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People's Republic of China: Roadmap for Carbon Capture and Storage Demonstration and Deployment
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Component A–Work Package 5a Report: Opportunities for CCS Deployment in China under Low Carbon Transformation Scenarios

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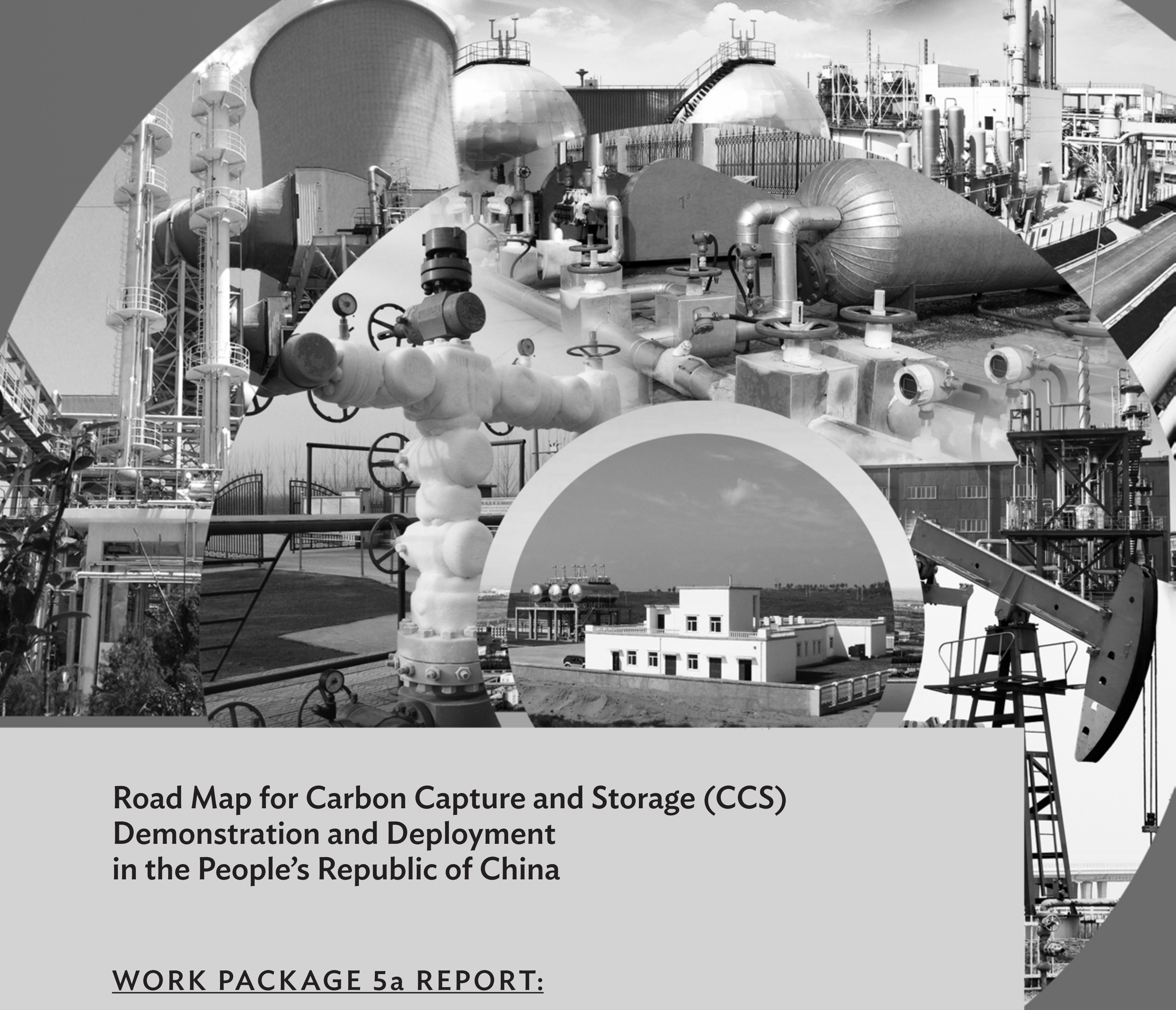

Road Map for Carbon Capture and Storage (CCS) Demonstration and Deployment in the People's Republic of China

WORK PACKAGE 5a REPORT:

Opportunities for CCS Deployment in China under Low Carbon Transformation Scenarios

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WP5 Sub Report of Roadmap for Carbon Capture and Storage Demonstration and Deployment

Final Report

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1. Introduction

Due to the economic growth, a rapid increase in electricity demand, and heavy reliance on coal in its energy mix, China now is one of the world's largest CO_2 emitters. Achieving decarbonization while producing more energy and maintaining economic growth is a challenge to be addressed by a number of clean energy solutions including energy efficiency and demand management measures, renewables and other low-carbon energy sources, and the use of fossil fuels with carbon capture and storage (CCS). Though China has strong incentives for energy efficiency, renewable and other low-carbon technologies, coal is likely to remain a substantial part of China's energy mix in the future. Thus to achieve its long-term climate change mitigation goals it is essential for China to develop and deploy low-carbon technologies such as CCS to decarbonize its power sector. CCS is assumed to have a high potential to be a cost effective solution in a low-carbon development transition not only in China, but also worldwide.

CCS from coal combustion is now widely viewed as imperative for the stabilization of global climate. Given the role of coal in China's energy system and the urgent need for cutting CO_2 emissions, CCS – currently the only available near-commercial technology that can cut CO_2 emissions from fossil fuel-fired power plants to the atmosphere by 80%-90% – is an important emission mitigation option for China. Although the ongoing CCS projects are making progresses, the pace is well below the level required for CCS to make a substantial contribution to climate change mitigation. Some technical problems of CCS still remain unsolved. The barriers such as high capital cost, technological uncertainty, and significantly high energy penalty are holding the development of CCS technology in a very slow pace around the world. Along with the technical problems of CCS, a more important issue is insufficient policy support exacerbated by poor public understanding of the technology.

As a high investment technology, CCS can only be well developed under a clear mitigation path and strong supporting policies, where it is more likely to obtain support from investors. Project proponents strongly highlight that there is too much policy uncertainty to support a business case for large-scale CCS projects, which have large capital costs and a long development circle. Investors need to be certain of the long-term predictability of the project if they are to invest in CCS. Thus China's mitigation scenario and targets are crucial to long-term development of CCS.

In this study, we evaluate the scenarios of CCS applications considering different global and national emission reduction goals. Specifically we simulate the impact on emission reduction, fuel switching and economic growth of CCS under different scenarios. More importantly, we also investigate the policy interventions that enable the energy transformation and CCS applications. This report organizes 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 in the future; 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 emissions; Section 4 focuses on scenario analysis, where the scenarios are described in detail and the results are discussed; Section 5 summarizes the report.

2. Policy Review

CCS is still at its demonstration stage worldwide, where the major influence on its development is policy and regulation. Thus it is important understand the current policy, which is a crucial influence factor on the demonstration and early-development of CCS. This section reviews the current situations policy, legal, and regulatory framework for the demonstration and deployment of CCS in China. Policies related to the deployment of renewable energies and fostering energy efficiency are also discussed, together with their impact on the development and the deployment of CCS. CCS support policies, related international cooperation, and demonstration projects, which are of great importance to CCS development are as well reviewed and assessed in this section.

2.1. Existing Mitigation Effort and Future Trend

China made a pledge to control its growing CO_2 emissions at the Copenhagen Climate Summit in 2009. The pledge has not only contributed to achieving the Copenhagen climate agreement, but also initiated substantial domestic efforts for promoting sustainable energy system transformation in China. China made two important climate commitments at the Copenhagen Climate Summit in 2009. One is to reduce its carbon intensity by 40-45% by 2020 compared to 2005 level. The other is to have at least 15% of primary energy produced from non-fossil energy sources by 2020. China had set a mandatory target of reducing its energy intensity by 20% over the Eleventh Five-Year Plan (2005-2010). To meet its Copenhagen pledge, China's Twelfth Five-Year Plan (2011-2015) emphasized a "green, low-carbon development concept" with two new targets: one is to reduce the carbon intensity of economy by 17% and the other is to increase non-fossil energy share to 11.4% by 2015. China has adopted a set of measures to achieve these targets. Among others, the major measures include disaggregating the national carbon intensity target by province, government-enterprise energy conservation agreements, forced retirement of the small-sized power plants and obsolete production capacities in the energy intensive sectors such as steel and cement, enhancement of energy efficiency standards, energy conservation allowance schemes, investment subsidies for energy conservation projects, and renewable electricity feed-in tariff.

