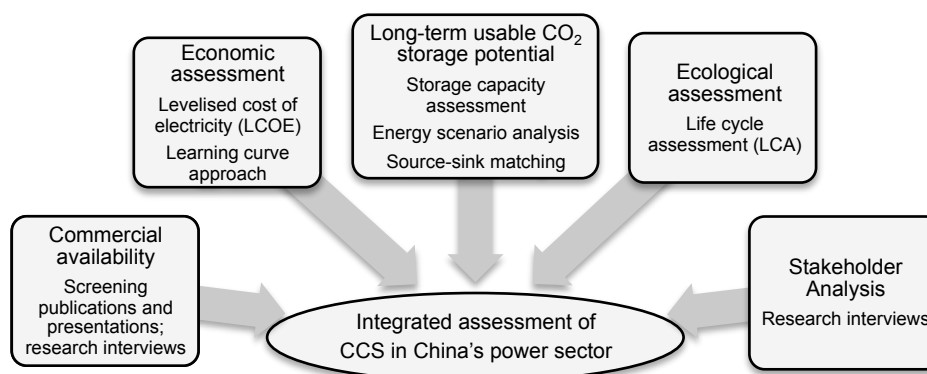   Döppersberg 19
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Graphical abstract

Abstract

Objective The aim of the present article is to conduct an integrated assessment in order to explore whether CCS could be a viable technological option for significantly reducing future CO_2 emissions in China.

Methods In this paper, an integrated approach covering five assessment dimensions is chosen. Each dimension is investigated using specific methods (graphical abstract).

Results The most crucial precondition that must be met is a reliable storage capacity assessment based on site-specific geological data. Our projection of different trends of coal-based power plant capacities up to 2050 ranges between 34 and 221 Gt of CO_2 that may be captured from coal-fired power plants to be built by 2050. If very optimistic assumptions about the country's CO_2 storage potential are applied, 192 Gt of CO_2 could theoretically be stored as a result of matching these sources with suitable sinks. If a cautious approach is taken, this figure falls to 29 Gt of CO_2. In practice, this potential will decrease further with the impact of technical, legal, economic and social acceptance factors. Further constraints may be the delayed commercial availability of CCS in China; a significant barrier to achieving the economic viability of CCS due to a currently non-existing nation-wide CO_2 pricing scheme that generates a sufficiently strong price signal; an expected life-cycle reduction rate of the power plant's greenhouse gas emissions of 59 to 60%; and an increase in most other negative environmental and social impacts.

Conclusion and practice implications Most experts expect a striking dominance of coal-fired power generation in the country's electricity sector, even if the recent trend towards a flattened deployment of coal capacity and reduced annual growth rates of coal-fired generation proves to be true in the future. In order to reduce fossil fuel-related CO_2 emissions to a level that would be consistent with the long-term climate protection target of the international community to

which China is increasingly committing itself, this option may require the introduction of CCS. However, a precondition for opting for CCS would be finding robust solutions to the constraints highlighted in this article. Furthermore, a comparison with other low-carbon technology options may be useful in drawing completely valid conclusions on the economic, ecological and social viability of CCS in a low-carbon policy environment. The assessment dimensions should be integrated into macro-economic optimisation models by combining qualitative with quantitative modelling, and the flexible operation of CCS power plants should be analysed in view of a possible role of CCS for balancing fluctuating renewable energies.

Keywords

CCS; China; integrated assessment; power sector, CO_2 storage potential

Table Nomenclature

Acronym		Abbreviation	
E1	high coal development pathway	CCS	carbon (dioxide) capture and storage
E2	middle coal development pathway	CCUS	carbon (dioxide) capture, use and storage
E3	low coal development pathway	EGR	enhanced gas recovery
S1	high storage scenario	EOR	enhanced oil recovery
S2	intermediate storage scenario	FGDS	flue gas desulphurisation units
S3	low storage scenario	FLH	full load hours
		GHG	greenhouse gas
		IGCC	integrated gasification combined cycle
		LCA	life cycle assessment
		LCOE	levelised cost of electricity
		NGO	non-governmental organisation
		O&M	operation and maintenance
		PC	pulverised coal
		PLF	plant load factor
		R&D(&D)	research and development (and demonstration)
		SC	supercritical
		USC	ultra-supercritical

1 Introduction

Carbon capture and storage (CCS) for reducing carbon dioxide emissions from fossil fuel-fired power plants and industrial sources is the subject of intensive global debate. CCS is considered a technology option that could contribute significantly to achieving the objective of decreasing greenhouse gas (GHG) emissions by 50 to 85% by 2050 [1]. This radical reduction is

imperative in order to prevent the rise in global average temperature from exceeding a threshold of 2°C above preindustrial times by 2100 [2]. For the time being, however, unabated use of coal is on the rise [3]. This development is mainly driven by coal-consuming emerging economies that are experiencing a rapidly growing demand for energy. The aim of the present article is to explore whether CCS in the power sector could be a viable low-carbon option for China, which is one of these key countries. Although coal consumption in China seems to have flattened since 2014 [4] following a steady increase for years [3], CCS may be necessary in China to enable the country to meet the long-term climate protection target of the international community to which China is increasingly committing itself [5]. A corresponding analysis for India has already been provided [6]; the case of South Africa will be presented in a separate publication.

In China, CCS has been discussed intensively, mainly by focusing on the concept to combine capture with the use of CO_2 (CCUS) for enhanced oil (EOR) or gas recovery (EGR). However, if a strong GHG reduction is required and CCS is deemed to be a key reduction strategy, CO_2 will also have to be sequestered in other formations. Thus, an important aspect for assessing CCS is knowing whether China has adequate storage capacity [7]. Our main research question is therefore to estimate how much CO_2 can potentially be stored securely in the long term in geological formations and to determine the relation between this storage potential and the potential required. Further research questions involve estimating when CCS technology could become commercially available, evaluating the costs involved and the ecological implications and stakeholder positions towards CCS. The present article does not aim to elaborate the role CCS could play in a future sustainable energy system in China compared to other low-carbon technology options such as renewable energies. Although this question is highly challenging, this article focuses on a sound analysis of CCS by providing the basis for a future comparative assessment.

To our knowledge, no assessment with a comparable comprehensive scope has been published before. As an analysis of peer-reviewed literature illustrates, CCS in China started gaining interest in 2007/2008, when publications first mentioned CCS as a possible mitigation measure in coal-consuming countries (Figure 1). While articles with a more general view on CCS peaked in 2009, the number of publications that explore the challenges of both CO_2 capture in the power sector and CO_2 storage grew from 2009. There were therefore very few one-dimensional assessments, most of which focused on public acceptance and life cycle analysis (LCA). An increasing number of authors refer to the uncertainties and challenges faced by CCS, such as increased energy and water consumption, inadequate storage capacities or potential CO_2 leakages, which could hamper the large-scale deployment of CCS [8–11].

Several authors pursued a more systems analytical approach from around 2009. They developed long-term energy scenarios, exploring the role played by CCS in a macro-economic optimised environment (for example, in [12–16], which modelled the Chinese energy system; in [17–20], which analysed China as part of long-term energy scenarios for Asia, and in [8,21–23], which modelled China as one of several regions within world energy models). In addition, roadmaps for CCS such as in [24,25] or strategic issues and policy measures such as in [26–28] were explored. However, these sources do not include different assessment dimensions in their roadmaps, resulting in an integrated view; nor do they attempt to scientifically verify the storage capacities that are implicitly assumed as the basis for their assessment. The only exception is [29], which developed a six-dimensional indicator set for evaluating different low-carbon technology pathways, albeit without considering important dimensions such as storage capacity and public acceptance. Our article therefore aims to close this gap by providing a holistic, long-term analysis of the potential role of CCS in China.
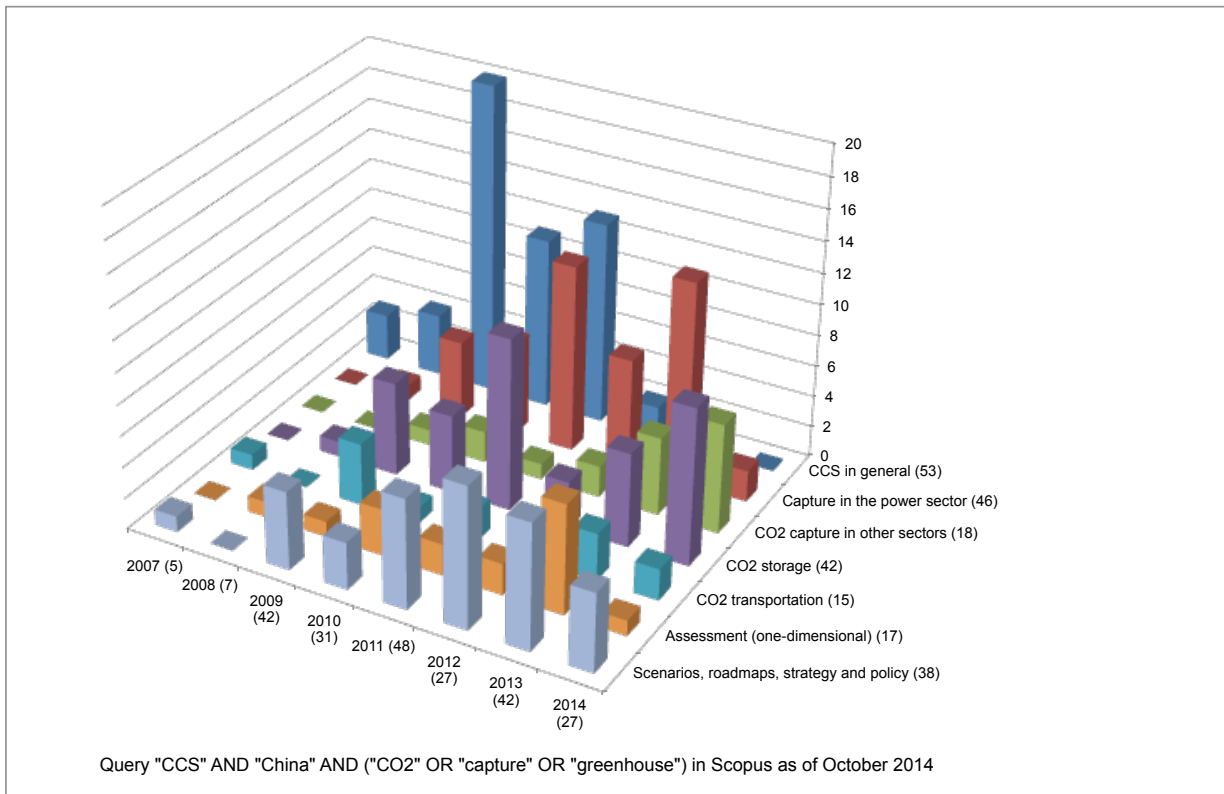

Figure 1: Peer-reviewed papers on CCS in China listed in the Scopus database

In this paper, we first describe the methodologies applied in the individual assessment aspects of the study (section 2). The outcome of each assessment step is given in section 3. Subsequently, we combine the assessment dimensions to present an overall result from an integrative perspective (section 4). We close with an outlook on the needs for further research (section 5).

