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Ronald G. Prinn and John M. Reilly,
Program Co-Directors

For more information, contact the Program office:
MIT Joint Program on the Science and Policy of Global Change

Postal Address:
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139 (USA)

Location:
Building E19, Room 411
400 Main Street, Cambridge

Access:
Tel: (617) 253-7492
Fax: (617) 253-9845
Email: ***globalchange@mit.edu***
Website: ***http://globalchange.mit.edu/***

The Impact of Climate Policy on Carbon Capture and Storage Deployment in China

Xiaohan Zhang[*], Tianyu Qi[*], and Xiliang Zhang[*†]

Abstract

Carbon capture and storage (CCS) from coal combustion is widely viewed as an important approach for China's carbon dioxide (CO_2) emission mitigation, but the pace of its development is still fairly slow. In addition to the technological and economic uncertainties of CCS, lack of strong policy incentive is another main reason for the wide gap between early expectations and the actual progress towards its demonstration and commercialization. China's mitigation scenario and targets are crucial to long-term development of CCS. In this research, impacts of CCS on energy and CO_2 emissions are evaluated under two mitigation scenarios reflecting different policy effort levels for China using the China-in-Global Energy Model (C-GEM). Results indicate that with CCS applications in the power sector China can achieve an added emissions reduction of 0.3 to 0.6 Gigatons CO_2 ($GtCO_2$) in 2050 at the same level of carbon taxes respectively in the two mitigation scenarios. Under the more ambitious mitigation scenario, approximately 56% of China's fossil fuel-fired power plants will have CCS installed, and CO_2 emission amounting to 1.4 $GtCO_2$ will be captured in 2050. A carbon price not lower than \$35/tCO_2 appears to be necessary for the large-scale application of CCS in the power sector, indicating the vital role of policy in the deployment of CCS in China's power sector.

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[*] 3E Institute, Tsinghua University, Beijing, China, 100084.

[†] Corresponding author (email: xh-zhang13@mails.tsinghua.edu.cn).

1. INTRODUCTION

As a result of rapid economic growth powered by a coal-intensive energy mix, China is now the largest contributing nation to global carbon dioxide (CO_2) emissions. Achieving de-carbonization while producing more energy and maintaining economic growth is a challenge that could be addressed by a number of clean energy solutions (e.g. energy efficiency and demand management measures; renewables and other low-carbon energy sources). One potential solution is to continue using fossil fuels with carbon capture and storage (CCS). Though China has strong incentives for the implementation of energy efficiency as well as renewable and other low-carbon technologies, coal is likely to remain a substantial part of China's energy mix for the foreseeable future. Therefore, for China to achieve its long-term climate change mitigation goals, solutions such as CCS should also be considered alongside other options. Indeed, CCS could potentially offer a cost-effective low carbon solution that would allow continued use of coal, not only in China, but across the globe.

Many view the development of CCS as imperative for global climate stabilization, yet the costs of the technology remain high. CCS is currently the only known but still pre-commercial technology that can cut CO_2 emissions from fossil fuel-fired power plants by 80%–90%. Although ongoing CCS projects in China have shown progress, the pace remains slow, and some technical problems still remain unsolved. Barriers such as high capital cost, technological uncertainty, and a significant energy penalty associated with operation are limiting the development of CCS around the world. Alongside these technical problems, CCS also suffers from insufficient support from policymakers and the general public.

As a "high investment" technology, CCS will only continue to develop with strong and stable policy incentives, such as a meaningful price on CO_2. CCS proponents have argued that there is too much policy uncertainty to support a business case for large-scale CCS projects, which incur large capital costs and a long development cycle. As such, China's targets for CO_2 reduction and policy designs for implementing them are crucial to the long-term development of CCS.

In this study, we evaluate scenarios of CCS application under different global and national emission reduction goals. Specifically, we simulate the impact of these policy goals on CO_2 emissions reductions, fuel switching, and the economic growth of CCS under different scenarios. The remainder of this report is organized as follows. Section 2 reviews China's current supporting policies for the development and deployment of CCS and summarizes policies and regulations that are crucial to CCS development. Section 3 describes the energy economic model developed for investigating impacts of low-carbon policies on the development of CCS and the impact of CCS on the economy and CO_2 emissions. Section 4 focuses on scenario analysis, where scenarios are described in detail and the results are discussed. Section 5 summarizes the report.

2. POLICY REVIEW

Currently, CCS is only operable on a demonstration scale. Since the technology is pre-commercial, policy and regulation will play an essential role in enabling the continued development of CCS. This section reviews the current state of policy, legal and regulatory, affecting the demonstration and deployment of CCS in China. Policies related to the deployment of renewable energy and energy efficiency are also discussed, including their impact on the development and the deployment of CCS. Policy support for CCS, international cooperation efforts, and CCS demonstration projects are reviewed in this section as well.

2.1 Climate Change Mitigation in China: Current Efforts and Future Trends

China pledged to control its growing CO_2 emissions at the Copenhagen Climate Summit in 2009. The pledge has not only contributed to achieving the overall Copenhagen Climate Agreement, but also initiated substantial domestic efforts within China to promote a sustainable energy system transformation. China's pledge in Copenhagen consisted of two elements. One was to reduce its carbon intensity by 40–45% by 2020 compared to 2005 levels. The other was to generate at least 15% of primary energy from non-fossil energy sources by 2020.

China set a mandatory target of reducing its energy intensity by 20% over the Eleventh Five-Year Plan (2005–2010). In order to meet its Copenhagen pledge, China's Twelfth Five-Year Plan (2011–2015) included two new targets: to reduce the CO_2 intensity of the Chinese economy by 17%, and to increase its non-fossil energy share to 11.4% by 2015. China has adopted a set of measures to achieve these targets. Among others, major measures include disaggregating the national carbon intensity target by province, government-enterprise energy conservation agreements, forcing retirement of small-sized power plants and obsolete production capacities in the energy-intensive sectors (e.g. steel and cement), enhancement of energy efficiency standards, energy conservation allowance schemes, investment subsidies for energy conservation projects, and a renewable electricity feed-in tariff.

Thanks to the implementation of these measures, China's carbon intensity has declined by approximately 21% from 2005 to 2010. Absolute CO_2 emissions, however, grew by approximately 34% during the same period, reaching 7217 Mt in 2010. China's coal consumption climbed to 2409 million tons of coal equivalent (mtce) in 2012, which was approximately 67% of that year's total energy consumption—an increase of 44% above 2005 levels. China's air pollution has recently increased due to the increased use of fossil fuels, particularly the use of coal. Several cities in Northern China and the lower reaches of Yangtze River have suffered unprecedented haze in recent years. The air pollution index (API) of Beijing, China's capital city, exceeded the daily recommended pollution level for 83.4% of the days in January 2013. The API of Shanghai, China's biggest economic and business city, exceeded the recommended level for 74.2% of the days in December 2013. Haze has become a large hazard to the residents of these cities. Environmental concerns alone are an urgent reason for China to take more aggressive efforts to accelerate its energy system transformation.