Thanks to the implementation of these measures China's carbon intensity declined by approximately 21 % from 2005 to 2010. The absolute CO_2 emission, however, grew by approximately 34% over the same period, reaching 7217 Mt in 2010. China's coal consumption climbed to 1662 mtoe in 2012, which was approximately 67% of the year's total energy consumption, growing by 44% to 2005 level. China's air pollution has recently deteriorated due to the increased use of fossil fuels, particularly 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, was above the pollution level for 83.4% of the days in January 2013. The API of Shanghai, China's biggest economic and business city, exceeded the pollution level for 74.2% of the days in December 2013. Haze has become a big hazard to the residents in these cities. There is a significantly urgent need 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 a 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 Cap-and-Trade scheme for CO_2 emissions (ChinaDaily 2013). Once implemented, these measurements would 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

High cost, high energy penalty, and long-term security and reliability still remain problems for the deployment of CCS, before which continuous research and large-scale demonstration are essential for improving the technology maturity. CCS related technologies have been investigated in China, but are still far from the stage of standardize and full-scale demonstration.

2.2.1. Policy Making

China's policy is supportive to CCS. On Feb. 9th of 2006, the State Council issued the "State Long-term Science and Technology Development Plan (2006-2020)", which included "efficient, clean, and near-zero carbon emissions fossil energy utilization technology" into advanced energy technology. On June 4th 2007, the National Development and Reform Commission issued "National Plan on Climate Change", which put forward "the development of carbon capture and storage technology". On June 14th, 2007, Ministry of Science and Technology, National Development and Reform Commission and other ministries jointly issued "Special Action on Climate Change and Technology", which included CCS as an important task. On Oct. 29th 2010, the Information Office of the State Council issued the white paper "Policies and Actions to Address Climate Change", which pointed out that "CCS is one of the GHG emissions reduction technologies that China will focus on investigating". In "the Twelfth Five Year Science and Technology Development Plan" released in July 2011, CCS is mentioned in both the "energy saving and environmental protection industry" section and the "combating climate change" section.

2.2.2. International Cooperation

Under the guidance and leadership of the Science and Technology Department and other related departments, research institutions, universities, and enterprises launched a wide range of technological communication and cooperation projects on CCS with institutions in Australia, Italy, Japan, and America. The international cooperation not only enforced capacity building in China's institutions and enterprises and formed the core research team on CCS in China, but also started investigations on capture technology choosing, technology economic evaluation, storage potential assessment, and source-sink matching, etc.. Major international CCS cooperation projects include: 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), Assessing 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 the aspects 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. R&D

The National Science and Technology Major Project has conducted specific investigation 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 has started R&D and demonstrations on CCS emissions reduction potential, CO_2 capture, biological utilization of CO_2, CO_2-EOR, and geological storage, designed different CO_2 sources, different capture technology options, different options for CO_2 utilization and transformation. The National Major Science and Technology Project “Large Oil and Gas Fields and Coal-bed Methane Recovery” involves R&D and demonstration of CO_2-EOR, ECBM technologies.

2.2.4. Demonstration Projects

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

CCS demonstration projects are mainly in electricity industry, where the CO_2 generated are concentrated, of large amount and has fixed sources. Coal chemical industry is an important industry for CCS demonstration. Deployment of CCS in coal chemical industry has huge potentials because the large number of coal chemical enterprises in China and the low energy penalty in the capture process due to the high concentration of CO_2. Several 10,000-ton CO_2 capture demonstration units were built in recent years, with the maximum capture capacity of more than 100,000 tons/year. CO_2-EOR pilot projects were started, with the biggest single project sequestrating approximately 167,000 tons of CO_2. 100,000 tons/year CO_2 saline aquifer storage demonstration project and 40,000 ton CO_2 capture and EOR coal power plant demonstration are also ongoing.

The development of CCS is having more controversies currently. Major worries include technology reliability, energy penalty, economic feasibility, and environmental security. Barriers for development of CCS in China include high cost, immature technology, lacking capital, market risks, and environmental impacts.

2.3. Support in the Development of CCS in the “Twelfth Five-Year Plan”

China continues to signal a strong policy commitment to reducing national carbon and energy intensity, with CCUS 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 Chinese Ministry of Science and Technology (MOST), hosted a workshop dedicated to the design of CCUS 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 CCUS in China. In particular, the workshop determined a clear need to develop further programs of study and continue working with international organizations to consider policy, legal, and regulatory frameworks for the technology.

China’s Ministry of Science and Technology issued the specific plan for CCS according to the Twelfth Five-year Plan, including the overall goals by the end of the Twelfth Five-year Plan: breakthrough of key CCUS theories and technologies, significantly lowering the cost and energy penalty, ability for the designing and integration of million-ton level CCUS systems, construction of CCUS system research and innovation platforms, completing 300,000-500,000 tons/year CCUS demonstration systems.

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

3. Development and Input of the China-in-Global Energy Model (C-GEM)

3.1. Overview

The China-in-Global Energy Model (C-GEM) is a multiregional, multisector, recursive–dynamic, computable general equilibrium (CGE) model of the global economy[1]. The model is one of the major analysis toolsdeveloped by the China Energy and Climate Project (CECP), a cooperative effort of Massachusetts Institute of Technology’s (MIT) Joint Program on the Science and Policy of Global Change and the Tsinghua Institute of Energy, Environment, and Economy. The primary goal of the model is to analyze the impact of existing and proposed energy and climate polices in China on technology, inter-fuel competition, the environment, and the economy within a global context.

The C-GEM is a computable general equilibrium (CGE) model with supplemental accounting for energy and emissions quantities. Its basis structure derives from

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[1] For detailed description of the model, see http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt262.pdf.

Walrasian General Equilibrium Theory formalized by Arrow and Debreu(Arrow and Debreu 1954, Sue Wing 2004). A key advantage of the CGE framework is its ability to capture policy impact across the interlinked sectors of the economy, including interactions with goods and factor markets and bilateral trade relationships between regions. CGE modelsare now well-established tools used to undertake quantitative analysis of the economic impacts of energy and environmental policies(Böhringer, Rutherford et al. 2003, Sue Wing 2004).

The CGE model simulates the circular flow of goods and services in the economy, as shown in Figure 3.1 below.

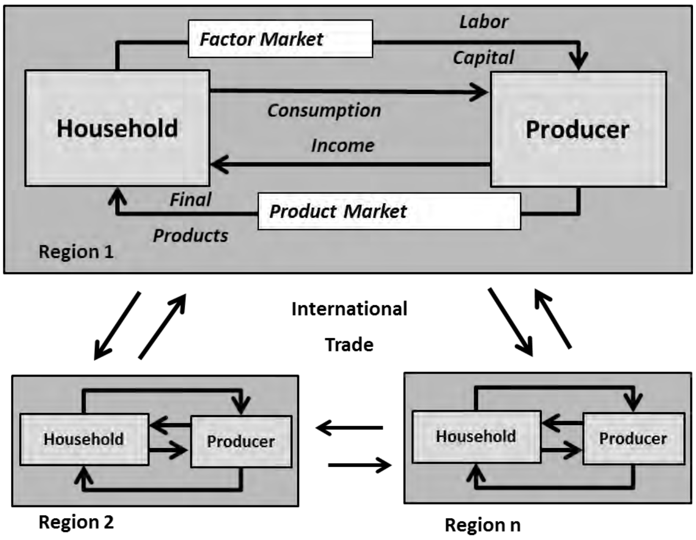

Figure 3.1 Economy-wide circular flow of goods and services in the C-GEM

The arrows in 错误!未找到引用源。 above show the flow of goods and services in the economic system in each world region. Firms (producers) purchase factor inputs (such as labor, capital, and land) from factor markets and intermediate goods and services from product markets, and then use them to produce final goods and services. Consumers (households) purchase these final goods from the product markets and sell their labor, capital, and other endowments in the factor markets to obtain income. In each region, the producers maximize profits given input costs, and consumers maximize utility while satisfying a budget constraint. Relative prices adjust endogenously to maintain equilibrium across product and factor markets.

Households allocate income to private consumption and savings with substitution across these two categories defined by the consumer utility function. In the recursive–dynamic model framework, the household savings decision is based only on current period variables. Households in the C-GEM are assumed to be homogenous, so that one representative household in each region owns all the factors of production and receives all factor payments. Tax is imposed in almost all transactions as specified in the base year data and is collected by government.

Savings and taxes provide funds for investment and government expenditures. The government in the C-GEM is modeled as a passive entity that collects tax revenue and recycles the money to the household as a lump-sum supplement to their income from factor returns(Sue Wing 2004). The expenditure of the government in each region is fully funded by households. Different regions are linked with international trade in that their products can be exported to the rest of the world, and imported goods are also sold in the domestic product market following the Armington assumption(Armington 1969). In the C-GEM international trade is limited to the product market; factors such as labor and endowments are not mobileacross regions. The international capital flows that account for the trade imbalance between regions in the base year are assumed to gradually disappear.

3.2. Model structure

The C-GEM disaggregates the world into 19 regions and 20 sectors, as shown in

Table 3.1 and Table 3.2 and

Figure 3.1 below.

We aggregate the C-GEM regions on the basis of economic structural similarities,membership in trade blocks, and geographical relationships. The regional aggregates can be separated into two distinct groups, developed economies and developing economies, according to the definitions used by the International Monetary Fund (IMF2012). The major developed economies (United States, European Union, Japan, Canada, Australia) and major developing countries (China, India, Russia, Brazil, South Africa), as well as major oil suppliers (mainly the Middle East) are explicitly represented. We further disaggregate the major economies around China, including South Korea, Japan, and Southeast Asia's developing countries as well as developed Asia as individual regions in the C-GEM.