2 Methodologies

In this paper, we chose an integrated approach covering five assessment dimensions. Each dimension is investigated using specific methods (see graphical abstract).

(1) The assessment of the *commercial availability of CCS technology* in China is based on screening publications and presentations by international CCS experts. The term *commercial availability* refers to the time when the complete CCS chain could be in commercial operation. This incorporates large-scale CCS-based power plants, transportation and storage, which cannot be considered independently [30].

(2) The derivation of China's *long-term usable CO_2 storage potential* consists of three different steps: A) The aim of the *storage capacity assessment* is to systematically analyse and compare existing capacity estimates for China using the methodology linked to the "techno-economic resource-reserve pyramid for CO_2 storage capacity" [31]. The resulting storage scenarios (S1–S3) represent a range between a high and a low estimate of China's storage potential. For the detailed methodology and the results of this step, the authors refer to [32].

B) An *energy scenario analysis* is used to estimate the amount of CO_2 emissions that could potentially be captured from power plants by 2050. Based on existing long-term energy scenarios for China, three long-term coal development pathways for power plants (E1–E3) are developed. They indicate a development between a "high carbon" and a "low carbon" strategy. In the next step, assumptions are drawn on how many of these power plants could be built or retrofitted with CO_2 capture. Finally, the quantity of CO_2 that could be separated is calculated for the pathways assuming different parameters such as the CO_2 capture rate and the efficiency penalty. CO_2 emissions are cumulated over the life time of all power plants newly built up to 2050. It should be noted that coal development pathways differ from energy scenarios: whilst energy scenarios provide a consistent framework for the analysis of long-term energy strategies, the pathways applied here are taken from different existing scenario studies. They are only used to illustrate the different CCS development pathways to obtain an understanding of the level of separated CO_2 emissions that could be available for storage.

C) In order to achieve a *source-sink match,* the storage scenarios are combined with the coal development pathways to obtain a total matched capacity for each combination of S1–S3 and E1–E3. The result is the matched capacity, which is the next step up in the storage pyramid concept [6]. Due to missing data and the consequential heuristic approach, matching is performed manually without using a geographic information system. The emission data from each pathway is divided amongst the administrative divisions where they occur. An investigation is made into whether the emissions located the closest to the storage formations of S1–S3 could be stored there. Since one basin comprises the area of several divisions, the match

is at the *division-to-basin level*. The selected aquifer basins extend several hundred kilometres and are usually larger than one division, which covers 100,000 km^2 on average. The exact position of sub-basins is not known. The maximum distance between sources and sinks is therefore arbitrarily defined as roughly 500 km, a transport distance that has been estimated to be economically viable [33]. Capacities within the storage scenarios are listed for each basin, and divisions are attributed to these basins. This is carried out in two steps: divisions in which at least parts of basins are situated are selected first; a qualitative geographical overlap is then conducted between storage basins and emission clusters in each selected division based on figures by [34]. Finally, a total matched capacity is derived for each combination of S1–S3 and E1–E3.

(3) The aim of the *economic assessment* is to conduct a comparative analysis of the long-term development of the levelised cost of electricity (LCOE) of coal-fired power plants with and without CCS in China. The analysis is built upon three main methodological principles: firstly, cost calculations are based on the capacity development of power plants up to 2050 given in E1–E3. Secondly, data from existing studies and the knowledge of numerous experts interviewed during the course of this study are used to define and quantify important cost parameters, such as capital costs and operation and maintenance (O&M) costs. Whenever possible, country-specific conditions and data are taken into account. This is particularly true for plant capital costs. Thirdly, the assessment uses learning rates to project a long-term cost development. All cost data and parameters are fed into the general equation to calculate the development of LCOE.

$$LCOE = \frac{\left(C_{Cap} + C_{O\&M}\right) \cdot af}{capacity} + C_{TS} + C_{fuel} \quad \text{(equation 1)}$$

where

$$af = \frac{I \cdot (1 + I)^n}{(1 + I)^n - 1}$$

and

LCOE	= levelised costs of electricity generation. [LCOE] = USD/kWh$_{el}$
C_{Cap}	= specific capital expenditure. [C_{Cap}] = USD/kW$_{el}$
$C_{O\&M}$	= specific operating and maintenance costs. [$C_{O\&M}$] = USD/kW$_{el}$
af	= annuity factor. [af] = %/a
I	= real interest rate. [interest] = %
n	= depreciation period. [n] = a
C_{TS}	= specific cost of CO_2 transportation and storage. [$C_{O\&M}$] = USD/kWh$_{el}$
C_{fuel}	= specific fuel costs (including CO_2 penalty). [C_{Fuel}] = USD/kWh$_{el}$
capacity	= full load hours. [operating lifetime] = h/a

(4) In order to assess the possible *environmental impacts of CCS*, a prospective LCA of potential future CCS-based coal-fired power plants in China is performed and the environmental impacts are compared with power plants without CCS. The LCA is performed according to the international standard ISO 14 040/44. The life cycle impact assessment (LCIA) is based on the method *CML 2001* [35]. The life cycle approach includes the upstream and downstream parts, such as the provision of additional fuels or the transportation and storage of CO_2.

(5) *Stakeholders* are key players in implementing and deploying new and innovative technologies. Hence, an important assessment instrument is to analyse their positions regarding the prospects of CCS. The overall aim of the analysis is to reflect the state of the CCS debate in China and to draw up a map of key stakeholders and their respective positions. The analysis is based mainly on 22 research interviews conducted with CCS and energy experts from the national government, science, industry and societal organisations in 2011. The interviews were guided by a questionnaire containing open questions, giving interviewees the opportunity to elaborate on their positions freely and to identify parameters affecting the prospects of CCS in China (see supplementary information).

3 Analyses and outcomes of the individual assessment aspects

3.1 Commercial availability of CCS technology

It is unlikely that CCS will be commercially available in China before 2030. At the international level, experts from scientific institutions and non-governmental organisations (NGOs) expect a later large-scale availability than previously assumed due to the low carbon pricing level, delayed demonstration projects and a lack of public acceptance in potential storage regions [36–41]. Although CO_2 capture is currently undergoing substantial development and several CCS demonstration projects have been launched in China [9], a lack of business cases and the uncertainties in climate change policy [10] are hampering the launch of commercial technology. We therefore choose the year 2030 as the start of operation of large-scale CCS projects in the "base case". In order to consider further possible delays, 2035 and 2040 are regarded as sensitivity cases AV1 and AV2.

3.2 Long-term usable CO_2 storage potential for China's power sector

3.2.1 Analysis of storage potential for China

An analysis of all known country-wide studies that analysed the CO_2 storage potential in China [34,42–45] revealed a huge range of CO_2 storage capacity from 32 to 3,090 Gt, covering oil and gas fields, saline aquifers and coal seams [32]. This capacity has to be classified as

theoretical on the techno-economic resource-reserve pyramid [6], since no efficiency factors were applied. In order to allow for the prevailing uncertainties, we developed three storage scenarios [32] (Table 1). These are based on existing country-wide results cross-checked with more basin- and site-specific study results to detect the most appropriate theoretical storage capacity. Furthermore, in the case of saline aquifers the wide range of storage efficiencies used in the basin- and site-specific studies was grouped into three categories and the mean efficiency of each group (2%, 13% and 50%) was determined for application in our storage scenarios. This results in *effective* storage capacity scenarios totalling 65, 402 and 1,551 Gt of CO_2. These scenarios are characterised by different assumptions on the main storage formations:

- Deep saline aquifers: application of the resulting storage efficiencies for saline aquifers to the capacities provided by [34], which was selected as the most detailed country-wide study. Since this study provides the highest capacity figures for aquifers (2,288 Gt CO_2 onshore and 779 Gt CO_2 offshore), the resulting capacity of scenario S3: low (65 Gt) is higher than the capacity of the country-wide study with the lowest capacity (32 Gt).

- Oil and gas fields: "best guess" for CO_2 storage in proven oil and gas fields or the inclusion of unproven resources.

- Coal seams: due to high levels of uncertainty, CO_2 storage in coal seams is only included in the most optimistic scenario.

Other storage options such as ocean storage and mineral carbonation are still under investigation. Mineral carbonation would necessitate additional mining activities for Mg-silicates, considerable energy consumption for grinding, huge reactors for carbonate reactions and large deposits on the land. There is a lack of demonstration plants at present, and it is more expensive than other storage options [46,47].

Table 1: Three scenarios of effective CO_2 storage capacity in China [32]

Formation	Location	Effective storage capacity			Based on
		S1: high	S2: intermediate	S3: low	
Oil and gas fields	Onshore and offshore	7.8	3.6	3.6	[44]
Saline aquifers	Onshore	1,144	297	45.8	
	Offshore	389	101	15.6	[34]
Coal seams	Onshore	9.9	-	-	[48]
Total		1,551	402	65	

All quantities are given in Gt CO_2.
For aquifers, efficiency factors of 50% (S1), 13% (S2) and 2% (S3) are applied.

3.2.2 Deriving the amount of CO_2 that may be captured in China's power sector

Both the literature review and the interviews conducted in China revealed that no suitable long-term energy scenario including CCS existed for China. Instead, the capacity of coal-fired power plants that could theoretically be operated with carbon capture is derived from coal development pathways E1–E3[1].

1. *Pathway E1: high* is based on the World Energy Outlook (WEO) 2009 Reference Scenario for China [50]. Since WEO scenarios extended to 2030 only, the scenario is extrapolated to 2050 as given in [51].