The Third Plenum of the Eighteenth Congress of the Chinese Communist Party was held in November 2013 in Beijing. The Third Plenum has established major new directions for reforming China's economic, political, and social system. Targets set at the Plenum include slower, but sustainable economic growth; a shift in the economic structure from investment towards consumption; and the development of an “ecological civilization.” The major measures to achieve the targets set by the Plenum include liberalizing energy prices, taxing energy-intensive and highly-polluting industries, levying taxes on resource inputs, and developing market-based approaches for protecting the environment such as a trading system for CO_2 emissions (ChinaDaily, 2013). Once implemented, these measurements could significantly foster the development of clean energy technology, and greatly impact the development of CCS in China.

2.2 Existing Efforts and Support to CCS in China

Continuous research and large-scale demonstrations are essential for CCS to mature. CCS-related technologies have been investigated in China, but are still far from the stage of standardization and full-scale demonstration.

2.2.1 Policy Making

China’s policy is supportive of CCS development efforts. In February of 2006, the State Council issued the “State Long-term Science and Technology Development Plan (2006–2020),” which included plans for “efficient, clean, and near-zero carbon emissions fossil energy utilization technology” into advanced energy technology. In June of 2007, the National Development and Reform Commission (NDRC) issued China’s National Climate Change Programme, which recommended “the development of carbon capture and storage technology” (NDRC, 2007). In June of 2007, the Ministry of Science and Technology (MOST), NDRC, and other ministries jointly issued a document entitled China’s Scientific and Technological Actions on Climate Change, which included CCS as an important part of its plan (MOST, 2007). In October of 2010, the Information Office of the State Council issued the white paper China’s Policies and Actions for Addressing Climate Change, which pointed out that “CCS is one of the greenhouse gas emissions reduction technologies that China will focus on investigating” (Information Office of the State Council, 2010). In the Twelfth Five-Year Science and Technology Development Plan released in July 2011, CCS are listed as key technologies to develop during the Twelfth Five-Year Plan period in both the “energy saving and environmental protection industry” section and the “combating climate change” section (MOST, 2011).

2.2.2 International Cooperation

Under the guidance and leadership of the MOST and other related government bodies, research institutions, universities, and enterprises have launched a wide range of technological communication and cooperation projects on CCS with similar institutions in Australia, Italy, Japan, and the United States. This international cooperation has led to the formation of a core research team on CCS in China. China has also started to investigate topics such as the choice of carbon capture technology, techno-economic evaluation, storage potential assessment, and source-sink matching. Major international CCS cooperation projects have included: a China-UK Cooperation on Near-Zero Emissions Coal (NZEC), Cooperation Action within CCS China-EU (COACH), Support to Regulatory Activities for Carbon Capture and Storage (STRACO2), Assessment of the Capacity for Geological Storage of Carbon Dioxide (Geo Capacity), China-Australia Geographic Storage (CAGS), Carbon Sequestration Leadership Forum (CSLF), U.S.-China Clean Energy Research Center (CERC), and Sino-Italy Cooperation on Clean Coal Technologies (SICCS). Those projects cover aspects of CSS such as development policy, capture technology, and storage assessment of CCS, and provide both financial and technological support for the development of CCS in China.

2.2.3 Research and Development (R&D)

A National Science and Technology key project involved conducting research on CCS. Since the Tenth Five-Year Plan, the National Basic Research (973) and the National High-Tech Development (863) Program, as well as the National Science and Technology Support Program and other science projects of China have started R&D and demonstration of the CO_2 emissions reduction potential, CO_2 capture, biological utilization of CO_2, CO_2-EOR (enhanced oil recovery), and geological storage. They have also designed different capture technology options, and different options for CO_2 utilization and transformation. The National Science and Technology key project "Large Oil and Gas Fields and Coal-bed Methane Recovery Project" involves R&D and demonstration projects of CO_2-EOR and enhanced coal bed methane (ECBM) recovery technologies.

2.2.4 Demonstration Projects

The Chinese government has supported studies, technology research, and pilot CCS projects in cooperation with bilateral and multilateral development partners. Nine pilot projects were operational by 2011, providing information for CCS demonstration studies and investigation. CCS demonstrations have been included as one of the most important actions in the National Program on Climate Change (NPCC). Studies, reports, and road maps by various government agencies, research centers, and energy companies have been published, yet China is still waiting for its first large-scale CCS demonstration project.

CCS demonstration projects are mainly in the electricity sector, which generates the most CO_2 and has fixed sources. The coal-to-chemicals industry is also an important industry for CCS demonstration. Deployment of CCS in the coal-to-chemicals industry has huge potential because of the large number of coal-to-chemicals enterprises in China and the low energy penalty of the capture process due to the high concentration of CO_2. Several 10,000-ton CO_2 capture demonstration units have been built in recent years, with a maximum capture capacity of more than 100,000 tons/year. CO_2-EOR pilot projects were started, with the biggest single project sequestering approximately 167,000 tons of CO_2. A 100,000-ton CO_2/year saline aquifer storage demonstration project and a 40,000-ton CO_2 capture and EOR coal power plant demonstration are also ongoing.

The development of CCS has generated controversy. Major worries include technology reliability, energy penalty, economic feasibility, and risk of CO_2 leakage. Barriers to the development of CCS in China include high cost, immature technology, lack of capital, market risks, and environmental impacts.

2.3 Development of CCS in the Twelfth Five-Year Plan

China continues to signal a strong policy commitment to the reduction of national carbon and energy intensity, with CCS being increasingly recognized as an important technology for realizing this ambition. In late 2012, the Administrative Centre for China's Agenda 21, together with the CSLF and the Chinese Ministry of Science and Technology (MOST), hosted a workshop dedicated to the design of CCS legal and regulatory frameworks. The workshop, held in Beijing, addressed a range of issues and regulatory models and reached several conclusions about the role of law and regulation for CCS in China. In particular, the workshop determined a clear need to develop further programs of study and to continue working with international organizations to consider the policy, legal, and regulatory frameworks necessary for the technology.

China's Ministry of Science and Technology issued a plan for CCS as part of the Twelfth Five-Year Plan, which included several overarching goals: a breakthrough in key CCS theories and technologies, which would significantly lower the cost and energy penalty; the ability to design million-ton level CCS systems; construction of CCS system research and innovation platforms; and the completion of 300,000–500,000 tons/year CCS demonstration systems.

In April 2013, NDRC released a Notice entitled Promoting Carbon Capture, Utilization and Storage Pilot and Demonstration, which highlighted several near-term tasks needed to assist in the promotion of CCS pilot and demonstration plants in China. One of the key tasks identified in the document is the promotion of CCS standards and regulation to "strengthen the impact assessment of CCS, assess the health, safety and environment impacts, strengthen long-term security, environmental risk assessment and control, and build up and improve related safety standards and a system of environmental regulations."

3. THE CHINA-IN-GLOBAL ENERGY MODEL (C-GEM)

3.1 Overview

This research is conducted using the China-in-Global Energy Model (C-GEM) (Qi *et al.,* 2014). C-GEM is a recursive-dynamic computable general equilibrium (CGE) model representing 20 sectors and 19 regions separately in the world economy, as demonstrated in **Table 1** and **Figure 1**. The data that C-GEM employs is based on version 8 of the Global Trade Analysis Project (GTAP) database. As an energy economic model focusing on China, C-GEM applies China's official economy and energy statistical data in order to have a more accurate representation of the economy. Introduction of a new technology like CCS and/or a different carbon price could bring changes to the whole economy, and a CGE model like C-GEM is an appropriate tool to analyze the related impacts through a comprehensive perspective.