Table 3.1 Definition of regions in the C-GEM

Regions in the C-GEM	**Detailed Countries and Regions Contained**
Developed Economies	
United States (USA)	United States of America
Canada (CAN)	Canada
Japan (JPN)	Japan
South Korea (KOR)	South Korea
Developed Asia (DEA)	Hong Kong, Taiwan, Singapore
Europe Union (EUR)	Includes EU-27 plus Countries of the European Free Trade Area (Switzerland, Norway, Iceland)
Australia-New Zealand (ANZ)	Australia, New Zealand, and rest of the world (Antarctica, Bouvet Island, British Indian Ocean Territory, French Southern Territories)
Developing and Undeveloped Economies	
China (CHN)	Chinese mainland
India (IND)	India
Developing Southeast Asia (SEA)	Indonesia, Malaysia, Philippines, Thailand, Vietnam, Cambodia, Laos, rest of Southeast Asia.
Rest of Asia (ROA)	Rest of Asia countries.
Mexico (MEX)	Mexico
Middle East (MES)	Iran, United Arab Emirates, Bahrain, Israel, Kuwait, Oman, Qatar, Saudi Arabia
South Africa (ZAF)	South Africa
Rest of Africa (AFR)	Rest of Africa countries.
Russia (RUS)	Russia

Rest of Europe (ROE)	Albania, Croatia, Belarus, Ukraine, Armenia, Azerbaijan, Georgia, Turkey, Kazakhstan, Kyrgyzstan, rest of Europe.
Brazil (BRA)	Brazil
Latin America (LAM)	Rest of Latin America Countries.

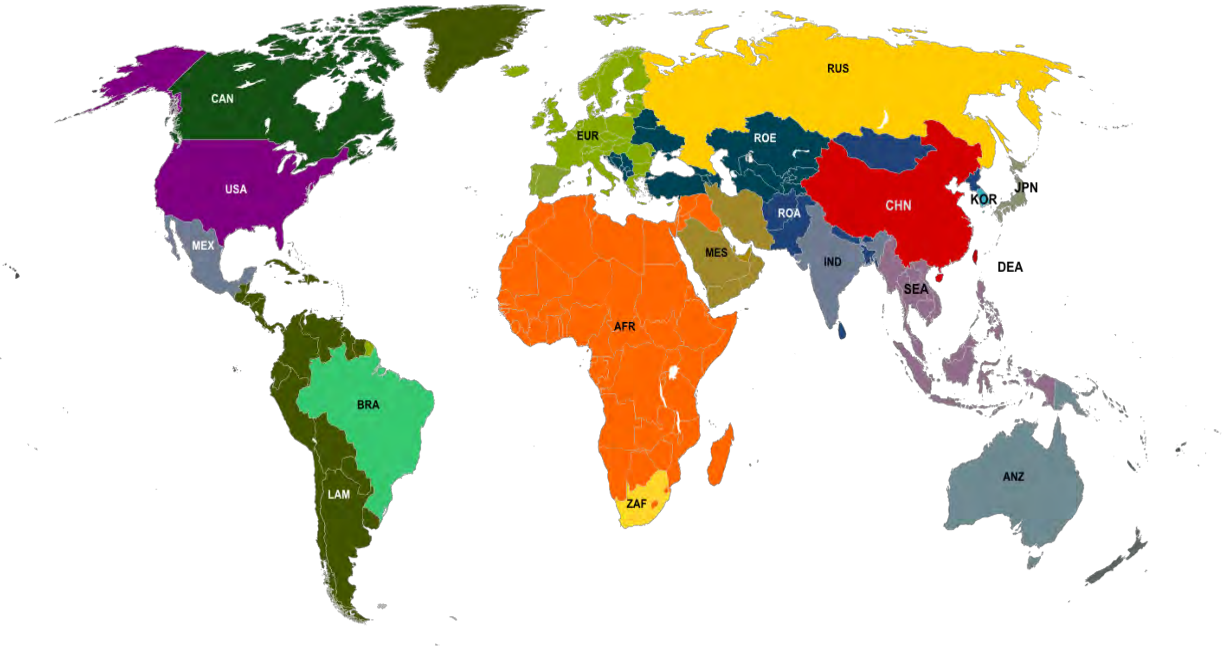

Figure 3.1 Regions in the C-GEM

Production in each of the 19 regions in the C-GEM is comprised of 20 sectors.This aggregation includes a detailed representation of the energy production sectors and the energy intensiveindustries. As shown in Table 3.2 below, five energy production sectors (coal, crude oil, natural gas, crude oil, and electricity), and five energy-intensive sectors (non-metallic mineral products, iron and steel, non-ferrous metals products, chemical rubber products, and fabricated metal products) are described in detail.

Table 3.2 Descriptions of the 20 sectors in the C-GEM

Type	Sector	Description
Agriculture	Crops (CROP)	Crops
	Forest (FORS)	Forest
	Livestock (LIVE)	Live stocks

Energy Sectors	Coal (COAL)	Mining and agglomeration of hard coal, lignite and peat
	Oil (OIL)	Extraction of petroleum
	Gas (GAS)	Extraction of natural gas
	Petroleum and Coke (ROIL)	Refined oil and petro chemistry product, coke production
	Electricity (ELEC)	Electricity production, collection and distribution
Energy-Intensive Industry	Non-Metallic Minerals Products (NMM)	Cement, plaster, lime, gravel, concrete
	Iron and Steel (I&S)	Manufacture and casting of basic iron and steel
	Non-Ferrous Metals Products (NFM)	Production and casting of copper, aluminum, zinc, lead, gold, and silver
	Chemical Rubber Products (CRP)	Basic chemicals, other chemical products, rubber and plastics products
	Fabricated Metal Products (FMP)	Sheet metal products (except machinery and equipment)
Other Industries	Food and Tobacco (FOOD)	Manufacture of foods and tobacco
	Mining (MINE)	Mining of metal ores, uranium, gems. other mining and quarrying
	Construction (CNS)	Building houses factories offices and roads
	Equipment (EQUT)	Electronic equipment, other machinery and Equipment
	Other industries (OTHR)	Other industries
Service	Transportation Services (TRAN)	Water, air and land transport, pipeline transport
	Other Service (SERV)	Communication, finance, public service, dwellings and other services

As a multiregional CGE model, the C-GEM is parameterized and calibrated based on a balanced social accounting matrix (SAM). The SAM is an array of input–output accounts that quantifiesthe flow of goods and services in the benchmark period(Sue

Wing 2004). The C-GEM is built based on the latest version of Global Trade Analysis Project database (GTAP 8) and China's official economy and energy data set (Narayanan, Aguiar et al. 2012). The C-GEM is formulated and solved as a Mixed Complementarity Problem (MCP) using MPSGE, the Mathematical Programming Subsystem for General Equilibrium (Mathiesen 1985, Rutherford 1999)and the Generalized Algebraic Modeling System (GAMS) mathematical modeling language (Brooke, Kendrick et al. 1992). The C-GEM keeps track of the physical flows of carbon-based fuels and resources in the economythrough time, and also tracks associated greenhouse gas emissions.

The C-GEM employs the GTAP data set Version 8, a global database that integrates national accounts on production and consumption (input-output tables) together with bilateral trade flows for 57 sectors and 129 regions for the year 2007(Narayanan, Betina et al. 2012). The volume of energy consumption and bilateral trade are also represented in GTAP for 2007.The energy volume data in GTAP is mainly from the International Energy Agency's "Extended Energy Balances" data set(McDougall and Lee 2006).

To develop the C-GEM, we use the General Algebraic Modeling System based on a modified version of "GTAPinGAMS" which was developed by Rutherford and Paltsev(Rutherford and Paltsev 2000). "GTAPinGAMS" also allows a flexible aggregation of sectors and regions upon the 57 sectors and 129 regions. We employ this function to aggregate the GTAP 8 database into 19 sectors and 19 regions to define the base year economic structure in the C-GEM.

3.3. Major Function

This section discusses in detail the production and consumption functions, international trade, and the representation of emissions.

The nested structure of production in the C-GEM is shown in

Figure below. At the top of the nest, natural resources combine with non-resource inputs. In the sub-level of non-resources input, there is a Leontief combination between non-energy intermediate inputs and a Capital-Labor-Energy bundle, which is comprised of a CES structure between energy and a value-added bundle. Capital and Labor are combined as a Cobb-Douglas structure. The Energy Input bundle is further divided into a CES substitution between the electricity and fossil fuels bundle (including coal, crude oil, refined oil, and natural gas).