2. *Pathway E2: middle* is based on the EmissionsControl (EC) Scenario, developed within the China Human Development Report [52]. It is characterised by improvements in energy efficiency, a diminished increase in coal with a peak in 2040, and a huge increase in nuclear power. This scenario enables CO_2 emissions from the power sector to be reduced by 41% in 2050, compared to the reference scenario of that study.

3. *Pathway E3: low* is based on the Sustainable China Energy Outlook as part of the global Energy [R]evolution Scenario 2010 [51,53]. The target of the global scenario is to reduce worldwide energy-related carbon dioxide emissions by 50% by the year 2050, from their 1990 levels. China's share of global greenhouse gas obligations is calculated by applying the Greenhouse Development Rights (GDR) framework. The scenario is based on a massive increase in renewables and energy efficiency; from 2030, both newly built coal-fired and nuclear power plants are excluded.

Figure 2 compares the development of coal-fired power plant capacity in the resulting pathways E1–E3. In addition, the installed power plant capacity as of 2010 and its expected decommissioning curve are illustrated. These result from a power plant analysis of each of China's 33 administrative divisions[2]. The figure illustrates that all pathways meet the 2010 installed capacity. Since the basic scenarios were published in 2010, for the purpose of validating our figures we compare these with values from current scenarios in which capacity development figures are explicitly published. In its scenarios given in Energy Technology Perspectives (ETP) 2015 [54] and in World Energy Outlook (WEO) 2014 [55], IEA follows a similar approach: WEO's "current policies" scenario and ETP's "6 degree" scenario represent the highest coal capacity development. From 2020 to 2040, WEO is higher and ETP is nearly

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[1] The preconditions for pre-selecting a study were: scenarios had to cover a period up to 2050; the installed capacity of coal-fired power plants had to be provided in at least decadal resolution; and scenarios had to been published in English. From the scenarios obtained, only the selected scenarios could be used to model different CCS development pathways [49].
[2] China's 33 administrative divisions cover 22 provinces, five autonomous regions, four municipalities and two special administrative regions.

the same than our pathway E1. WEO's "new policies" scenario and ETP's "4 degree" scenario are in the beginning nearly the same than the upper scenarios and from 2040 somewhere between pathways E1 and E2. WEO's "450" scenario and ETP's "2 degree" scenario comply with our pathway E3 from 2030/2040 after representing a higher level between 2010 and 2030/2040. [13] applied a multi-period optimisation model, which complies with our pathway E3. [8] presents a BASE scenario in the absence of any climate policy instruments and extremely positive conditions for the use of coal, topping our pathway E1 and IEA's ETP "6 degree" scenario by about 40%. Considering a climate policy scenario POL, coal development is largely restrained by an increasing carbon tax enabling to reach the 2°C target. This scenario roughly complies with our pathway E3 and IEA's ETP "2 degree" scenario. Recent analyses of China's coal market show a trend towards the flattened deployment of coal capacity, taking into account reduced annual growth rates of coal-fired generation and coal demand in China up to expected peak-coal as early as 2030 or even 2020 [4,55,56]. If this trend proves to be true, a development somewhere between pathways E2 and E3 may be most realistic.
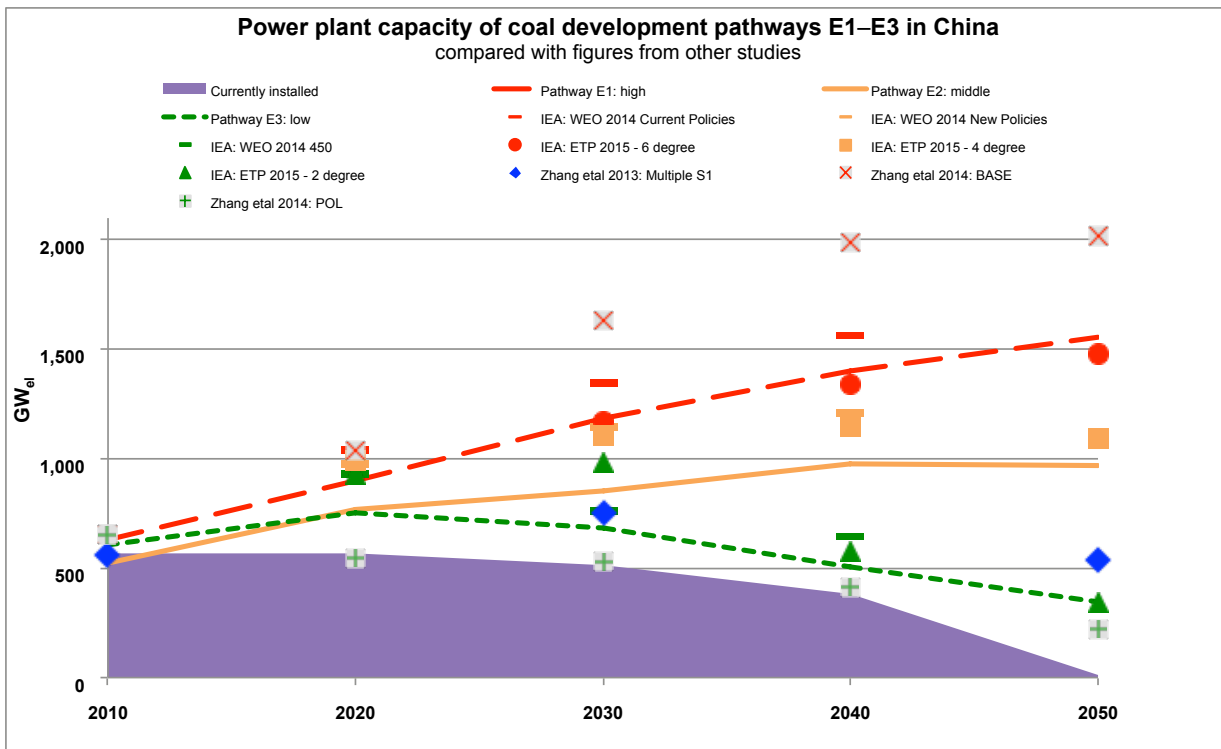

Figure 2: Coal-fired power plant capacity in China (2010 installed, decommissioning curve, envisaged according to coal development pathways E1–E3, and values from other scenarios)

Our assumptions behind the application of CCS in the pathways are as follows:

- In *E1: high* the deployment of CCS will have to be as high as possible to decrease the high CO_2 emissions resulting from this pathway.

- In both *E2: middle* and *E3: low*, the deployment of CCS could be a "fall back" option which may have to be used if other measures to reduce CO_2 emissions from the power sector cannot be realised as envisaged in the respective scenarios (usually the considerable use of nuclear energy in *E2: middle* and renewable energy deployment in *E3: low*, as well as energy efficiency improvements in both scenarios).

In order to calculate the possible capacity of CCS-based power plants, the following assumptions are made for coal-fired power plants in all three pathways: only supercritical, IGCC and ultra-supercritical power plants (USC) will be built, fuelled by hard coal. New plants are distributed proportionately to currently operating power plants, since no plans for any future regional allocation are known. From 2030, all new plants will be built as CCS-based power plants. Power plants built pre-2030 are only retrofitted if they are no older than 12 years [57]. One third of the power plants built between 2020 and 2030 will be retrofitted from 2030 in the base case (CCS available from 2030). If CCS is available only from 2040, 50% of power plants built between 2030 and 2040 and 10% of those built between 2020 and 2030 are retrofitted. Figure 3 shows the resulting CCS-based power plant capacity in the base case. It also illustrates the penalty load caused by efficiency losses introduced by the use of carbon capture technology (which may probably lead to a "very adverse impact on China's coal supply-transportation systems" [9]). The penalty load must also be included in the load given in the coal development pathways (black line), increasing the total load of coal-fired power plants in 2050 by 7% (*E3: low*) to 13% (*E1: high*).
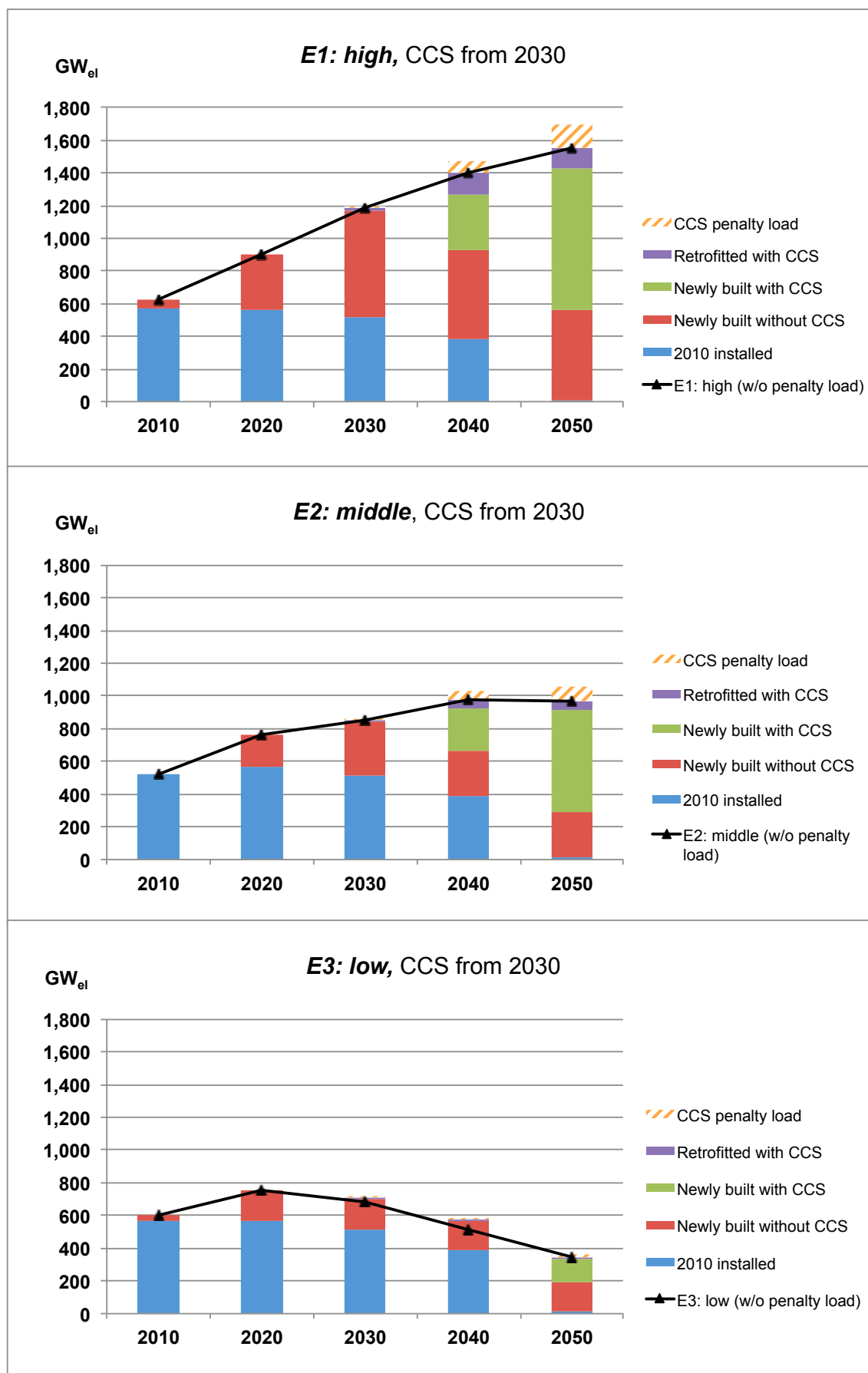
Figure 3: Conventional and CCS-based coal-fired power plant capacity installed in China in the three pathways E1–E3 for the base case (CCS from 2030)