3.2 Detailed Representation of CCS in the Model

For this study, a detailed representation of CCS for the energy supply sector is designed for C-GEM, as shown in **Figure 2**. In the model, the cost of transmission and distribution and that of generation and sequestration are separately described in the CES nested structure. This separate representation allows for greater flexibility in the production structure. In scenarios where carbon emissions are taxed or limited by policy, carbon permits required when CCS is used enter in a CES nest with generation and sequestration. The base capture rate is 90%. The capture rate is parameterized by a variable that is allowed to increase with the carbon permit price. Specifically, the substitution between the carbon permit input and sequestration allows deployment of additional capital and labor to reduce the required input of carbon permits, resulting in a higher percentage of

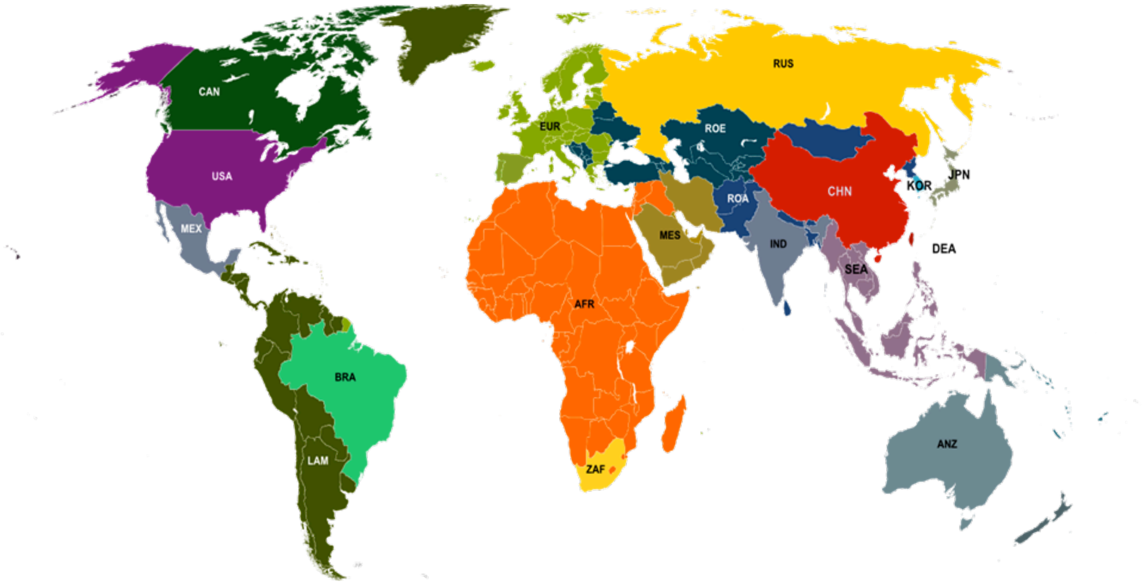

Figure 1. Regions in the C-GEM.

Table 1. Sectors in the C-GEM.

Type	Sector	Description
Agriculture	CROP	Crops
	FORS	Forest
	LIVE	Livestock
Energy	COAL	Mining and agglomeration of hard coal, lignite and peat
	OIL	Extraction of petroleum
	GAS	Extraction of natural gas
	ROIL	Refined oil and petro chemistry product, coke production
	ELEC	Electricity production, collection and distribution
Energy-Intensive Industry	NMM	Cement, plaster, lime, gravel, concrete
	I&S	Manufacture and casting of basic iron and steel
	NFM	Production and casting of copper, aluminum, zinc, lead, gold, and silver
	CRP	Basic chemicals, other chemical products, rubber and plastics products
	FMP	Sheet metal products (except machinery and equipment)
Other Production	FOOD	Manufacture of foods and tobacco
	MINE	Mining of metal ores, uranium, gems, other mining and quarrying
	EQUT	Electronic equipment, other machinery and equipment
	CNS	Construction
	OTHR	Other industries
Services	TRAN	Water, air and land transport, pipeline transport
	SERV	Communication, finance, public service, dwellings and other services

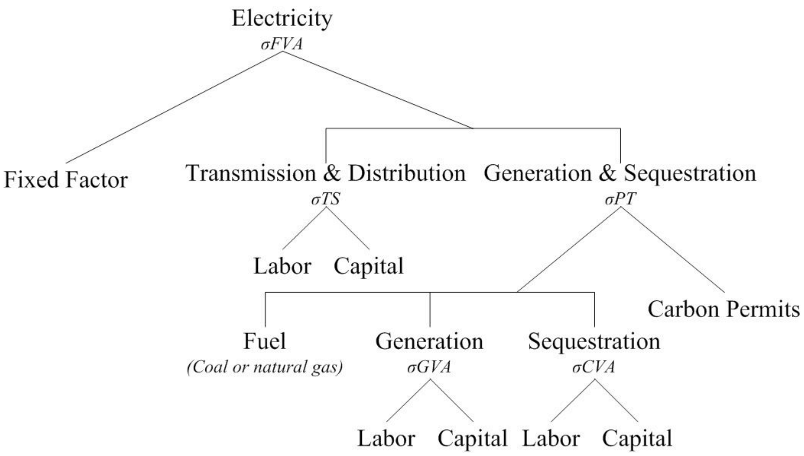

Figure 2. CES production structure for CCS.

CO_2 captured. The penetration rate of CCS is further controlled by a technology-specific factor at the top level of the nested structure, similar to other backstop technologies.

Since C-GEM is an economic model, it is difficult to include an exhaustive representation of technological options in the same way that detailed sector- or technology-specific models do, because adding highly-resolved technological detail across all sectors would require a substantial data collection effort and decrease computational tractability, without vastly improving the insightfulness of the results. Thus, C-GEM only provides representation of CCS as one technology, and does not divide into specific technologies such as post-combustion, oxy-fuel or pre-combustion. Here, we use Integrated Gasification Combined Cycle (IGCC) with pre-combustion CCS to represent CCS in the energy supply sector.

New technologies (backstop technologies) do not enter the market under current economic conditions. The higher cost of new technologies is represented by a cost markup factor, which indicates the ratio of backstop technology costs to conventional production technologies. Each electricity technology as well as biofuels has an estimated markup factor. For CCS, the markup factor is calculated and calibrated using the data in Section 3.3. The input structure of a backstop technology is also required input in the model, which is also generated from the data in Section 3.3.

3.3 Calibration of CCS Parameters

3.3.1 CCS Cost Review

The CCS-related parameters applied in the China region of the model are calibrated according to firsthand data from China. Carbon capture is estimated to account for around 70% of the total cost of CCS. We conducted a detailed review of CCS cost estimation based on the existing literature, comparing the elements of cost structures, estimation methodologies, model assumptions, and results across studies (see summary in **Table 2**). Capture costs reported in China are about half of some costs reported in OECD countries, mainly due to lower labor and location-related costs. According to the estimates, the cost of CO_2 avoided ranges from nearly 140 RMB/ton to over 300 RMB/ton, and the markup factor of CCS ranges from 1.35 to 1.93.