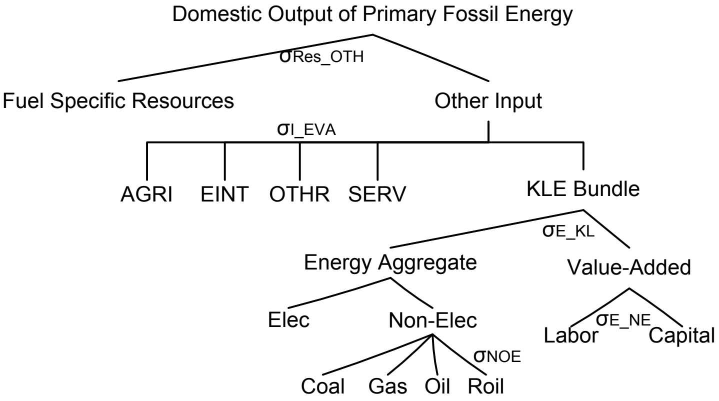

Figure 3.3 The structure of the primary fossil energy sectors in the C-GEM

The structure of the electricity sector is shown in Figure 3.4. The top two nestspermit substitution among various generation technologies. Twelve types of power generation technologies are represented in the base version of C-GEM as listed in electricity sector in the C-GEM

Table 3.3, including five existing technologies that produce in the base year. The model also includes seven advanced electricity generation technologies that do not exist in the base year, but become available in later years and start producing when their relative cost falls below the levelized cost of incumbent generation. The structure of these advanced technologies will be discussed in detail in the following sections.

With the exception of wind and solar, we treat advanced power generation technologies as perfect substitutes for existing technologies as shown in the second level of the nested structure in Figure 3.4 below. We capture transition costs associated with scaling up each technology, which fall with an increase in their share of total generation. Wind and solar electricity generation technologies are treated as imperfect substitutes.

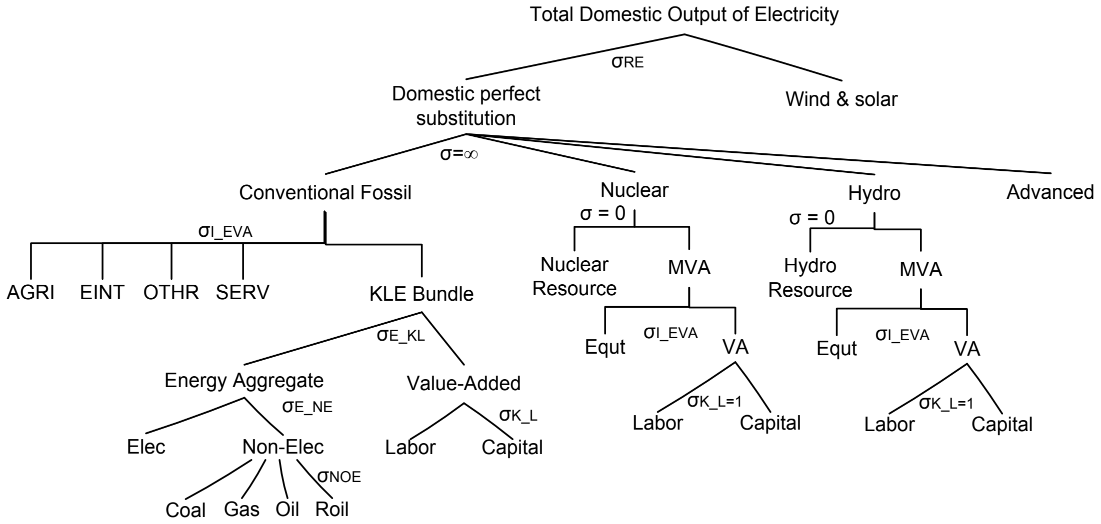

Figure 3.4 Structure of the electricity sector in the C-GEM

Table 3.3 Electricity technologies in the C-GEM.

Existing Technologies	**Advanced Technologies**
Coal	Wind
Refined oil	Solar
Gas	Biomass power
Nuclear	Natural Gas Combined Cycle (NGCC)
Hydro	Integrated Gasification Combined Cycle (IGCC)
	Natural Gas Combined Cycle with Carbon capture and storage (NGCC-CCS)
	Integrated Gasification Combined Cycle with Carbon capture and storage (IGCC-CCS)

Conventional power generation consists of a Leontief combination of non-energy intermediate inputs and energy-capital-labor bundle. Fossil fuels such as coal, oil, and gas are bundled together with imperfect substitution to avoid take-over effect when one fuel is cheaper than the other fossil fuels.

Household consumption in the C-GEM is also represented as shown in

Figure3.5. We use consumption (excluding savings) as a consistent measure for

welfare accounting.[2] In the consumption bundle, we have separated private transportation from other goods and services. Private transportation refers to the transport service supplied by the household through the purchase and operation of passenger vehicles. Inputs to the private transportation sector draw from the equipment industry (purchase of vehicle), services, and refined oil sectors. Included as a substitute for private transportation is purchased transportation, which is supplied by the transportation industry and includes both short- and long-distance road, air, rail, and marine modes. Refined oil use in other consumption reflects home heating and other miscellaneous uses after subtracting the refined oil used directly by private vehicles.

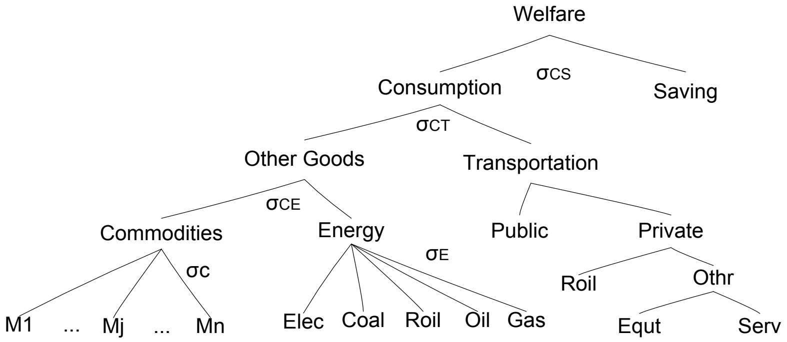

Figure 3.5 The nested structure of the consumption function in the C-GEM

Production and consumption in each region in the C-GEM are linked through bilateraltrade. Capturing this links allows the model to forecast how policy impactspropagate across regions. Trade flows in all goods, including energy products, are explicitly represented in the GTAP bilateral trade flow data sets for the base year 2007. All the other goods except crude oil are treated as Armington goods(Armington 1969). Crude oil in the C-GEM is modeledas homogeneous good with a single global price. The Armington CES structure is shown in

Figure 3.6. The top level nest captures the tradeoff between domestic and imported goods, including imported goods that are comprised of imports from different regions.

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[2] We use consumption measured as equivalent variation in constant 2007 US$ as a measure of welfare. Measures of welfare that include savings over time run the risk of double counting the contribution of savings, which show up in investment, and supplements household income through factor payments.

Bilateral trade flows, which include export taxes, import tariffs, and international transport costs, are represented in the C-GEM.

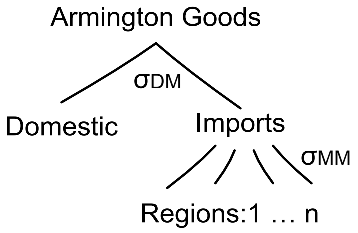


Figure 3.6 The nested Armington structure consisting of domestic and imported goods in the C-GEM

As discussed, the government in the C-GEM is modeled as a passive entity that collects tax revenue on intermediate inputs, outputs, and consumer expenditure and transfers it to the household as a lump-sum payment. Government expenditure is assumed to be part of final consumption and is fully funded by households. Government consumption decisions maximize utility subject to revenues available. Government consumption in the C-GEM adoptsthe same nested CES as household consumption.

Investment in the C-GEM is represented by a sector that producesan aggregate investment good using inputs of inventories by sectorswhich sum to the level of savings determined by the utility function. Investment becomes available as new capital in the next period and drives the growth of the economy.

In the C-GEM, CO_2 emissions are accounted for by applying constant emission factors to the fossil fuel energy flows of coal, refined oil, and natural gas based on the2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories(IPCC 2006). The emission factors are assumed to remain constant across regions and over time. Energy-related CO_2emissions enter into a Leontief structure with fuel, implying that the reduction of emissions in production sectors can only be achieved with reductions in fuel use. In the current version of the C-GEM, only fossil-fuel-related carbon dioxide (CO_2) emissions are projected.

However, the model framework could be readily extended to account for other non-CO_2 greenhouse gases, including methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFC), sulfur hexafluoride (SF_6), and other pollution gases such as sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_X). Those non-CO_2 greenhouse gases are still under extending and thus cannot be reflected in the model at present.

The static foundation of the C-GEM was used to develop a recursive–dynamic model that allows assessment of energy markets and policy impacts through 2050. By solving the model in each period sequentially and then updating parameter values in the next period to reflect dynamic trends, a recursive–dynamic model assumes that economic agents make decisions based on information available in the current period only. The dynamic process of the C-GEM is mainly driven by labor supply growth, capital accumulation, fossil fuel resource depletion, structure change in consumption, and new technology availability.

3.4. Technology Details

The C-GEM also includes a full suite ofadvanced "backstop" technologies to capture the potential impact of energy supply technologies that are not yet commercial, and may enter the economy later if and when they become cost-competitive with existing technologies. The cost of each new technology depends on the equilibrium price of all the inputs, which are endogenously determined within the CGE framework.