Further assumptions are required to calculate the *quantity of CO_2* that could be separated (Table 2 and supplementary information): the maximum *efficiency* for newly-built non-CCS power plants in 2050 is set at 46% for supercritical power plants. The efficiency of USC and IGCC is assumed to exceed the efficiency of supercritical power plants by 2 and 6 percentage points, respectively. For CO_2 capture and compression, an *efficiency loss* declining over time from 8.5 to 5 percentage points for the period from 2020 to 2050 is assumed for post-combustion, whilst loss due to pre-combustion ranges from 6.5 to 6 percentage points [58–62]. Retrofitting power plants with CCS technology would cause an additional efficiency loss of 1.5 percentage points [63].

Table 2: Efficiencies and efficiency losses through CCS assumed for future newly built coal-fired power plants in China

		2010	2020	2030	2040	2050
Subcritical	%	37				
Supercritical	%	40	41	42	44	46
Ultra supercritical	%	42	43	44	46	48
IGCC	%	46	47	48	50	52
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

The technical *lifetime*, and hence the time available for capturing CO_2 from new power plants, is assumed to be 40 years [64][3]. A CO_2 *capture rate* of 90% is assumed [34,68] and an average *net calorific value* of the domestically produced coal feedstock of 23 MJ/kg [67] is applied. A *plant load factor* (PLF) of 80% (7,000 full load hours) is chosen as the average value of a range covered by several sources [34,64,69]. In order to consider a potential future increase in competition from nuclear and renewable energy plants, both of which produce electricity at a lower marginal cost than coal, a PLF of 69% (6,000 full load hours) is considered as sensitivity case PLF.

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[3] This partly contrasts with other studies, which assume a shorter average lifetime of power generating capacities in China, ranging from 20 years [65] and 25 years [66] to 35 years [67]. This, however, is mainly due to the fact that, in many cases, the national government requires power plant operators to shut down small and inefficient power stations in order to gain approval for erecting new coal-fired capacities.

The cumulated amount of CO_2 separated per power plant is calculated by adding the annual CO_2 emissions captured by each power plant over its lifetime. For power plants built in 2050, for example, this means that their annual emissions up to 2090 are included. In the base case, between 34 and 221 Gt of CO_2 could be available for sequestration in total (Table 3). Considering only the annual figures, between 0.9 and 5.7 Gt/a would have to be sequestered in 2050.

Table 3: Separated CO_2 emissions in China according to coal development pathways E1–E3, cumulated over the lifetime of all CCS-based power plants newly built by 2050

Availability of CCS	7,000 full load hours (base case)			6,000 full load hours (sensitivity case PLF)		
	E1: high	E2: middle	E3: low	E1: high	E2: middle	E3: low
		Gt CO_2			Gt CO_2	
CCS from 2030 (base case)	221	151	34	190	129	29
CCS from 2035 (sensitivity case AV1)	189	129	33	162	111	28
CCS from 2040 (sensitivity case AV2)	157	108	32	134	92	28

The year of commercial availability and the PLF were identified as the most relevant parameters for estimating separated CO_2 emissions. Considering sensitivity cases AV1 and AV2, the CO_2 emissions provided for storage will be 15 or even 29% lower, respectively, in both pathways E1 and E2. Only slight changes occur in pathway E3, since most CCS-based power plants will be built between 2040 and 2050. Varying the operation time by 1,000 full load hours (sensitivity case PLF) decreases the amount of CO_2 captured by 14%.

3.2.3 Deriving China's CCS potential as a result of matching sources and sinks

Finally, the range of effective CO_2 storage capacity is compared with the cumulated quantity of CO_2 emissions. 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. Since emissions from more than one division can potentially be stored in one basin in most cases, once emissions from the 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. If capacity exceeds the total emissions of neighbouring divisions, this storage site is not filled entirely. After filling onshore basins, the same process is repeated for *offshore basins*. The detailed match of each scenario combination is given in the supplementary information.

In the next step, values from the regional breakdown are aggregated, leading to the matched capacity for the whole of China for each scenario combination. This figure ranges from 29 to 192 Gt of CO_2 (upper third of Table 4). The central third indicates that the storage potential is exploited by less than 70%, and is therefore never fully used. Less than half of the storage potential is used in 7 out of 9 combinations, one of which in the low storage scenario S3. The lower third represents the share of emissions that can be stored in the respective scenario combination. In seven out of nine scenario combinations, 80 to 87% of the emissions can be stored. The quantity of captured emissions available is restricted only by the limit set for the distance between sources and sinks. Less than 30% of the emissions is sequestered in the low storage scenario and the middle and large pathways E1 and E2 only. For this scenario, insufficient space is available for emission clusters in several divisions.

Table 4: Matched capacities for China in the base case (CCS from 2030)

Effective storage capacity scenarios	Power plant emissions from coal development pathways		
	E1: high (221 Gt CO_2)	E2: middle (151 Gt CO_2)	E3: low (34 Gt CO_2)
	Matched capacity (Gt CO_2)		
S1: high (1,551 Gt CO_2)	192	131	29
S2: intermediate (402 Gt CO_2)	176	131	29
S3: low (65 Gt CO_2)	45	43	29
	Share of effective storage capacity used (%)		
S1: high (1,551 Gt CO_2)	12	8	2
S2: intermediate (402 Gt CO_2)	44	33	7
S3: low (65 Gt CO_2)	69	67	45
	Share of emissions that can be stored (%)		
S1: high (1,551 Gt CO_2)	87	87	86
S2: intermediate (402 Gt CO_2)	80	87	86
S3: low (65 Gt CO_2)	20	29	86

The matched capacities of sensitivity cases AV1 and AV2 have not been analysed in detail. However, since only 85 and 71% of the power plant emissions of the base case are available in pathways E1 and E2, respectively (Table 3), a higher share of these emissions could become sequestered than in the base case, while the storage potential may be exploited to a lesser extent than in the base case. In sensitivity case PLF, the available emissions are reduced by (a further) 14%, which reinforces the implications deduced.

3.3 Economic assessment of CCS in China's power sector

The assessment of LCOE of coal-fired power plants in China is based on a comprehensive set of assumptions for the base case. Although an increasing capacity of USC plants has been installed in China in recent years, our estimation concentrates on SC plants because most of the existing cost assessments refer to these plants. Furthermore, SC plants constitute approximately 40% of China's coal-fired power capacities commissioned over the last five years [70]. They are still expected to remain a relevant plant type in China in the decades ahead because they constitute a widely deployed, mature and reliable technology. IGCC plants are not considered since the technology is stagnant at the demonstration stage and involves rather high uncertainties [71], in spite of ambitious demonstration projects such as the GreenGen initiative. The basic plant parameters for SC plants with and without CCS are for the most part consistent with those presented for the base case in section 3.2.2 (see also supplementary information).

For newly built SC plants, an average net thermal efficiency of 41% is assumed for the pre-2020 period and 44% for post-2030 as the mean of the expected development from 2030 to 2050. An efficiency loss of 6 percentage points is chosen as the mean of the efficiency penalties from 2030 to 2050. Since in the base case CCS starts no earlier than 2030, with capacities being installed gradually in the ensuing years, the cost assessment provides figures for CCS plants for 2040 and 2050 only.

Our figures for *current* plant capital costs and costs of operation and maintenance (O&M) represent an average value of several existing cost assessments [65–67,72–74], all factoring in China's country-specific conditions. Capacities of SC plants considered in these sources range from 559 to 1,320 MW$_{el}$. Their capital costs range from 520 to 874 USD/kW$_{el}$, due to the effect of economies of scale and differing basic assumptions, such as plant designs with or without flue gas desulphurisation units (FGDS). We choose the mean value of this range (625 USD/kW$_{el}$) as it reflects a good balance of anticipated economies of scale due to increasing plant units in China and a rising share of plants equipped with FGDS units. O&M costs are given as a percentage rate of plant capital costs and are assumed to be 4% [73].

If post-combustion equipment is added to SC plants, its capital costs are estimated to be equivalent to 75% of non-CCS plant capital costs; O&M costs are assumed to increase by 83% (both figures represent an average value of figures from [36,63,75]). The total capital costs for the power plants considered are allocated to individual years on an annuity basis. An interest rate of 10% and a depreciation period of 25 years according to [66,69] yield an annuity factor of approximately 11% per annum (see general LCOE equation in the supplementary information).

The cost development of *future* power plants is derived by applying learning rates, taking into account newly installed capacities of SC units with and without CCS at the global level. As projected in the Blue Map scenario of IEA [76], it is assumed that 663 GW CCS-based coal-fired power plants will be installed globally by 2050. Based on [77], the learning rates for power plants with and without CCS are derived as 3.9% and 1.7% for capital costs and 5.8% and 2.5% for O&M costs, respectively. For CCS-based power plants, these are lower than one might expect because in the case of CCS only the additional expenditure for CO_2 capture follows the learning curve, whilst the current SC plant is a widely mature and deployed technology.