Table 2. Cost Analysis of Carbon Dioxide Capture in China.

Author	*Huang et al. (2010)*	*Xiong et al. (2009)*	*Xiong et al. (2009)*	*Yan et al. (2008)*	*Wang et al. (2010)*	*NZEC (2009)*	*NZEC (2009)*	*NZEC (2009)*	*NZEC (2009)*	*NZEC (2009)*
Ref. Year	2008				2008	2009	2009	2009	2009	2009
Fuel Price		$2/GJ	$2/GJ			￥16/GJ	￥16/GJ	￥16/GJ	￥16/GJ	￥16/GJ
Plant Life				20 years	30 years	25 years	25 years	25 years	25 years	25 years
Construction Time					3 years	3 years	3 years	3 years	3 years	3 years
Reference Plant										
Technology	Subcritical	Subcritical	Subcritical		Subcritical	Supercritical	Subcritical	Ultra-supercritical	IGCC	Poly-generation
Capacity	845MW/4	297.44MW	297.44MW		558MW	574.1MW	295.1MW	824.3MW		
Efficiency	295 g/kWh				5632t/ d	40.28%	38.15%	43.9%		
Utilization Hours		8000	8000	5500	6000	85%	85%	85%		
CO_2 Emissions	0.95 kg/kWh	281.8t/h	281.8t/h		0.80 kg/kWh	868.2 g/kWh	916.6 g/kWh	796.6 g/kWh		
Capture Plant										
Capture Technology	MEA	Oxy-fuel combustion	MEA	15%MEA Membrane contactor	Oxy-fuel combustion	MEA	MEA	Oxy-fuel combustion	Pre-combustion	Pre-combustion
Power Output		232.94MW	245.96MW		438.53MW	398.1MW	202.5MW	672.5MW	661.7MW	398.2MW+310 kt methanol/a
Capture Rate	85%	90%	90%		90%	90%	90%	90%	90%	86.4%
CO_2 Emissions		28.18t/h	28.18t/h		0.23 kg/kWh	125.5g/kWh	133.6 g/kWh	98.2 g/kWh	95.44 g/kWh	196 g/kWh
CO_2 Captured	0.65t/h				5685.04 t/d	1126.9g/kWh	1202.6 g/kWh	884.1 g/kWh	859 g/kWh	1375.4 g/kWh
CO_2 Pressure	1.4 bar					11MPa	11MPa	11MPa		
Economic Analysis										
Cost w/o CO_2 Capture		$28.86/MWh	$28.86/MWh		$47.34/MWh	￥270.1/MWh	￥283.1/MWh	￥271.3/MWh		
Cost w/ CO_2 Capture		$45.862/MWh	$49.049/MWh		$63.80/MWh	￥512.4/MWh	￥545.2/MWh	￥368.9/MWh	￥412.5/MWh	￥453/MWh
Cost Increase	￥0.139 /kWh									
Cost of CO_2 Avoided		$20.572/t	$24.241/t		$28.93/t	￥326.2 /t	￥334.7/t	￥139.7/t	￥201.4/t	￥302.5/t
Capture Cost	￥170/t (O&M only)			￥137.6/t (Capture only)						

The cost of CO_2 transportation is largely known and understood from practical experience over the years. Both top-down and bottom-up models are able to produce cost estimates of CO_2 transportation. Unlike the cost of CO_2 capture, the cost of CO_2 transportation has more consistent cost elements across different studies, yet it only takes up a small proportion of the total cost of CCS.

The cost of CO_2 storage estimated by different studies also varies vastly, ranging from EUR 1/tCO_2 to EUR 20/tCO_2 (GCCSI, 2011),[1] due to different site types and sizes, uncertainty and variability of geophysical characterization of certain site types, and large regional variances, among other factors.

3.3.2 Calibration of CCS Cost

As shown, literatures give diverging estimations of the cost of CCS. To ensure the accuracy of projections and consistency among the work packages, we collaborated with the Institute of Engineering Thermal Physics at the Chinese Academy of Sciences to calibrate the technology-related parameters of CCS represented in the model, as shown in **Table 3**. In this C-GEM calculation, the markup factor of CCS is assumed to be 1.4.

Table 3. The calibrated cost of CCS used in the C-GEM model.

	IGCC (/kWh)	**IGCC Capturing CO_2 (/kWh)**
Capital ($/kW)	2200	2950
Efficiency	0.46	0.38
Operating Cost Coefficient	0.04	0.04
Fuel Price (￥/kg)	0.6	0.6
Calorific Value of Coal (MJ/kg)	26.71	26.71
Annual Operating Time Ratio	0.68	0.68
Plant Life	30	30
Total Electricity Generated (kWh)	178704	178704
Coal Consumption (kg)	52360.7	63383.9
Equipment Cost ($/KW)	13860	18585
Fuel Cost	31416	38030
Capital	54636	73262
Labor	16632	22302
Cost per kWh / per MJ		
Equipment Cost	0.078	0.104
Fuel Cost	0.176	0.213
Capital	0.306	0.410
Labor	0.093	0.125
CO_2 Emissions (kg/kWh)	0.85	0.05
Total Cost (￥/kWh)	0.652	0.852
Cost Structure		
Equipment Cost	0.119	0.122
Fuel Cost	0.270	0.250
Capital	0.469	0.481
Labor	0.143	0.147
Share of Transport & Storage Cost	--	20%

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[1] Average exchange rate of Euro to United States Dollar in 2011 is 1.3920.

4. CCS DEPLOYMENT IN CHINA: SCENARIO ANALYSIS

In this section, we show how we applied the established C-GEM in order to evaluate CCS application scenarios, taking into account different national emission reduction efforts. Section 4.1 describes scenarios and macro-economic assumptions, and Section 4.2 discusses CCS impacts on emissions, energy, and economic outcomes in different scenarios.

4.1 Scenario Descriptions

To illustrate China's possible long-term emission reduction pathways, we designed three scenarios—S1, S2A, and S2B—each to reflect different levels of policy efforts. To assess the impact of CCS, each of the three scenarios is simulated with and without CCS availability. Abbreviations for each simulation are shown in **Table 4**. The key assumptions of S1, S2A, and S2B are shown in **Table 5**.

Table 4. Scenario design.

	S1	**S2A**	**S2B**
w/o CCS	S1-N	S2A-N	S2B-N
w/ CCS	S1-C	S2A-C	S2B-C

Table 5. Policy assumptions for S1, S2A, and S2B.