We represent 11 classes of advanced technologies in the C-GEM as shown inTable 3.4. Three technologies produce perfect substitutes for conventional fossil fuels (crude oil from shale oil, refined oil from biomass, and gas from coal gasification). The remaining eight technologies are electricity generation technologies. Electricity generated from wind, solar, and biomass is treated as an imperfect substitute for other sources of electricity due to their intermittency. The final five technologies—NGCC, NGCC with CCS, IGCC, IGCC with CCS, and advanced nuclear—all produce perfect substitutes for conventional fossil electricity output.

Table 3.4 List of new technologies in the C-GEM

Technology	Description
Wind	Convert intermittent wind energy into electricity
Solar	Convert intermittent solar energy into electricity
Biomass electricity	Convert biomass into electricity
IGCC	Integrated coal gasification combined cycle to produce electricity
IGCC-CCS	Integrated coal gasification combined cycle with carbon capture and storage to produce electricity
NGCC	Natural gas combined cycle to produce electricity
NGCC-CCS	Natural gas combined cycle with carbon capture and storage to produce electricity
Advanced nuclear	Nuclear power with new technology
Biofuels	Converts biomass into refined oil
Shale oil	Extracts and produces crude oil from oil shale
Coal gasification	Converts coal into gas as a perfect substitute for natural gas

The CES production structure for coal gasification technology is shown in3.7. Coal, equipment, and a value-added bundle enter as a Leontief structure at the top of the level of the production structure.

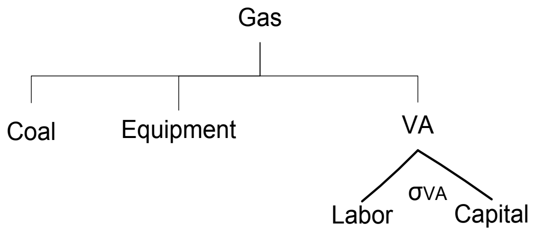


Figure 3.7 CES production structure for coal gasification

3.5. Detailed representation of CCS in the Model

3.5.1. Represent the CCS technology in the model

C-GEM has designed detailed production structures CCStechnology for the energy supply sector, as shown in Figure 3.8. In the structure, the cost of transmission and distribution (T&D), and generation and sequestration are separatelydescribed 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 generated by CCS use enter in a CES nest with generation and sequestration. 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 allowsdeployment of additional capital and labor to reduce the required input of carbon permits and results in a higher percentage of CO_2 captured. The penetration rate of CCS technology is further controlled by a fixed factor at the top level of the nested structure, similar to other backstop types.

It is necessary to point out that it is difficult for C-GEM, an economic model, to reflect specific technology details as technical models do, because a large quantity of data is needed to support the technology details in economic models, and it is usually difficult to obtain those relevant data. Thus C-GEM only provides representation of CCS technology as one technology(without dividing into specific technologies such as post-combustion, oxy-fuel, and pre-combustion technologies) in the energy supply sector.

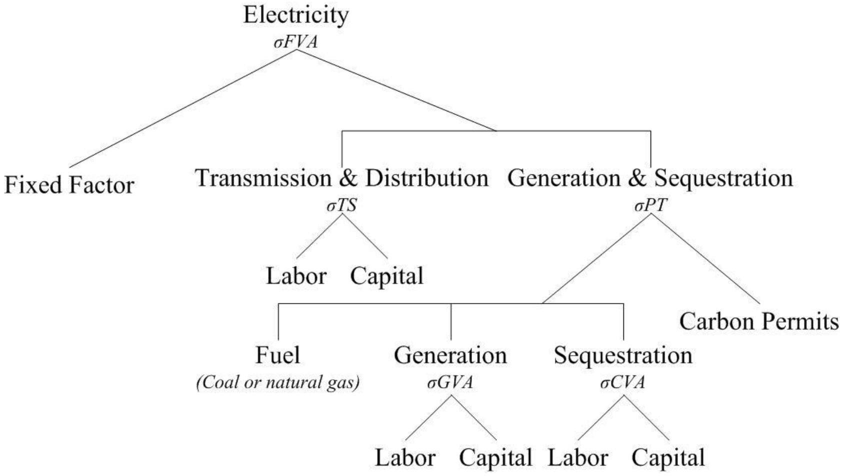


Figure 3.8 CES production structure for CCS

To specify the production cost of these new technologies, we first set input shares for each technology in each region. This evaluation is based on demonstration project information or expert elicitations. A markup factor captures how much more expensive the new technologies are than traditional fossil technologies. All inputs to advanced technologies are multiplied by this markup factor. For electricity technologies and biofuels, we estimate the markups, shown in Specifically, the markup factors of CCS related technologies are calculated and calibrated using the data in Section 3.6.3.

Table3.5, for each technology based on a recent report by the Electric Power Research Institute that compares the technologies on a consistent basis. Specifically, the markup factors of CCS related technologies are calculated and calibrated using the data in Section 3.6.3.

Table 3.5 Markup factors for backstop technologies in the C-GEM

Backstop Technologies	**Markup Factors**	**Remarks**
Wind	1.1	USA/EU
	1.2	China
	1.5	Other regions
Solar	1.8	USA/EU
	2.3	Other regions
Biomass electricity	1.51	China
	1.84	Other regions
IGCC	1.02	USA/EU
	1.2	Other regions
IGCC-CCS	1.52	USA/EU
	1.7	Other regions
NGCC	1.02	USA/EU
	1.2	Other regions
NGCC-CCS	1.42	All regions
Advanced nuclear	1.47	USA/EU
	2.5	Other regions
Biofuels	1.04	All regions
Shale oil	2.8	All regions

Coal gasification	3.5	All regions

3.6. Calibration of CCS parameters

3.6.1. CCS cost Review

It is important that the CCS related parameters applied in the model are calibrated according to first-hand data of China, which makes the result more accurate representing the real situation of CCS technology in China. Capture is an important procedure in CCS. Cost of carbon capture takes up around 70% of the total cost of CCS as estimated. We conducted a detailed review of CCS cost estimation based the existing literatures (as shown in Table 3.6). The element of cost structures, estimation methodologies, model assumption, and their results are investigated and compared by studies. Through the comparison, we found that in these literatures, different assumptions and methodologies lead to various estimated costs.Capture cost reported in China is about half of some costs reported in OECD countries, mainly due to lower labor costs and other location-related costs. Table 3.6 concludes the variables, assumptions, and results of some capture cost studies in China.

Table 3.6 Cost Analysis of Carbon Dioxide Capture in China

Author	Huang Bin(Huang, Xu et al. 2010)	Xiong Jie(Xiong, Zhao et al. 2009)	Xiong jie (Xiong, Zhao et al. 2009)	Yan Shuiping(Yan, Fang et al. 2008)	Wang Yun(Wang , Zhao et al. 2010)	NZEC(NZEC 2009)	NZEC(NZEC 2009)	NZEC(NZEC 2009)	NZEC(NZEC 2009)	NZEC(NZEC 2009)
Reference 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	297.4436MW	297.4436MW		558MW	574.1MW	295.1MW	824.3MW		
Efficiency	295g/kWh				5632t/ d	40.28%	38.15%	43.9%		
Utilization		8000	8000	5500	6000	85%	85%	85%		

hours										
CO_2emissions	0.95kg/kWh	281.8t/h	281.8t/h		0.80 kg/kWh	868.2g/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		232.9436MW	245.9636MW		438.53MW	398.1MW	202.5MW	672.5MW	661.7MW	398.2MW+310kt 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 without CO_2 capture		$28.86/MWh	$28.86/MWh		$47.34/MWh	￥270.1/MWh	￥283.1/MWh	￥271.3/MWh		
Cost with		$45.862/M	$49.049/MW		$63.80/M	￥512.4	￥545.2	￥368.9	￥412.5	￥453

CO_2 capture		Wh	h		Wh	/MWh	/MWh	/MWh	/MWh	/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 cost only)			￥137.6/t (Capture unit only)						

The cost of CO_2 transportation is largely known and understood from the practical experience over the years. Both top-down and bottom-up models are able to produce cost estimate of CO_2 transportation. Different from the cost of CO_2 capture, 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 € 1/t to € 20/t CO_2 stored(GCCSI 2011), due to different site type and size, uncertainty and variability of geophysical characterization of certain types of site, and large regional variances, etc.

3.6.2. Calibration of CCS Cost

As shown above, literatures give diverging estimations of the CCS cost. To ensure the accuracy of the projection and its consistency among the work packages, we worked together with the team of the Institute of Engineering Thermophysics of Chinese Academy of Sciences, which is pioneer in the research field of CCS technologies， to calibrate the technology related parameters of CCS technology represented in the model, as shown in Table 3.7.