Coal prices are an important parameter of LCOE. Since energy security is a top priority of China's national government, the figures given below will showcase the development of LCOE in China under a 90:10 balance of domestic and imported coal, an import rate also assumed by [55]. This assessment follows the assumption by [67] that the price of domestic hard coal in China will increase at a growth rate (exponent) of 0.9%/a, starting with USD 86.34 per tonne in 2010 [72]. The price of imported hard coal is assumed to follow the growth rate of the international oil price based on evidence from previous decades ($_{2011}$ 87/barrel in 2010, $_{2011}$ 115/barrel in 2030, and up to $_{2011}$ 132/barrel in 2050, based on [50]). This price path leads to feedstock costs of the envisaged hard coal mix of $_{2011}$ 3.44/kWh in 2010, $_{2011}$ 3.89/kWh in 2030 and $_{2011}$ 4.63/kWh in 2050 for China's SC plants without CCS. For SC plants with CCS, feedstock costs increase to $_{2011}$ 4.55/kWh, $_{2011}$ 4.51/kWh and $_{2011}$ 5.36/kWh, accordingly.

Average transport costs over a distance of 250 km under specific Chinese conditions are assumed to be $_{2011}$ 3.30/t CO_2 [78]. This estimate is significantly below international figures due to lower costs for labour and, in particular, equipment in China.

Due to their rather low learning rates, cost reductions of CCS over time are merely moderate and overcompensated by increasing fuel costs (Figure 4). Overall, LCOE of CCS plants are 29 to 32% higher than those without CCS.
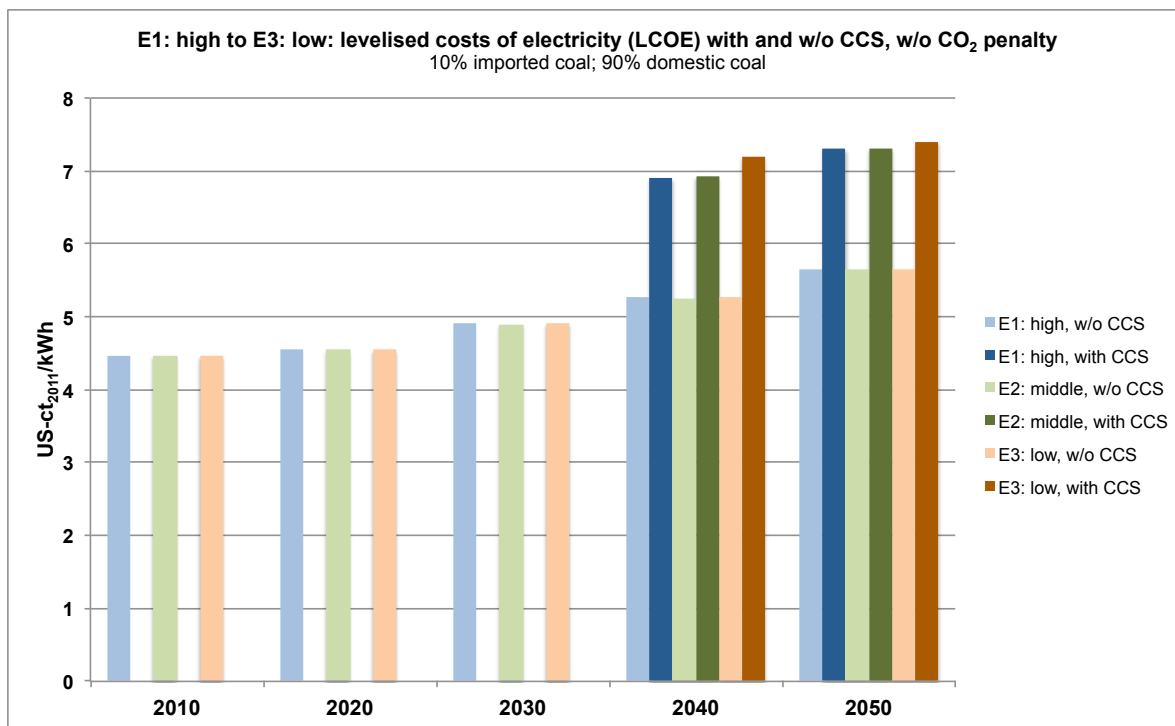
Figure 4: LCOE in China with and without CCS in coal development pathways *E1: high* to *E3: low*

Illustrating LCOE by cost category shows which parameters are responsible for the high cost penalty of CCS. In pathway E2 (Figure 5), additional fuel costs represent the largest share (44%) of the additional LCOE of $_{2011}$ 1.69/kWh in 2050, followed by capital expenditure for CO_2 capture (22%) and CO_2 storage (20%).
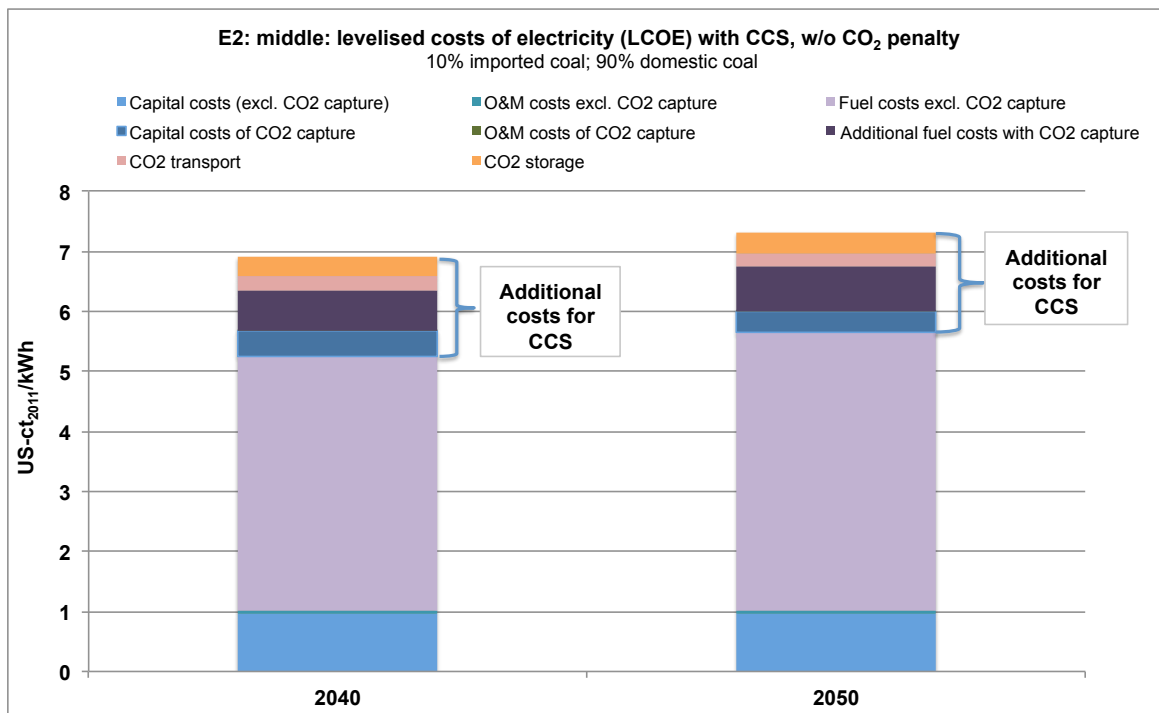

Figure 5: Additions to LCOE in China resulting from CCS by cost category in coal development pathway *E2: middle*

The high impact of fuel costs is due to significantly lower plant capital costs in China compared to industrialised countries. This could lead to the conclusion being drawn that the cost barrier that needs to be overcome to achieve the economic viability of CCS plants is significantly lower in China than in industrialised countries. However, even in other emerging economies such as India [6], specific ambient conditions lead to higher plant investment costs. Furthermore, it must be noted that sensitivities in the development of Chinese domestic coal and imported coal may significantly affect the results of the cost analysis presented. Some authors now assume an increasing quantity of imported coal and thus an increasing foreign dependency rate. The reasons for this are the expected peaking of coal in China [4,56,79–81] and the limited availability of cheap coal [8]. As a sensitivity case, we therefore analyse the case that coal imports would provide 50% of the feedstock used in 2050. The feedstock costs for non-CCS plants and CCS plants would grow to $\$_{2011}$ 5.28/kWh or $\$_{2011}$ 6.11/kWh, respectively, and therefore increase by 14% compared to a 90:10 balance of domestic and imported coal in the same year. In pathway E2, illustrated in Figure 5, LCOE of non-CCS plants and CCS plants would increase by 10 to 11% in 2050, making it highly sensitive to changes in feedstock costs. Although feedstock costs account for 75% of LCOE, other cost parameters may be subject to sensitive developments. In particular, the development of plant capital costs under different learning rates and gradually increasing labour costs in China may have a notable impact on plant LCOE, and could be part of further more comprehensive cost assessments of CCS plants in China. Finally, a lower operation time as assumed in sensitivity case FLH (6,000 instead of 7,000 full load hours and therefore a 14% lower average utilisation rate) would nearly proportionally increase LCOE according to equation 1.

Despite the potential impact of sensitivities on the economic performance of CCS plants in China, our analysis enables the robust conclusion to be drawn that the cost penalty of CCS will most likely remain significant, requiring stimulating policy incentives such as a CO_2 price to induce the technology's commercialisation. Since several Chinese administrative divisions have recently introduced emission trading pilot schemes, the vision of a nation-wide carbon pricing system is taking shape. For this reason, the present study investigates the impact of a CO_2 penalty on LCOE of CCS of power plants with and without CCS (see Figure 6 illustrating pathway E2). In our scenarios, CO_2 costs start at $\$_{2011}$ 42/t CO_2 in 2020, reaching $\$_{2011}$ 56/t CO_2 in 2040 and rising to $\$_{2011}$ 63/t CO_2 in 2050 [49].