	S1	**S2A**	**S2B**
I. Low-Carbon Energy System Transformation Targets			
Carbon Intensity Reduction	17% during 2011–2015, 3% per annum 2016–2050	17% during 2011–2015, 4% per annum 2016–2050	17% during 2011–2015, 4% per annum 2016–2030, 4.5% per annum 2031–2050
II. Policy			
Carbon Tax	Explicit carbon tax. 16.0$/ton CO_2 in 2030, 33.5$/ton CO_2 in 2050	Explicit carbon tax. 35.0$/ton CO_2 in 2030, 94.5$/ton CO_2 in 2050	Explicit carbon tax. 35.0$/ton CO_2 in 2030, 112.0$/ton CO_2 in 2050
Fossil Resource Tax	Crude oil & natural gas: 7.5% of the price Coal: 10% of the price	Crude oil & natural gas: 7.5% of the price Coal: 10% of the price	Crude oil & natural gas: 7.5% of the price Coal: 10% of the price
Feed-in Tariff for Wind, Solar and Biomass Electricity	Higher surcharge rate on the electricity consumption to implement the policy	Higher surcharge rate on the electricity consumption to implement the policy	Higher surcharge rate on the electricity consumption to implement the policy
Hydro Resource Development Policy	Achieve existing target of 350 GW in 2020; slowly increase to economic potential of 400 GW by 2050.	Achieve existing target of 350 GW in 2020; slowly increase to economic potential of 400 GW by 2050.	Achieve existing target of 350 GW in 2020; slowly increase to economic potential of 400 GW by 2050.
Nuclear Power Development Policy	Achieve existing nuclear development planning target of 40 GW in 2015 and 58 GW in 2020; With projected plants sites availability of 450 GW.	Achieve existing nuclear development planning target of 40 GW in 2015 and 58 GW in 2020; With projected plants sites availability of 450 GW.	Achieve existing nuclear development planning target of 40 GW in 2015 and 58 GW in 2020; With projected plants sites availability of 450 GW.

S1: Annual Carbon Intensity of GDP Reduction by 3% from 2016 to 2050. The S1 scenario was developed to reflect China's existing efforts, which will lead to the achievement of China's Copenhagen commitment. As mentioned in Section 2.1, China made a pledge at the Copenhagen Climate Summit in 2009 to reduce its carbon intensity by 40–45% by 2020 compared to 2005 levels. By the end of the Eleventh Five-Year Plan (2010), China's carbon intensity had declined by approximately 21% compared to 2005 levels. As for the Twelfth Five-Year Plan, China has set a mandatory target for carbon intensity reduction by 17% by 2015, relative to 2010 levels. To meet the Copenhagen target, CO_2 intensity will need to decrease by 3% per annum during the Thirteenth Five-Year Plan (2016–2020). China is planning to achieve a 44% carbon intensity reduction from 2005 to 2020, which will meet the Copenhagen commitment of 40–45% carbon intensity reduction by 2020.

In this scenario, we assume that China will maintain its Copenhagen pledge momentum and will achieve a carbon intensity reduction rate of approximately 3% per year from 2016 through 2050. In this context, this scenario can largely be named a *Continued Effort* scenario. At the same time, we also assume that the Copenhagen non-fossil energy share commitment of 15% will be kept over the same period according to China's low-carbon transformation targets. Policies to achieve the above targets include 1) levying resource tax for fossil fuel energy consumption according to present tax rate; 2) fostering the development of hydro power, obtaining a 350 GW capacity by 2020 and a 400 GW capacity by 2050; 3) fostering the development of nuclear energy, obtaining a 58 GW capacity by 2020 and a 450 GW capacity by 2050; and 4) subsidizing renewable energy according to present level of a benchmarked electricity price by a renewable energy surcharge imposed on terminal electricity consumption. Also, there is an assumption of an increasing carbon tax—ensuring the annual carbon intensity reduction rate of 3% from 2016 to 2050, which will be US \$16.0/tCO_2 in 2030 and US \$33.5/tCO_2 in 2050.

S2A: Annual Carbon Intensity of GDP Reduction by 4% from 2016 to 2050. According to the joint announcement of national targets on limiting greenhouse gas emissions by China and the United States on November 12th, 2014, China committed to its CO_2 emissions peaking no later than 2030 and to increasing the share of energy consumption from non-fossil-fuel (zero-emission) energy sources to 20%, also by 2030. To achieve these commitments, our modeling work shows that China will need to reduce its carbon intensity by approximately 4% per year on average from 2016 to 2030. To achieve its domestic target for the Twelfth Five-Year Plan, China needs to achieve an annual carbon intensity reduction rate of 3%, so an annual reduction rate of 4% could be regarded as an *Accelerated Effort* scenario. Similar to S1, the policy assumptions of S2A include: 1) levying a resource tax on fossil fuel energy consumption according to present tax rate (an *ad valorem* tax of 7.5% of the price for oil and gas and 10% for coal); 2) fostering the development of hydro power, obtaining a 350 GW capacity by 2020 and a 400 GW capacity by 2050; 3) fostering the development of nuclear energy to obtain a 58 GW capacity by 2020 and a 450 GW capacity by 2050, and 4) imposing an electricity price surcharge to fund a feed-in tariff for renewable energy. The carbon tax under S2A is higher than that under

S1 to ensure the annual carbon intensity reduction rate of 4% from 2016 to 2050. The carbon tax rises to be US \$35.0/tCO_2 in 2030 and US \$94.5/tCO_2 in 2050.

S2B: Annual Carbon Intensity of GDP Reduction by 4% from 2016 to 2030 and by 4.5% from 2031 to 2050. To explore the possibility of further mitigating China's CO_2 emissions, we designed a more aggressive policy scenario and designated it S2B. With the U.S.–China Deal on Climate Change, China's CO_2 emission pathway becomes much more certain before 2030, and requires a 4% annual reductions in China's carbon intensity reduction rate. It is also widely accepted that the large-scale deployment of CCS, if it occurs, will not take place until after 2030. Compared with S1 and S2A, S2B can be regarded as another version of the *Accelerated Effort* scenario. With other policy assumptions the same as those under S1 and S2A, the carbon price simulated with the model under S2B will reach US \$35.0/tCO_2 in 2030 and US \$112.0/tCO_2 in 2050.

In these three policy scenarios with CCS, the technology is introduced without changing the carbon tax, which ensures the carbon intensity reduction target in the corresponding non-CCS scenarios.

4.2 Macroeconomic Assumptions

The population of China in 2010 was 1.34 billion. It is assumed that China's population will peak in 2030 with 1.43 billion, and fall to 1.36 billion by 2050, according to the medium fertility projection results of United Nations' report on World Population Prospects 2012, shown in **Table 6**.

The annual growth rate of labor productivity of China in 2010 was 11%, according to China's GDP growth rate in 2010. It is assumed on that basis that China's labor productivity growth rate will approach 2.5% per year—the projected labor productivity growth rate in developed countries—by 2050, at an average rate of 7% per annum. China's saving rate is projected to diminish from 48% in 2010 to 30% in 2050 based on Johansson *et al*. (2013). In C-GEM we employ the above saving rate projection as a scenario assumption. In the model, there is an assumption that China's GDP was \$4.69 trillion in 2010 and will be \$25.32 trillion in 2050 (in constant 2007 dollars), accounting for 8% of global GDP in 2010 and 15% in 2050 respectively, with an annual growth rate that decreases from 9.8% in 2010 to 2.9% in 2050.