Table 3.7 Calibrated Cost of CCS

	IGCC (/kWh)	**IGCC capturing CO_2 (/kWh)**
Capital ($/kW)	2200	2950
Efficiency	0.46	0.38
Operating Cost Coefficient	0.04	0.04
CRF	0.12	0.12
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	178704	178704

(kWh)		
Coal Consumption (kg)	52360.7	63383.9
Cost per kW		
Equipment Cost	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 Emission (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 in Total Cost Structure	--	20%

4. Scenario Analysis of the CCS Deployment in China

In this section, we apply the established China-in-Global Energy Model (C-GEM) to evaluate CCS technology application scenarios taking into account different national emission reduction efforts. Section 4.1 describes the scenarios and macroeconomic assumptions; Section 4.2 discusses CCS technology's impact on emissions, energy and economy in different scenarios.

4.1. Scenario description and assumptions

4.1.1. Scenario description

To illustrate China's possible long-term emission reduction pathways, we designed three scenarios – S1, S2A, and S2B to reflect different levels of policy efforts. Under these three mitigation scenarios, the impacts of CCS technology are analyzed, as shown in Table 4.1.

Table 4.1. Scenario Design

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

The key assumptions of S1, S2A, and S2B are shown in Table 4.2.

1) S1: Annual carbon intensity of GDP reduction by 3% from 2016 to 2050

S1 is 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 has made a pledge at Copenhagen Climate Summit in 2009 to reduce its carbon intensity by 40-45% by 2020 compared to 2005 level. By the end of the Eleventh Five-Year Plan (2010) China's carbon intensity has declined by approximately 21% compared to 2005 level. As for the Twelfth Five-Year Plan, China has set a mandatory target for carbon intensity to reduce by 17%. That means by reducing the carbon intensity by 3% per annum during the Thirteenth Five-Year Plan (2016-2020), China is going to achieve a 44% carbon intensity reduction from 2005 to 2020, well meeting the Copenhagen commitment of 40-45% carbon intensity reduction by 2020.

We assume that China will maintain its Copenhagen pledge momentum, and achieve a carbon intensity reduction rate of approximately 3% per year from 2016 through 2050. In this context, this scenario can largely be named as Continued Efforts 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 under S1 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 350GW capacity by 2020 and a 400GW capacity by 2050, 3) fostering the development of nuclear energy, obtaining a 58GW capacity by 2020 and a 450GW capacity by 2050, 4) subsidizing renewable energy according to present level of benchmark electricity price by renewable energy surcharge imposed on terminal electricity consumptions. Also, there is an increasing carbon tax ensuring the annual carbon intensity reduction rate of 3% from 2016 to 2050, which will be 16.0$/ton CO_2 in 2030 and 33.5$/ton CO_2 in 2050.

2) S2A: Annual carbon intensity of GDP reduction by 4% from 2016 to 2050

According to the joint announcement on November 12th, 2014 of national targets on limiting GHG emission by China and the United States, 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 the 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 an annual carbon intensity reduction rate of 3%, so an annual reduction rate of 4% can be well regarded as an Accelerated Efforts scenario. Similar with S1, the policy assumptions of S2A include 1) levying resource tax for fossil fuel energy consumption according to present tax rate, 2) fostering the development of hydro power, obtaining a 350GW capacity by 2020 and a 400GW capacity by 2050, 3) fostering the development of nuclear energy, obtaining a 58GW capacity by 2020 and a 450GW capacity by 2050, 4) subsidizing renewable energy according to present level of benchmark electricity price by renewable energy surcharge imposed on terminal electricity consumptions. The carbon tax under S2A will be higher than that under S1 to ensure the annual carbon intensity reduction rate of 4% from 2016 to 2050. The carbon tax will be 35.0$/ton CO_2 in 2030 and 94.5$/ton CO_2 in 2050.

3) 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 – the S2B. With the U.S.-China Deal on Climate Change, China's CO_2 emission pathway becomes much more certain before 2030, which can be largely represented by a 4% of carbon intensity reduction rate. It is also widely accepted that the large scale deployment of CCS technology will take place after 2030. In this regard, this scenario is designated for analyzing the range of CCS technology application in China after 2030. Compared with S1 and S2A, it can be regarded as another Accelerated Efforts scenario as well. With other policy assumptions the same as those under S1 and S2A, the carbon tax simulated with the model under S2B will reach 35.0$/ton CO_2 in 2030 and 112.0$/ton CO_2 in 2050.

Table 4.2 shows the design of the three scenarios.

Table 4.2 Policy Assumptions for S1, S2A, and S2B

	S1	**S2A**	**S2B**
I. Low-Carbon Energy System Transformation Targets			
Carbon Intensity	17% reduction during 2011-2015, 3% reduction per annum from 2016 to 2050	17% reduction during 2011-2015, 4% reduction per annum from 2016 to 2050	17% reduction during 2011-2015, 4% reduction per annum during 2016-2030, 4.5% reduction per annum from 2031 to 2050
II. Policy			
Carbon tax	Explicit carbon tax. 16.0$/ton CO_2 in 2030 and 33.5$/ton CO_2 in 2050	Explicit carbon tax. 35.0$/ton CO_2 in 2030 and 94.5$/ton CO_2 in 2050	Explicit carbon tax. 35.0$/ton CO_2 in 2030 and 112.0$/ton CO_2 in 2050
Fossil	Crude oil & Nature	Crude oil & Nature	Crude oil & Nature

resource tax	gas: 7.5% of the price Coal: 10% of the price	gas: 7.5% of the price Coal: 10% of the price	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 the existing target of 350 GW in 2020 and slowly increase to its economic potential of 400 GW by 2050.	Achieve the existing target of 350 GW in 2020 and slowly increase to its economic potential of 400 GW by 2050.	Achieve the existing target of 350 GW in 2020 and slowly increase to its economic potential of 400 GW by 2050.
Nuclear power development policy	1) Achieving the existing nuclear development planning target of 40GW in 2015 and 58 GW in 2020; 2) With projected plants sites availability of 450GW.	1) Achieving the existing nuclear development planning target of 40GW in 2015 and 58 GW in 2020; 2) With projected plants sites availability of 450GW.	1) Achieving the existing nuclear development planning target of 40GW in 2015 and 58 GW in 2020; 2) With projected plants sites availability of 450GW.

4.1.2. 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 in 2050, according to the medium fertility projection results of United Nations’ report “World

Population Prospects 2012", shown in Table 4.3.

Table 4.3 Population Projection of China in 2010-2050

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
CHN	13.36	13.78	14.09	14.26	14.30	14.26	14.13	13.92	13.64

The growth rate of labor productivity of China in 2010 is 11% according to China's GDP growth rate in 2010. It is assumed on that basis that China's labor productivity growth rate approaches 2.5% – the labor productivity growth rate in developed countries – in 2050, with an average changing speed of 7% per annum. China's saving rate is projected to be diminishing from 48% in 2010 to 30% in 2050 based on OECD Economics Department Working Paper "Long-term growth scenarios" published in 2013. The model uses the above saving rate projection as a scenario assumption. In the model assumption, China's GDP is \$4.69 trillion in 2010 and \$25.32 trillion in 2050 (constant 2007 dollars), accounting for 8% of global economy share in 2010 and 15% in 2050 respectively, with a decreasing growth rate which reaches 2.9% in 2050 from 9.8% in 2010.

4.2. CCS Technology's Impact on energy and CO_2 Emissions in Different Scenarios

4.2.1. Impact on Emissions

Our analysis shows a remarkable change in the trajectory of CO_2 emissions under the Accelerated Efforts scenarios compared to the Continued Efforts scenario. Under S1, China's CO_2 emission 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 Efforts scenarios, however, China's CO_2 emission will reach the peak earlier, at approximately 10.6 Gt in 2030, and begin to decline from then on. Under S2A where the carbon intensity reduction continues to be 4% per annum, the carbon emission in 2050 will be 9.0 Gt, and under 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 4.1.

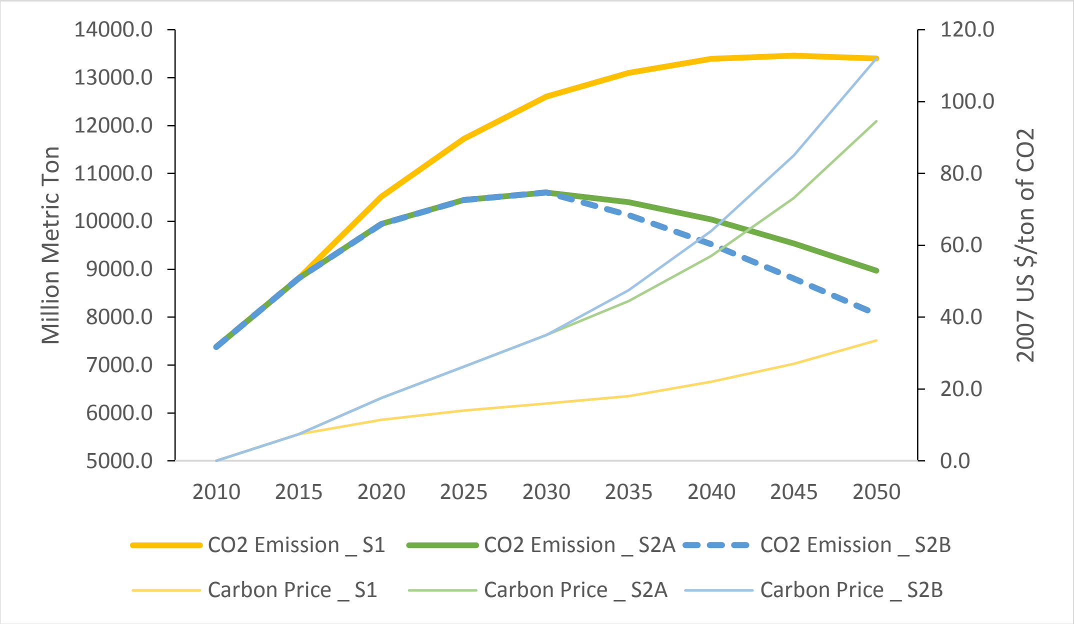


Figure 4.1 Trajectories of Total CO_2 Emission and Carbon Price

CCS technology will be playing an important role in emission mitigation under the Accelerated Efforts scenarios. In our analysis, CCS enters the market as a cost effective technology after 2030 under S2B and after 2035 under S2A. As shown in Figure 4.2, CCS will contribute a 0.6 Gt CO_2 emission reduction under S2A and a 1.4 Gt CO_2 emission reduction under S2B in 2050, respectively. Under S1, however, CCS technology will hardly play a role in CO_2 mitigation with a carbon tax lower than \$35/t CO_2 which provides insufficient incentives.