E2: middle: levelised costs of electricity (LCOE) with and w/o CCS - with and w/o CO$_2$ penalty
10% imported coal; 90% domestic coal

- ◆ E2: middle, w/o CCS, w/o CO2 penalty
- ■ E2: middle, with CCS, w/o CO2 penalty
- ▲ E2: middle, w/o CCS, with CO2 penalty
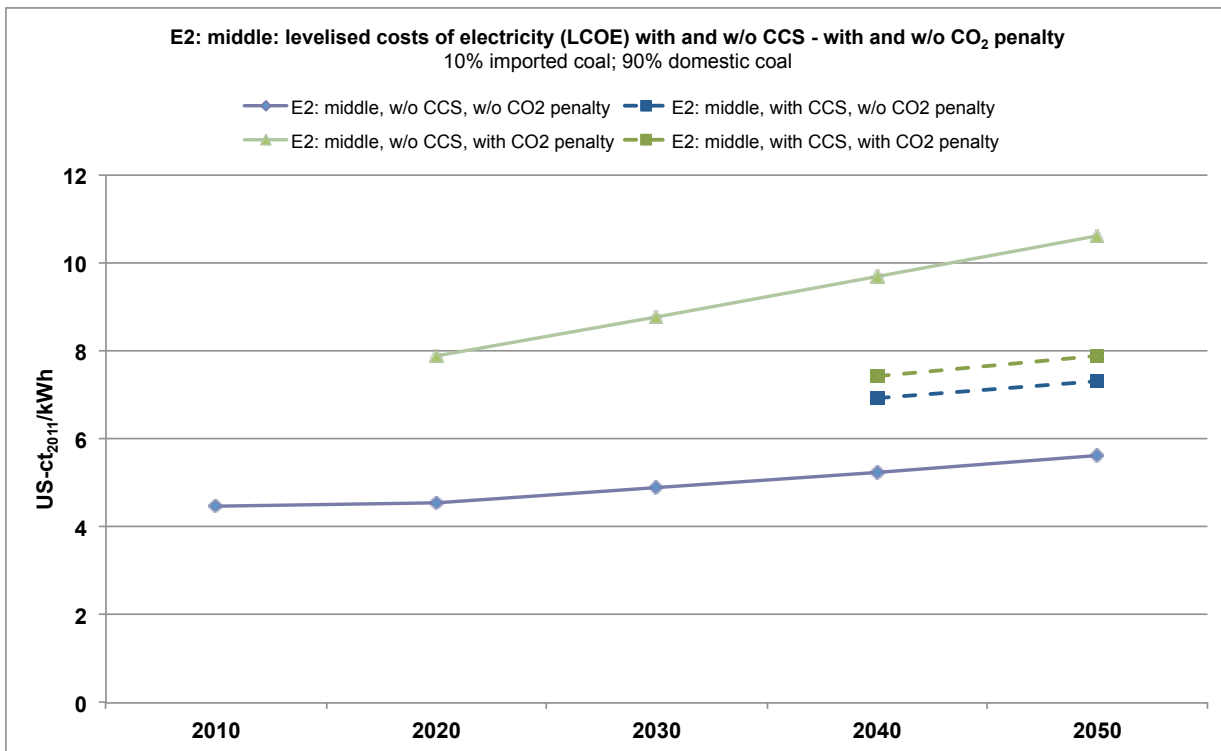- ■ E2: middle, with CCS, with CO2 penalty

Figure 6: LCOE in China with and without CCS and with and without a CO$_2$ penalty in coal development pathway *E2: middle*

It becomes apparent that a carbon price as assumed in this scenario would make CCS clearly more cost competitive than the same plant type without CCS. Although the calculation presented does not consider variations in plant operation on a daily basis and is thus simplified, it may lead to the conclusion that CCS would be an economic mitigation option under the considered carbon price pathway.

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

The LCA, based on [82], is performed for both supercritical PC power plants (using post-combustion capture using the solvent monoethanolamine, MEA) and IGCC power plants (using pre-combustion capture using the solvent methyl diethanolamine, MDEA), referring to the year 2030. Saline aquifers without any leakage of CO$_2$ are assumed to be the storage medium; the average transport distance is set at 250 km. The hard coal supply is based on 100% indigenous coal. The coal import rate of 10% assumed in the economic part cannot be considered here due to the lack of coal supply datasets for the main country that exports coal to China (Indonesia). In order to consider possibly lower GHG emission factors of imported coal, we will perform a sensitivity analysis for coal mine methane (CMM), the parameter most relevant for the coal supply stream. Most of the basic LCA datasets (mining, transport, generation, etc.) are taken

from the LCA database ecoinvent 2.2 and adapted to the conditions considered (for example, the transport distance of CO_2, the calorific value of coal, etc.). Efficiencies and efficiency losses in the year 2030 are taken from Table 2. A CO_2 separation rate of 90% is assumed.

Despite the fact that China has several large uncontrolled coal fires that emit substantial amounts of carbon dioxide and other greenhouse gases, these emissions are disregarded in our analysis (and consistently excluded from the original ecoinvent dataset "Hard coal, at mine [CN]"). Since coal fires are not only ignited naturally, but usually through human influence [83], they cannot essentially be connected to coal mining activities caused by large-scale power production, although this context has not yet been fully discussed. CMM emissions are included as given in the aforementioned ecoinvent dataset (0.0169 kg CH_4/kg coal), representing the situation in China in 1990. Depending on the calorific value and the efficiency of the power plant, CMM causes additional GHG emissions of 154 and 137 g $CO_{2\text{-eq}}$/kWh$_{el}$ (in the case of the modelled PC and IGCC, respectively).
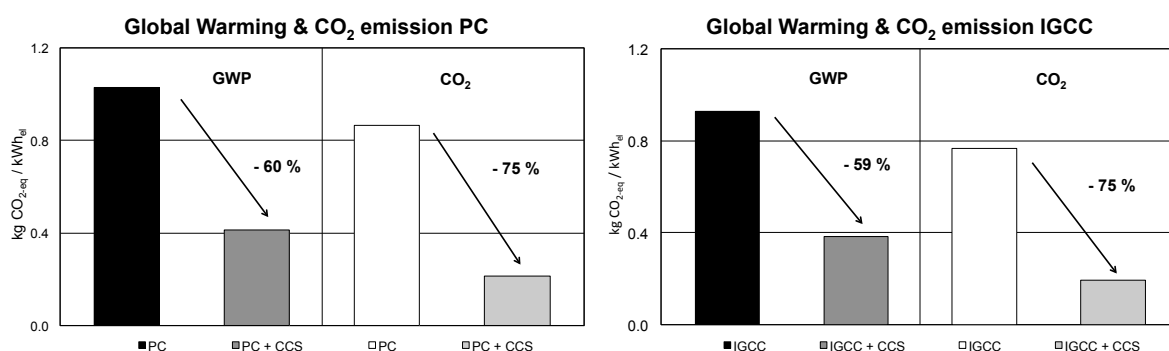

Figure 7: Specific GWP and CO_2 emissions for supercritical PC and IGCC power plants with and without CCS in China in 2030

The overall reduction rates of both CO_2 (75%) and GHG (59-60%) emissions (impact category *global-warming potential, GWP* Figure 7) are lower than one would expect. This is because of the life cycle perspective and CMM emissions (see Figure 8 in detail for the case of PC). Focusing only on the CO_2 capture rate excludes:

• The excess consumption of fuels required by the use of CCS technology. It causes more CO_2 emissions, with the consequence that *separated* CO_2 emissions are higher than *avoided* CO_2 emissions;

• The CO_2 emissions released into the upstream and downstream parts of the system, which are the provision of additional fuels and further processes such as the production of solvents and the transportation and storage of CO_2;

• Other GHG emissions released in upstream and downstream processes, the most relevant of which is CMM (responsible for 68 and 65% of coal supply emissions, respectively).
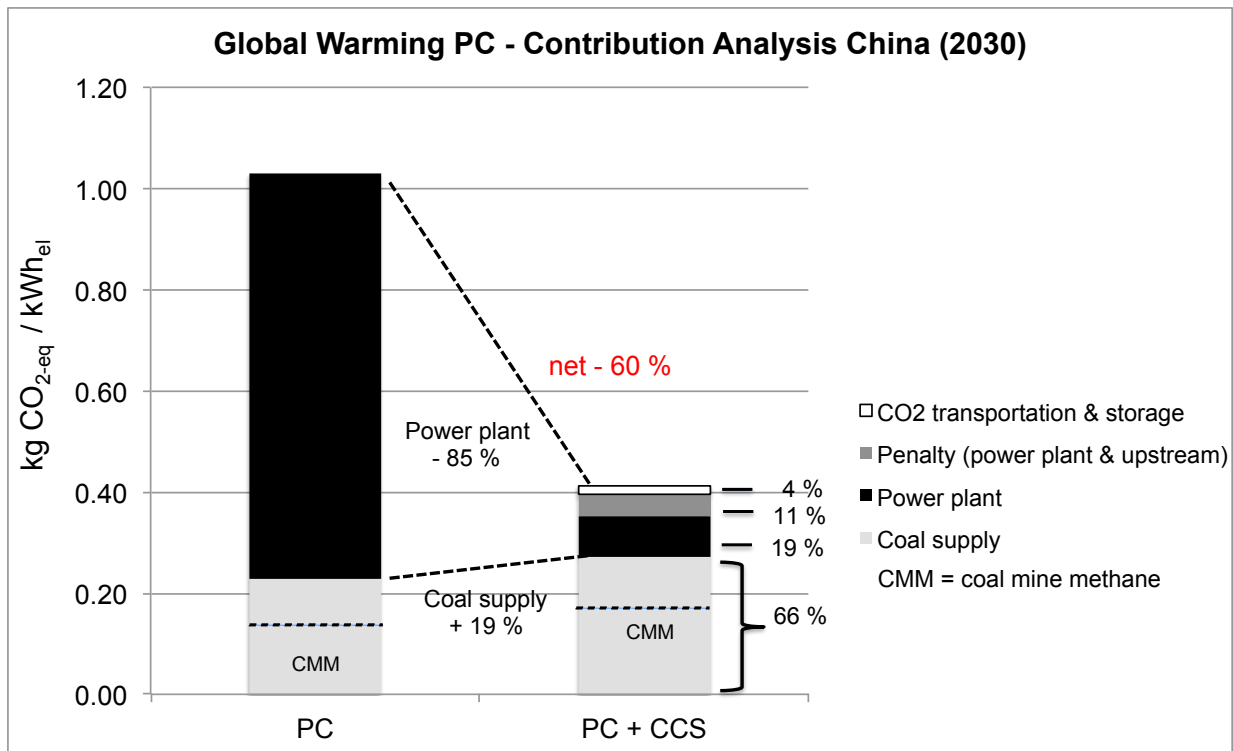
Figure 8: Contribution of individual life cycle phases to the global-warming potential for supercritical PC with and without CCS in China in 2030

Due to the high share of CMM emissions, we performed a sensitivity analysis of the specific CMM factor. We introduced a utilisation rate of CMM, assuming that currently discussed utilisation measures for methane [84,85] may increasingly be applied in the future, and varied the rate from 10 to 50% (sensitivity cases CM1 to CM5). The analogous reduction of the CMM factor (0.0169 kg CH_4/kg coal) by 10 to 50% results in a 1.5 to 7.5% reduction in the total GHG emissions of the power plant. The total emissions are therefore not very sensitive to the change in the CMM factor; CMM emissions as a fraction of coal supply emissions, however, are reduced considerably by 4.2 to 22.2%. Based on this result, the overall GHG emission reduction rate in the case of CCS would increase from 60% to 61 to 66% (PC) and from 59% to 60 to 65% (IGCC), demonstrating the high relevance of CMM emissions in the case of CCS.