Table 6. Population projection for China, 2010–2050, in billions.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
CHN	1.336	1.378	1.409	1.426	1.430	1.426	1.413	1.392	1.364

5. IMPACT OF CCS ON ENERGY AND CO_2 EMISSIONS IN DIFFERENT SCENARIOS

5.1 Impact on Emissions

Our analysis shows a remarkable change in the trajectory of CO_2 emissions under the *Accelerated Effort* scenarios compared to the *Continued Effort* scenario. Under Scenario S1 (*Continued Effort*), China's CO_2 emissions will keep increasing from 7.4 Gt in 2010 to 13.5 Gt in 2045 and then fall back to 13.4 Gt in 2050, following the Copenhagen pledge trajectory. Under the *Accelerated Effort* scenarios, however, China's CO_2 emissions will reach their peak earlier, at approximately 10.6 Gt in 2030, and begin to decline from then on. Under Scenario S2A, where the carbon intensity reduction continues to be 4% per annum, the carbon emissions in 2050 will be 9.0 Gt, and under Scenario S2B, where the carbon intensity reduction is 4.5% per annum from 2031 to 2050, the carbon emission in 2050 will be even less—around 8.1 Gt, as shown in **Figure 3**.

The results indicate that CCS plays an important role in emissions mitigation under the *Accelerated Effort* scenarios. In our analysis, CCS enters the market as a cost-effective technology after 2030 under Scenario S2B, and after 2035 under Scenario S2A. As shown in **Figure 4**, CCS will contribute a 0.6 $GtCO_2$ emissions reduction under S2A and a 1.4 $GtCO_2$ emissions reduction under S2B in 2050, respectively. Under S1, however, CCS will hardly play a role in CO_2 mitigation with a carbon tax lower than $35/$tCO_2$ since this tax provides insufficient incentives.

Shown in **Figure 5** are the total CO_2 emissions trajectories under *Accelerated Effort* scenarios (with and without CCS). Introducing CCS under Scenario S2A results in a 0.3 Gt emissions reduction addition in 2050. The emissions reduction when CCS is introduced under S2B is more significant: approximately 0.6 $GtCO_2$ emissions reductions would be added by 2050. This shows that CCS would become a more cost effective solution for China's long-term mitigation initiatives.

The share of fossil fuel-generated electricity produced with CCS is presented in **Figure 6**. In both *Accelerated Effort* scenarios, the share of fossil electricity produced with CCS increases after CCS enters the market. Under S2A, the amount of CCS electricity in total fossil electricity increases to 17.9% in 2050. The CCS electricity share in total fossil electricity under the S2B scenario during 2030 to 2050 also increases, faster than that under S2A. In 2050, under S2B, the share of CCS electricity in total fossil electricity reaches 56%, which is more than double that under S2A, indicating the crucial role of CCS in achieving an ambitious climate change mitigation target.

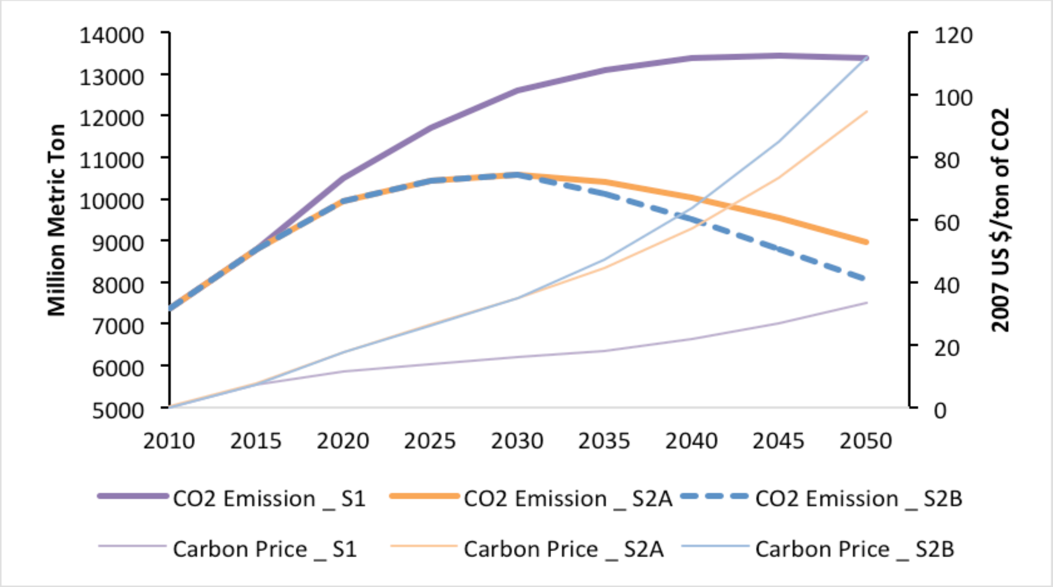

Figure 3. Trajectories of total CO_2 emission and carbon price.

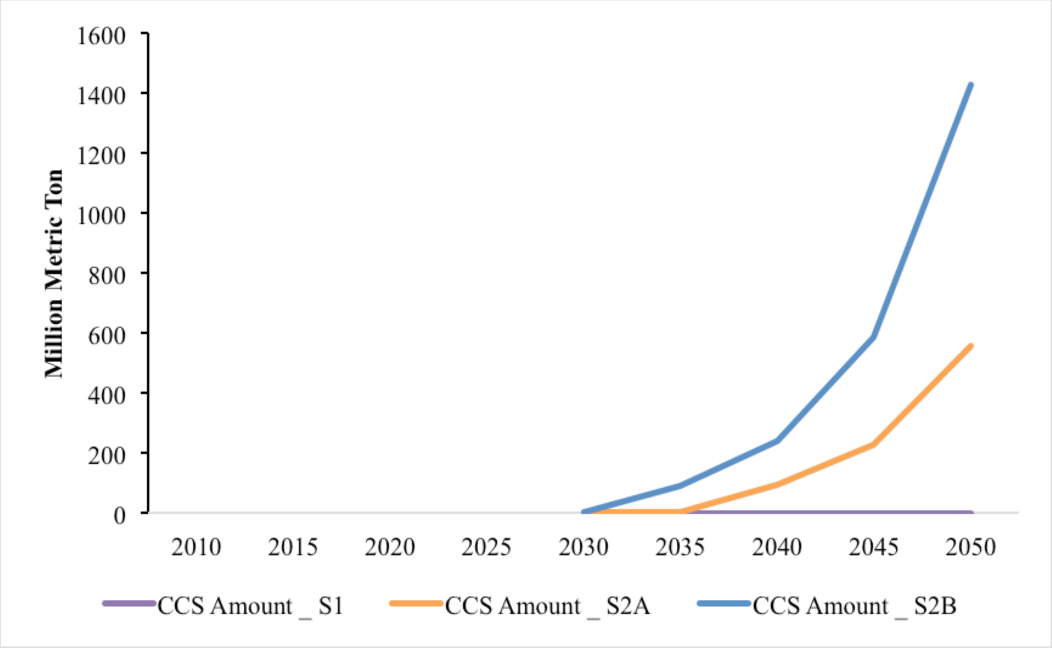

Figure 4. CO_2 emission reduction due to CCS.