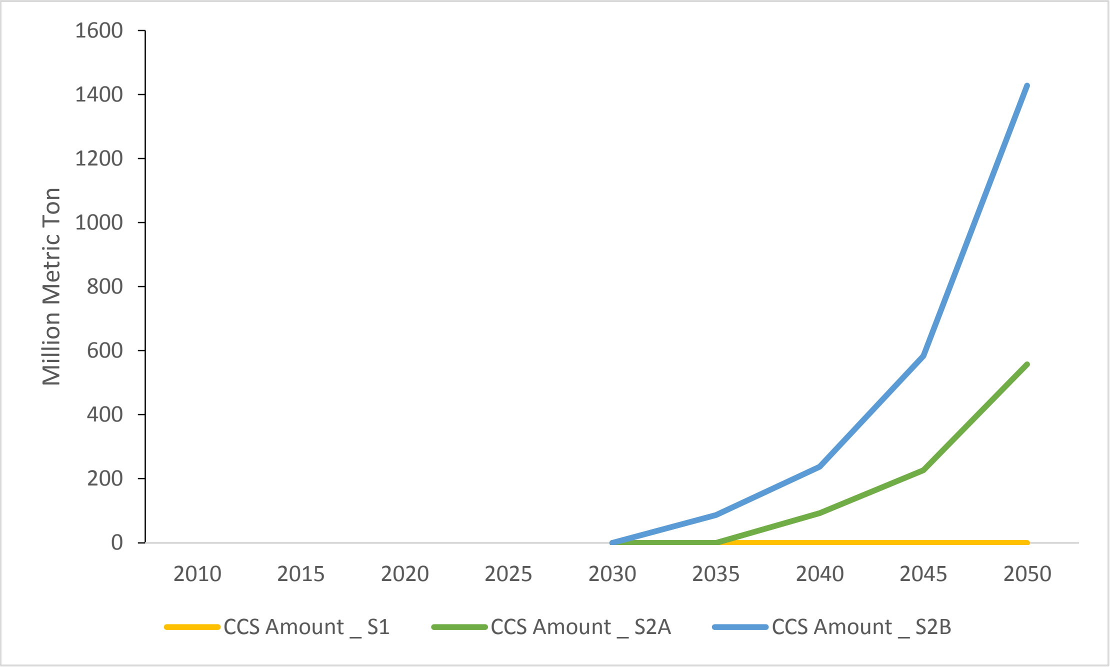


Figure 4.2 CO_2 Emission Reduction by CCS Technology

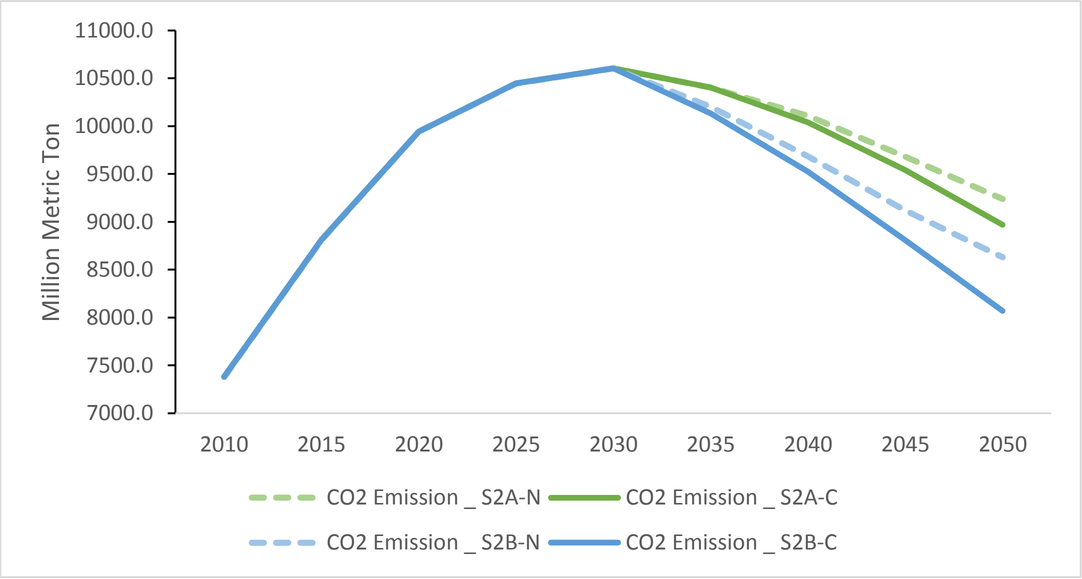


Figure 4.3 Total CO2 emission in S2A-N, S2A-C, S2B-N, and S2B-C

Shown in Figure 4.3 are the total CO_2 emission trajectories under the two Accelerated Efforts scenarios both with and without CCS. Introducing CCS technology under S2A will result in a 0.3 Gt emission reduction addition in 2050. Emission reduction when CCS technology is introduced under S2B is more significant. Approximately 0.6 Gt CO_2 emission reduction will be added under S2B in 2050 when CCS technology is introduced. It shows that CCS will become a more cost effective solution for China's long-term migitgation initiatives.

The share of fossil electricity produced with CCS technology is presented in Figure 4.4. In both the Accelerated Efforts scenarios, the share of fossil electricity produced with CCS technology increase 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 S2B scenario during 2030 to 2050 also will show an increasing tendency, which is 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 of that under S2A, indicating the crucial role of CCS technology in achieving an ambitious climate change mitigation target.