In contrast to GHG emissions, most other environmental impact factors increase per kilowatt hour of electricity in the case of CCS for both PC and IGCC (we considered eutrophication, human toxicity, terrestrial ecotoxicity, freshwater and marine aquatic ecotoxicity and stratospheric ozone depletion), whilst acidification and summer smog decrease in the case of PC. Figure 9 illustrates the results for the most commonly discussed categories.
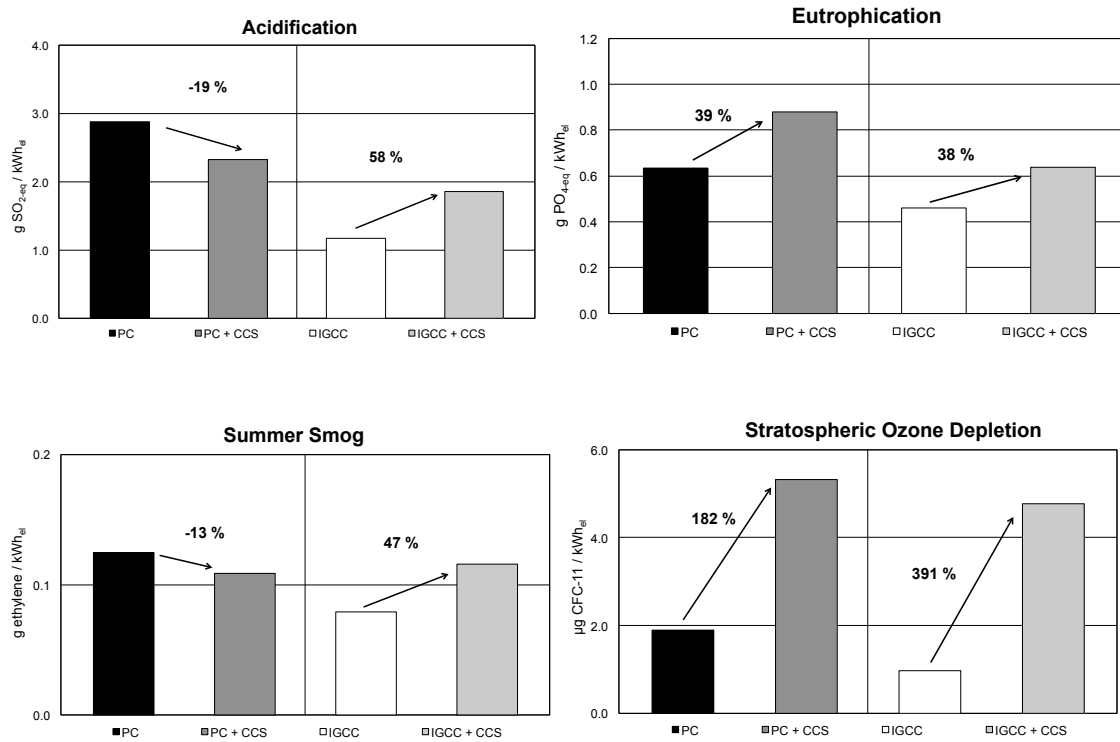
Figure 9: Results of selected non-GHG impact categories for PC and IGCC power plants with and without CCS in China in 2030

Similar to the case of GHG emissions, two issues are responsible for these results: firstly, the energy penalty leads to higher emissions per unit of electricity generation at the power plant itself. Only CO_2, NO_x, SO_2, HCL and PM (particulates) can be removed during the CO_2 scrubbing process. Secondly, the upstream and downstream processes cause an increase in several emissions. The net result depends on the extent to which the decrease in emissions at the power plant's stack is outweighed by an increase in the upstream and downstream processes.

With regard to the CCS-induced relative change in performance of emissions, in most cases PC power plants outperform IGCC power plants. The stronger increase in the case of IGCC depends on the emissions released during the upstream and downstream processes, which cannot be balanced by decreasing direct emissions. However, the absolute values also need to be considered, which are usually lower or equal in the case of IGCC power plants compared to PC power plants. The reasons for this are the greater efficiency of IGCC and the lower energy penalty for capture processes.

3.5 Analysis of stakeholder positions

During the interviews we conducted within this study (see supplementary information), it became apparent that China's national government recognised CCS as a potentially relevant technology option for mitigating CO_2 emissions from large-scale, fossil-fired plants in 2007. This was the year when former President Hu Jintao highlighted research on CCS as one element of a research agenda towards the introduction of a low-carbon development [86]. Former Premier Wen Jiabao hosted a workshop on reducing CO_2 emissions in the same year, which further boosted the attraction of CCS as a mitigation pathway. These statements and actions by China's national leaders were translated into national plans and policy initiatives in the ensuing years. The national government increased its R&D budget for CCS-related activities for the period of the 12th Five Year Plan (2011-2015). For example, the budget for the first year of the 12th Five-Year Plan period was estimated to be nearly as high as the overall budget for CCS in the whole 11th Five-Year Plan period [87]. The focus of the government's efforts, though, is not merely on CCS, but on CCUS in order to exploit additional value creation opportunities. Due to the activities described, China has made significant progress in recent years in establishing pilot plants at industrial scales, proving that it can realise such projects in very short timescales [9].

Despite these steps, CCS was not a top priority on China's carbon mitigation agenda in the past. The government choose a rather cautious approach, considering CCS as a reserve technology that may be required in the future, whilst its large-scale application was expected to be some time away [87]. Possible future binding mitigation obligations arising from international climate negotiations were thought to be a potential trigger for the future deployment of CCS in China [64,87,88]. The introduction of regional emission trading pilots could enhance such a development. China has since become a front-runner on CCS, by accumulating significant know-how on the CO_2 capture process and achieving significant progress in establishing pilot plants on an industrial scale whilst other demonstration plant activities throughout the world stagnate [40]. Furthermore, climate policy in China focuses increasingly on the goal of reducing CO_2 and instruments for achieving this goal. Examples include the recent U.S.-China Joint Announcement on Climate Change, which lends considerable support to CCS; the introduction of an emissions cap; and a 40% carbon intensity reduction target for the industry [5,89].

The governmental strategy on CCS is led by the National Energy Administration (NEA) as part of the National Development and Reform Commission (NDRC). However, several other

ministries and governmental units are responsible for specific sub-questions, such as the Ministry of Science and Technology (MOST), which is in charge of CCS-related research and development activities, and the Ministry of Environmental Protection (MEP), which is responsible for the potential long-term environmental impacts of CCS.

In the industry sector, some of China's major industrial stakeholders have become increasingly active in the field of developing, testing and demonstrating carbon capture, use and storage technologies. They have accumulated significant technical know-how on CO_2 capture processes and are assumed to be able to build most parts of a power plant with CO_2 capture equipment based on Chinese technologies [89,90]. One of China's most active players is China Huaneng Group, China's largest power producer. This group established the GreenGen Corporation to promote CCS in a 250 MW IGCC plant in Tianjin City, Bohai Rim. Shenhua, China's largest coal-mining company, launched a small-scale CCS operation at its coal liquefaction plant in Inner Mongolia. In the oil industry, PetroChina and Sinopec are fostering the research, development and demonstration (RD&D) of CO_2 storage in combination with EOR. China's oil companies are considered key players for realising CO_2 storage projects because they have exclusive access to geological data on underground potential storage sites [91].

Environmental NGOs, such as the World Resources Institute (WRI), WWF China, Greenpeace China, the Climate Group and the U.S. NGO Natural Resources and Defense Council (NRDC) also address CCS in China, but it is not their top priority. Their positions are mixed. For example, while WWF China considers CCS as a "necessary evil" [92], Greenpeace China opposes it [93]. **Figure 10** illustrates the constellation of actors in the Chinese CCS discourse.
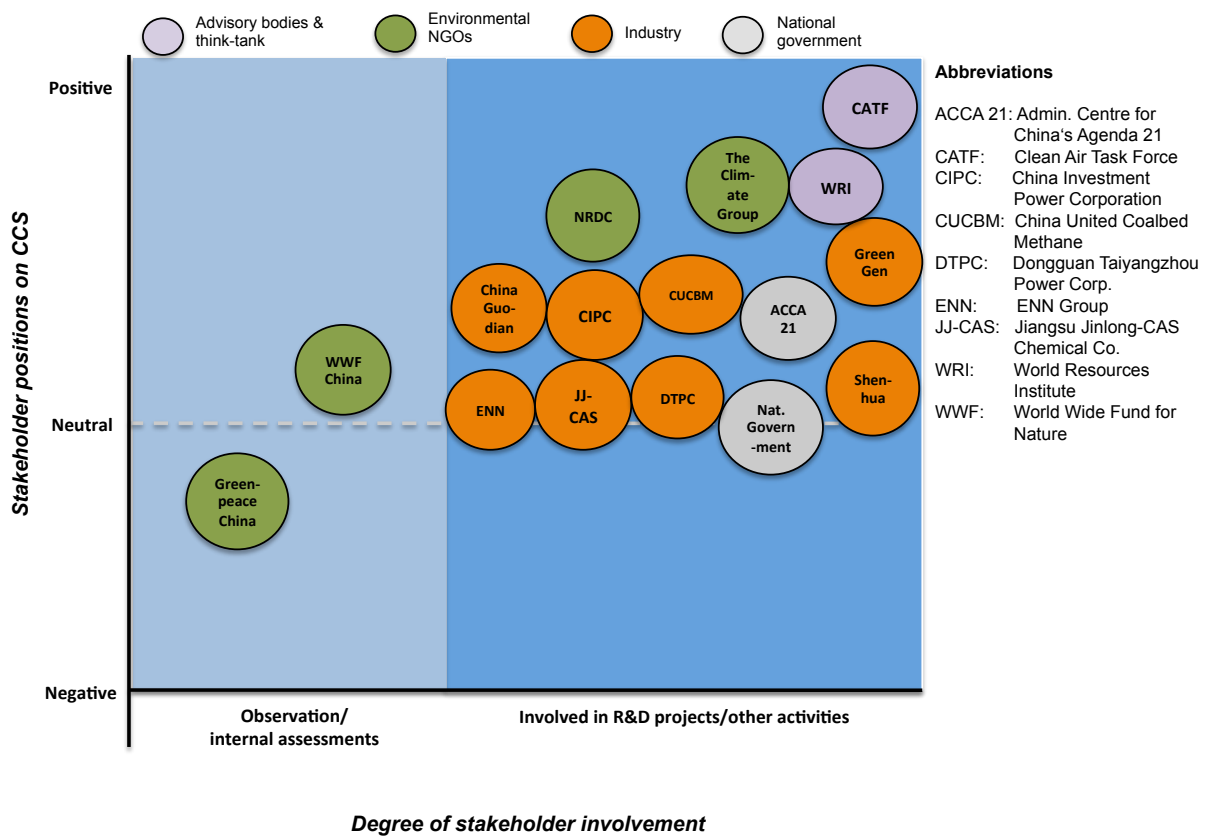
Figure 10: Constellation of key CCS stakeholders in China