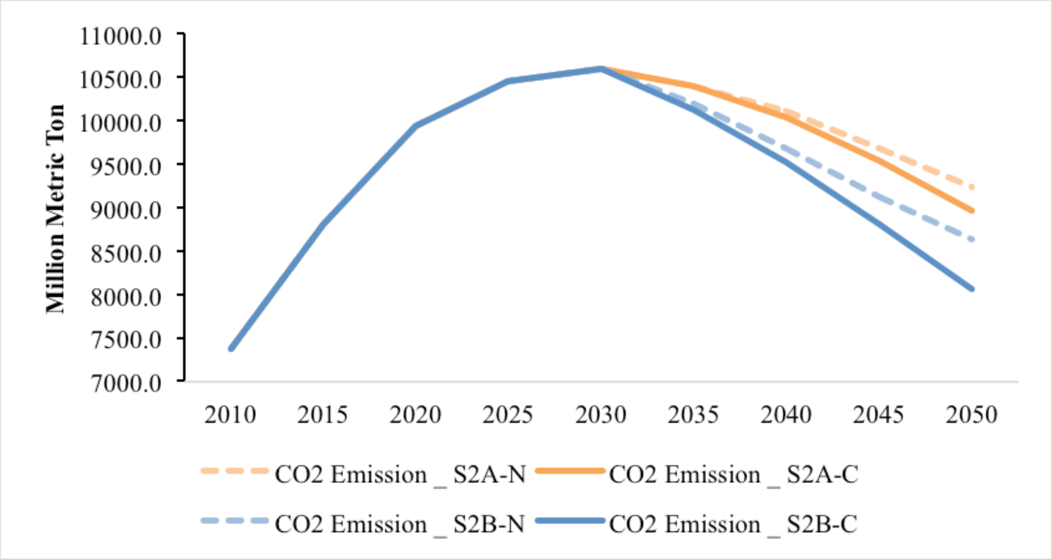

Figure 5. Total CO_2 emission in Scenarios S2A-N, S2A-C, S2B-N, and S2B-C.

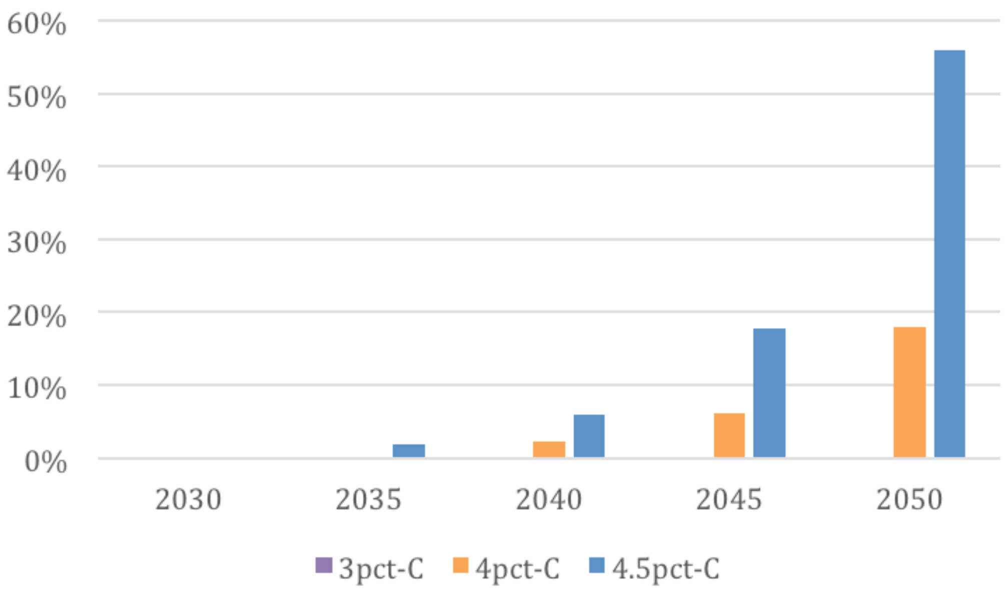

Figure 6. Share of electricity generated with CCS in total fossil electricity under Scenarios S1, S2A, and S2B.

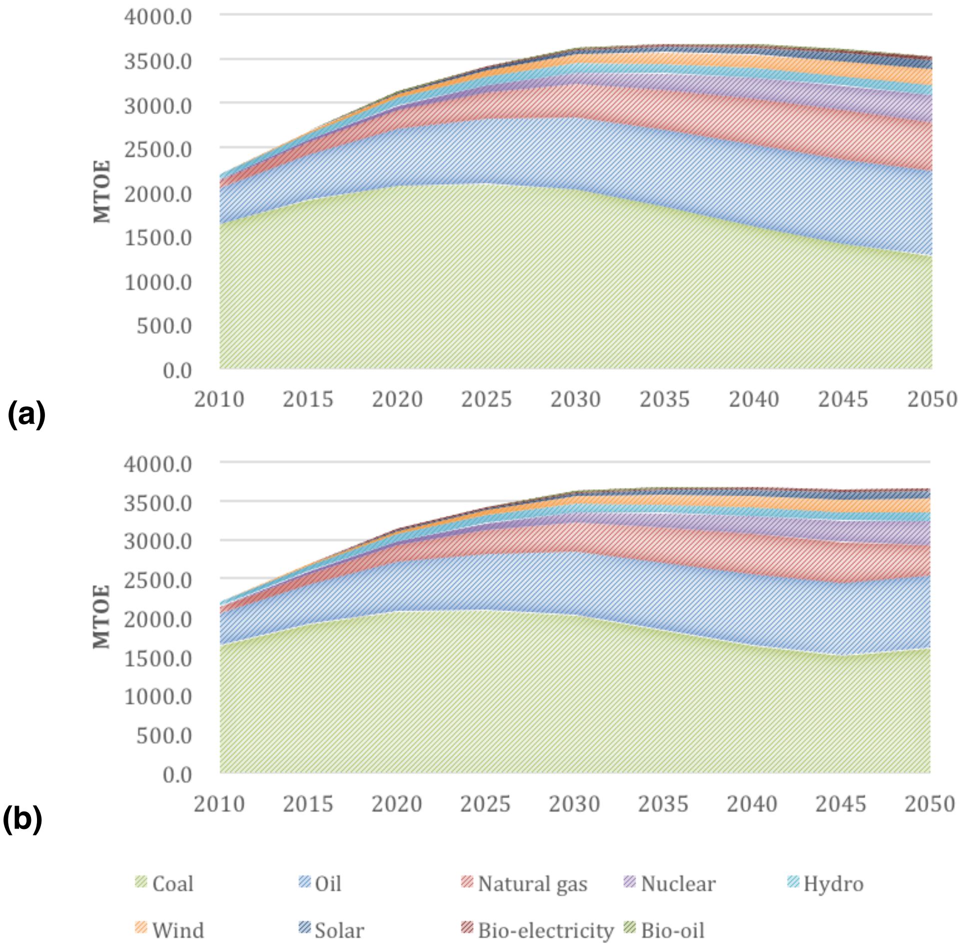

Figure 7. Primary energy structure from 2010 to 2050 in China under Scenario S2B (a) without and (b) with CCS.

5.2 Impact on Energy Supply

Deployment of CCS exerts an impact on energy supplies, especially the supply of coal. **Figure 7a** shows energy demand in case S2B-N. It shows that coal consumption would be well-controlled and will reach a peak during 2020-2025. **Figure 7b** shows the energy demand in case S2B-C. This has the same shape as **Figure 7a** before 2030, when there is no CCS deployment. The difference between the two scenarios occurs in the longer term, due to the introduction and deployment of CCS. In Scenario S2B-C, coal consumption in China would reach its peak during 2020–2025, with an amount of approximately 2.09 Gtoe, and would keep declining quickly after that peak year. After 2045, coal consumption rises back to 1.60 Gtoe with more CCS applications in place. Further, as shown in Figure 7b, the increased coal use will lead to a reduction in natural gas use, indicating that coal-fired power generation with CCS would be more competitive than natural gas fired power plants.