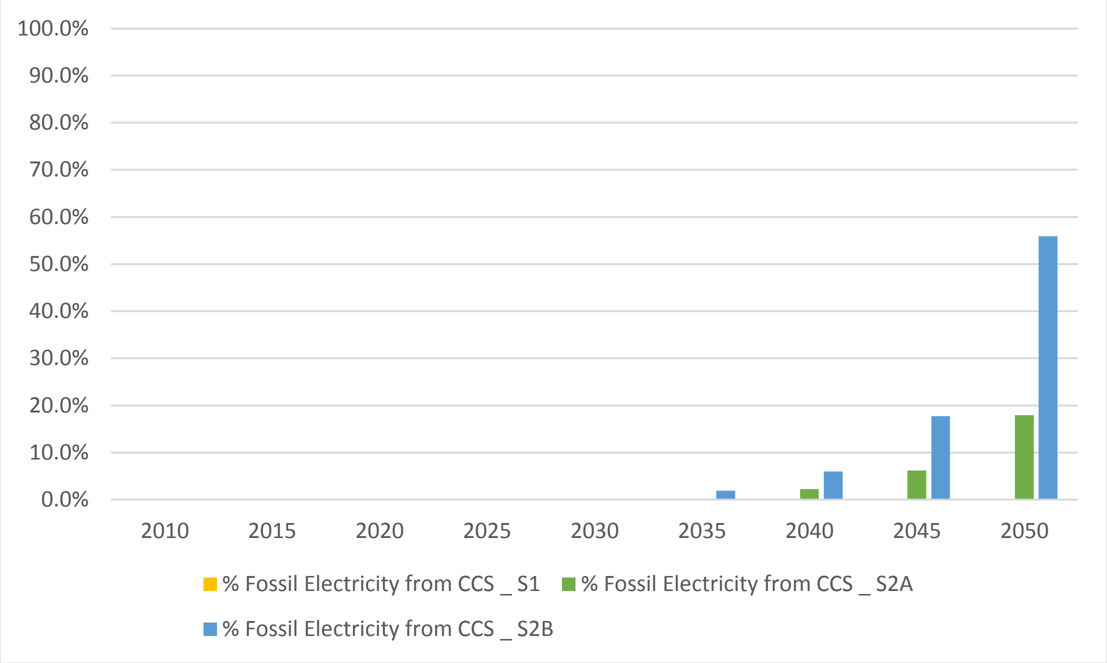
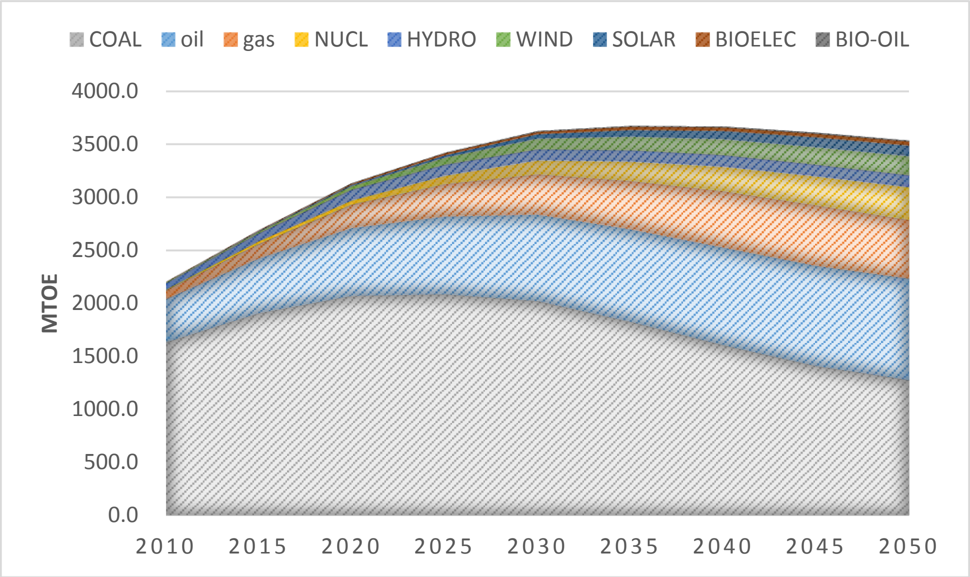
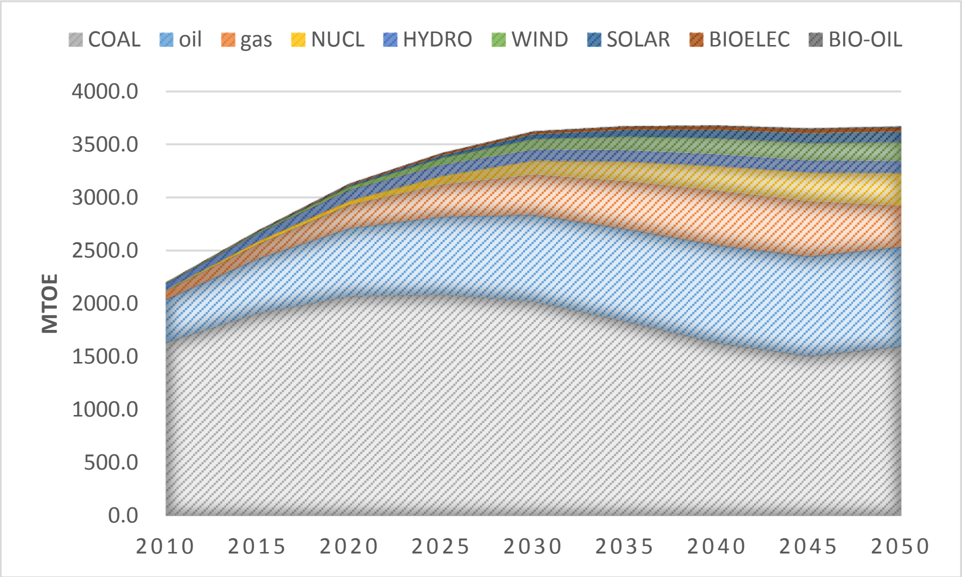


Figure 4.4 Share of Electricity Generated with CCS in Total Fossil Electricity under scenarios S1, S2A, and S2B

4.2.2. Impact on Energy Supply



(a)



(b)

Figure 4.5 Primary Energy Structure from 2010 to 2050 in China under S2B (a) w/ and (b) w/o CCS

Deployment of CCS technology exerts certain impact on energy supply, especially coal supply. Figure 4.5(a) is the energy demand in case S2B-N, and it shows that coal consumption will be well-controlled and will reach the peak during 2020-2025. Figure 4.5(b) is the energy demand in case S2B-C, which has the same shape with Figure 4.5(a) before 2030 when there is no CCS deployment. The difference occurs in the longer term due to the introduction and deployment of CCS technology. In case S2B-C, coal consumption in China will reach its peak during 2020-2025, with an amount of approximately 2.09 Gtoe, and keep declining fast after the peak year. After 2045 coal consumption rises back to 1.60 Gtoe with more CCS applications in place. Further, as shown in Figure 4.5(b), the increased coal use will lead to a reduction in natural gas use, indicating that coal-fired power generation with CCS is more competitive than natural gas fired power plants.

4.2.3. Economic Impact

Shown in Figure 4.6 are China's GDP and GDP growth rate under the six cases. The emission reduction measures will result in a GDP loss of around 3.2% in 2050 under S2B compared with under S1. Introduction of CCS technology could lead to a less GDP loss of 0.1% compared with the no CCS case under S2B.

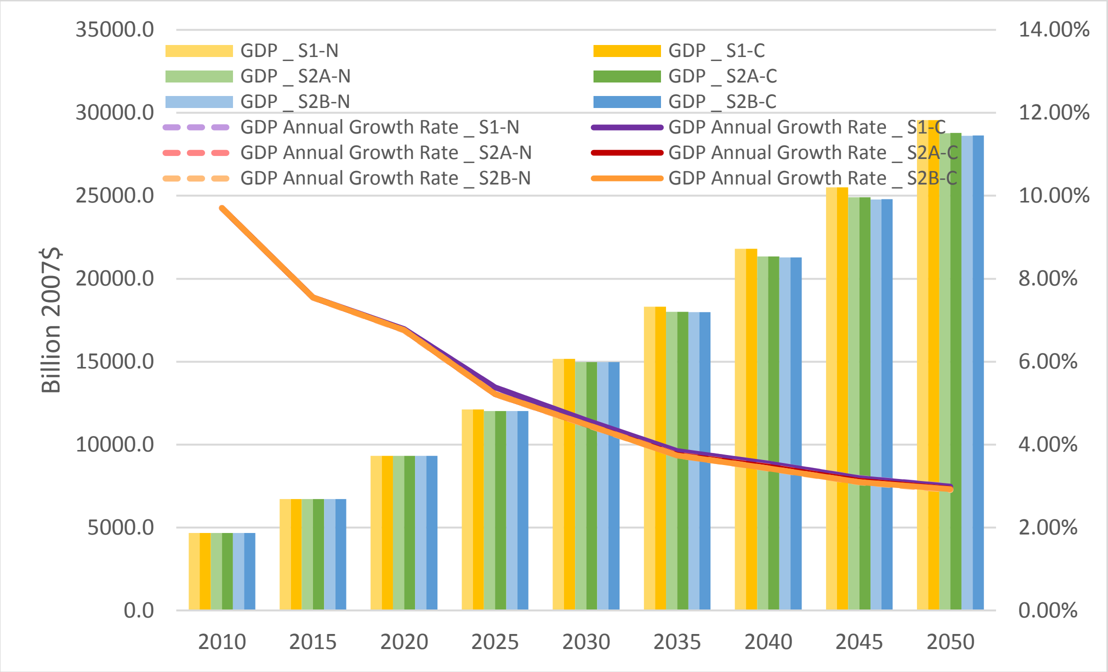


Figure 4.6 China's GDP and GDP annual growth rate 2010-2050

5. Conclusions

(1) CCS could become a cost-effective solution after 2030, thus play an increasingly important role in China's long-term CO_2 mitigation initiatives. With the CCS technology applications in the power sector, China can achieve an added CO_2 emission reduction of 0.6 Gt in 2050 at the same level of carbon tax. Approximately 56% of China's fossil fuel-fired power plants will choose to install CCS technology to achieve a more aggressive low carbon transformation with a total captured CO_2 emission amounting to 1.4Gt .

(2) Approximately 13% and 27% of the CO_2 emission reduction from the Continued Effort scenario (S1) to the Accelerated Efforts scenario (S2A) and to the more aggressive Accelerated Efforts scenario (S2B) could come from the application of CCS technology in the power sector in 2050, respectively, indicating that the more aggressive China's low carbon transformation is the more CCS technology can contribute.

(3) The introduction of a higher level of carbon tax will enable coal-fired power plants with CCS technology to be more cost effective than natural gas fired ones, leading to the occurrence of a substitution of coal for national gas after 2040. It does not only bring new opportunities for coal use but also has important implications for improving China's energy security given the fact that China's natural gas supply relies heavily on overseas markets.

(4) 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 technology applications in the power sector, respectively, indicating that CCS applications in the power sector could avoid a GDP loss of 0.1%.

(5) Public policy will play a vital role in wide deployment of CCS technology in China's power sector. A carbon price not lower than \$35/t CO_2 appears to be a necessity for the large-scale application of CCS technology in the power sector.

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