4 Overall results and discussion

The previous sections reveal that a successful implementation of CCS in China is affected by a wide variety of aspects, even if CCS is explored without assuming competition from other low-carbon technology options. The findings generated by the five assessment dimensions provide the overall result that several preconditions need to be met if CCS is to play a future role in significantly reducing CO_2 emissions in China:

- The time of the *commercial availability* of CCS in China may depend, on the one hand, on the successful implementation of CCS technology in industrialised countries. Current global and regional studies [13,23,74,94,95] do not expect CCS to be applied in China before 2030 in an appreciable way either. In addition, a number of modelling studies expect the substantial deployment of CCS to take place as early as in the 2030s [12,94]. These results conflict with those generated by other models, which state that the "window of opportunity for its deployment is limited to the near- to mid-term future", making a quick phase-in necessary to contribute to short-term mitigation as long as other low-carbon options are economically inadequate [8]. On the other hand, if recent developments in China's climate policy are considered, CCS may play a much more important role in China in the future. This could lead to an earlier commercial availability of the whole CCS chain

than previously assumed. However, complex legal and regulatory aspects, such as property issues related to the land above CO_2 storage sites or responsibilities for ensuring long-term safety along the full chain of CCS systems, would have to be settled first.

- From our point of view, the most crucial requirement for being able to derive a long-term CCS strategy for China is a reliable *storage capacity assessment* for the country. Most of the analysed publications on CCS in China take sufficient storage potential for granted or refer to literature sources that suggest a large effective storage capacity [32]. In contrast, the present analysis shows the high uncertainty inherent in existing storage capacity assessments, thus confirming the lack of knowledge, also stated in [11,25]. This would have direct implications on the results given in the scenario analyses and roadmaps, since large-scale CCS would become more difficult and costly [96]. As a general rule, due to the lack of detailed and reliable geological data, any calculations of storage capacity in China can only be highly speculative and should therefore be viewed with caution. If very optimistic assumptions (high efficiency factors) are applied, 192 Gt of CO_2 could be stored as a result of the matching process. If a cautious approach is taken (efficiency factor of 2%), this amount is reduced to 29 Gt of CO_2 because insufficient space is available for emission clusters in several administrative divisions. In addition, if storage is limited to onshore basins for reasons of expense and technology, the matched capacity is reduced further, meaning that a large quantity of emissions from industrial centres on China's coast could not be stored. In practice, this *effective* potential will decrease further with the impact of technical, legal, economic and social acceptance factors. Our study mainly differs to existing source-sink matching studies [34,97] in that we used coal development pathways based on long-term energy scenarios up to 2050; we applied different efficiency factors derived from existing site-specific storage capacity calculations; and we based our match on emissions at the administrative division level.

- Hence, in the future, more in-depth assessments of the country's effective and matched storage potentials are required, as also suggested by [98,99]. Based on such assessments, an optimisation model could be applied to the whole country, as performed in the past for single regions [98,100]. The overall aim should be to identify cost-optimal sites for CCS power plants, taking into account the transportation costs of electricity, coal and the separated CO_2 emissions. In addition to technical, social and economic issues [98], such a model should also involve ecological issues such as the availability of cooling water. The significant increase in water consumption, the lack of cooling water and the treatment of extra waste water are considered critical issues in the operation of coal-fired steam power plants in water-scarce regions [9,11,101,102].

- The *economic assessment* reveals a significant barrier to achieving the economic viability of CCS in China under current conditions, making policy incentives a crucial precondition for CCS commercialisation. However, due to lower plant capital costs, the cost penalty in China is significantly lower than in industrialised countries or other emerging economies. Introducing a carbon price could therefore significantly improve the competitiveness of CCS plants over non-CCS plants and outweigh the cost penalty of CCS plants. However, the stimulating economic framework conditions in China may be offset in the decades ahead as Chinese labour and equipment costs are expected to increase steadily. Bearing in mind that the share of imported coal could grow in the future, the future development of the coal markets should be observed carefully with regard to possible implications for China's energy security

- The findings of the *prospective LCA* comply with results of earlier studies [103–105], but yield conflicting results. Firstly, the total GHG emissions per unit of electricity output are considerably reduced. However, the reduction rate over the whole life cycle of only 59 to 60% may call into question the benefits of the huge investments that would be required for the deployment of a comprehensive CCS infrastructure in China. This rate is 14 percentage points lower than that calculated for India [6], mainly due to high coalbed methane emissions. Furthermore, it is presumed here that there would be no leakages at the storage sites. This is somewhat optimistic, not only taking into account the fact that considerable technology advancements on monitoring and modelling CO_2 long-term storage safety would be necessary [106]. The assumption of some leakage over time could significantly change the balance of CO_2 emissions. Secondly, most other environmental and social impacts of coal-fired power plants would increase with the use of CCS. Due to the additional primary energy demands of CCS, further environmental and social issues that were not included in our LCA will also increase (for example, air quality, noise, mine waste, health risks, displacement and resettlement). Thirdly, the development of scrubbing technology was only considered in terms of decreasing efficiency losses. If more environmentally benign technologies entered the market, the results of the prospective LCA could change due to different upstream processes. Finally, an LCA does not include a risk analysis, which would have to cover the risks of transporting and storing CO_2 or health risks due to additional coal mining.

- As [8] also emphasises, *strong advocates* for CCS from government and business would be needed to establish optimal conditions for a prominent development of CCS in China. A wide range of stakeholders are currently working on CCS and fostering the technology's demonstration and development. The industry seems to be able to build most parts of a

power plant with CO_2 capture equipment based on Chinese technologies, meaning that China could potentially benefit from future export opportunities for CO_2 capture technologies.

- Last but not least, it should be pointed out that a long-term roadmap of CCS in China's industry could refine our source-sink match by including separated CO_2 emissions from cement, iron and steel industries as well as non-power gasification-based coal to the oil, gas and chemicals sector [9]. Since only 12 to 69% of the effective storage capacities is used, even in pathway *E1: high* (Table 4), a considerable amount of industrial CO_2 emissions could additionally be stored. A rough calculation by the authors revealed that additional CO_2 emissions from industry would only slightly increase the share of theoretical storage capacity used, but would not alter the results fundamentally [49]. This is supported by results from [107], which estimates that 446 and 937 Mt of CO_2 may be separated in the cement, iron and steel, and chemicals industries by 2050 and 2095, respectively. These amounts would equal less than 1.5% of the available effective storage capacity in the low storage scenario S3. Besides capturing CO_2, the analysis of the potentials and constraints of CO_2 usage in both the industry and for EOR and EGR would complement such a roadmap.

5 Conclusions and outlook

China, the biggest emerging economy, is experiencing a rapidly growing demand for energy. Although the deployment of renewable energies is growing strongly, most experts expect a striking dominance of coal-fired power generation in the country's electricity sector, even if the recent trend towards flattened the deployment of coal capacity and reduced annual growth rates of coal-fired generation proves to be true in the future. In order to reduce fossil fuel-related CO_2 emissions to a level that would be consistent with the long-term target of the international community to which China is increasingly committing itself, this option would require the introduction of CCS. However, a precondition for opting for CCS would be finding robust solutions to the constraints highlighted in this article. In this connection, it should be noted that our findings are subject to a number of highly uncertain assumptions and data. Although the most relevant parameters were varied via a sensitivity analysis, our analysis should be extended as soon as more precise data becomes available in the different assessment dimensions.

Furthermore, it needs to be taken into account that CCS plants will face strong competition from other low-carbon technologies, especially renewable energy technologies. Thus, CCS plants would need to be compared with other low-carbon technology options to draw fully valid conclusions on the economic, ecological and social viability of CCS in a low-carbon

policy environment. Most renewable energy technologies, for example, indicate much higher learning rates than those expected for supercritical PC plants with CCS. Such a comparative analysis was previously conducted for Germany [38]. It might be extended by weighting all the dimensions considered, for example, by applying a multi-criteria analysis involving different stakeholder groups.

Finally, in our opinion a set of different assessment dimensions (those considered here plus others such as risk assessment, public welfare, acceptance, technology innovation and management efforts as considered in [8,10,29,106]) should be integrated into macro-economic optimisation models. Such models usually aim to provide the lowest cost options of different scenarios for achieving long-term mitigation goals. However, these models lack the integration of qualitative issues. This means that they risk drawing incorrect conclusions for policy-makers if CCS is presented as the most cost-effective technology option whilst neglecting important issues that could hinder implementation or make it difficult, yielding higher costs than initially calculated. However, this task involves a great deal of methodological challenges. Furthermore, the role of CCS in the electricity sector needs to be assessed with models with a high time resolution in order to account for the difference between CCS and stochastic renewables in terms of power supply security and stability. First of all, work on the flexible operation of CCS power plants [108,109] should be extended to obtain a complete picture of the possible role played by CCS in an integrated energy system.

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