5.3 Economic Impact

Shown in **Figure 8** are China's GDP and GDP growth rate under S1. S1-N and S1-C have the exact same results because CCS does not emerge under S1-C. The emissions reduction measures would result in a GDP loss of around 3.2% in 2050 under S2B, compared with under S1. **Figure 9** demonstrates the GDP change relative to S1 in all S2 scenarios. As the results indicate, CCS contributes to China's economic development. Under S2B, GDP would be more than 0.1% higher with CCS compared to the situation in which CCS is not introduced.

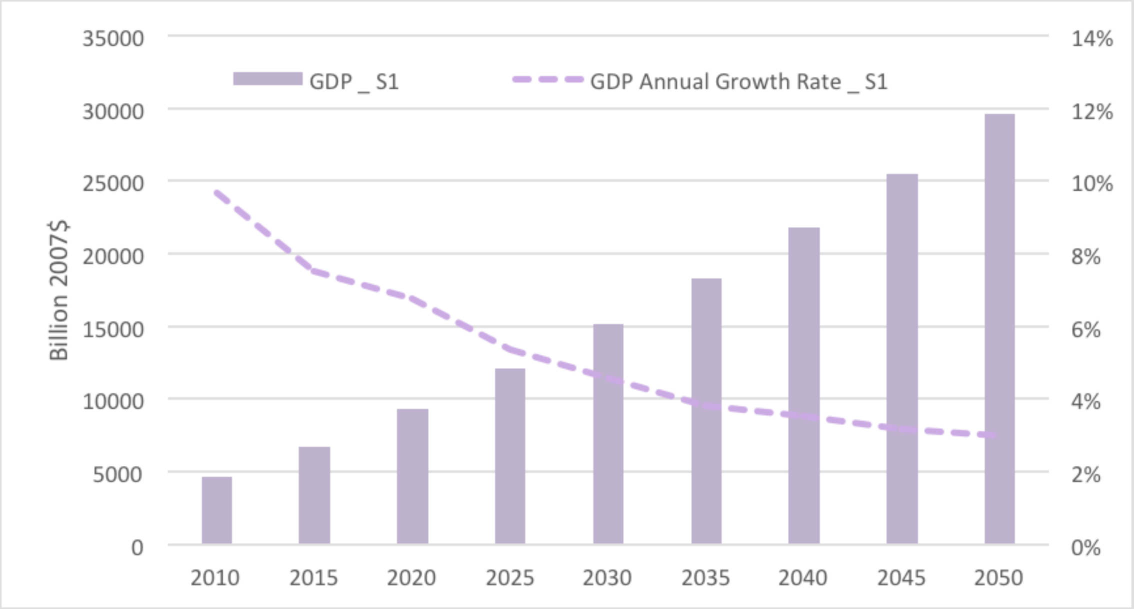

Figure 8. China's GDP and GDP annual growth rate 2010–2050 under S1.

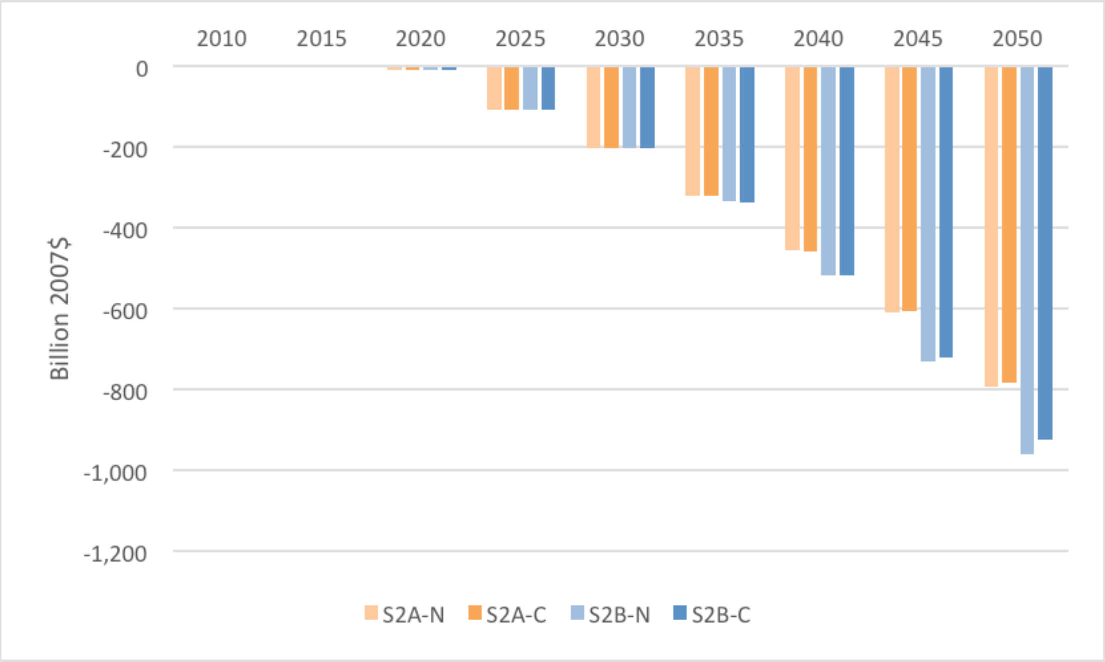

Figure 9. GDP change relative to S1 in S2A-N, S2A-C, S2B-N, S2B-C.

6. CONCLUSION

Carbon capture and storage (CCS) could become a cost-effective solution after 2030, and thus play an increasingly important role in China's long-term CO_2 mitigation initiatives. With CCS application in the power sector, China can achieve an added CO_2 emissions reduction of 0.6 Gt in 2050 if the carbon price from the *No CCS* case is applied. Approximately 56% of China's fossil fuel-fired power plants would have to install CCS to achieve a more aggressive low carbon transformation with a total captured CO_2 emission amounting to 1.4 Gt.

Compared to the *Continued Effort* scenario, the application of CCS in the power sector in the *Accelerated Effort* scenarios (S2A and S2B) could contribute significantly to CO_2 emissions reductions by 2050—approximately 13% and 27%, respectively. As Scenario S2B involved a more aggressive approach, this indicates that the more aggressive China's low carbon transformation is, the more CCS can contribute.

The introduction of a higher level of carbon tax would enable coal-fired power plants with CCS to be more cost effective than natural gas fired plants. This would lead to the occurrence of a substitution of coal for natural gas after 2040. This would not only bring new opportunities for coal use, but also suggests an improvement in China's energy security given that China's natural gas supply relies heavily on overseas markets.

The analysis shows that China's aggressive low carbon transformation will bring a GDP loss of approximately 3.1% and 3.2% in 2050 with and without CCS applications in the power sector, respectively. This indicates that CCS applications in the power sector could avoid a GDP loss of 0.1%.

Public policy, especially a carbon price, will play a vital role in the deployment of CCS in China's power sector. A carbon price not lower than $\$35/tCO_2$ appears to be necessary for the successful large-scale application of CCS in the power sector.

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