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Component A–Work Package 5b Report: Opportunities for CCS Deployment in China under Low Carbon Transformation Scenarios

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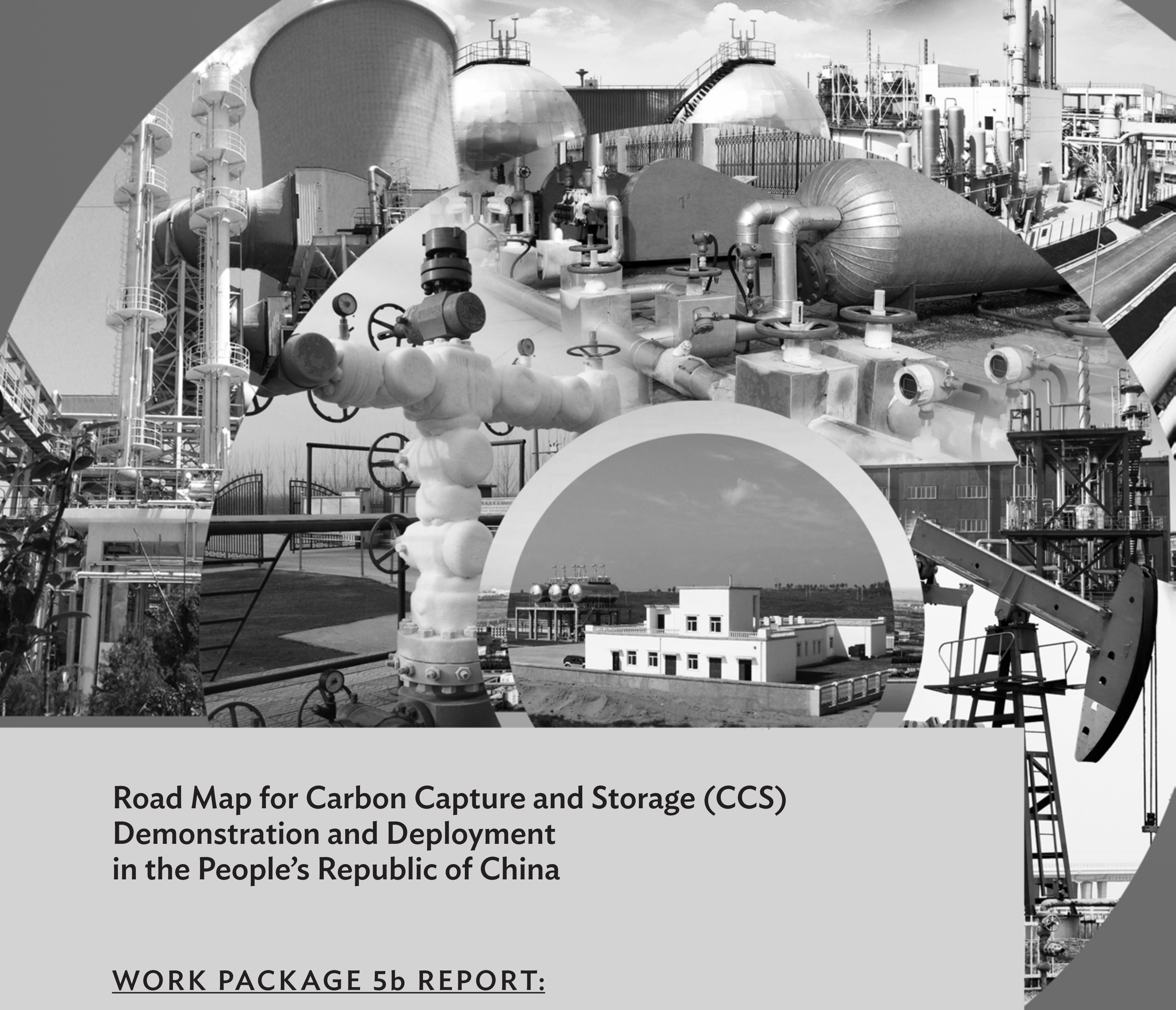

Road Map for Carbon Capture and Storage (CCS) Demonstration and Deployment in the People's Republic of China

WORK PACKAGE 5b 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

GLOBAL CCS INSTITUTE

Department of Energy & Climate Change

Road Map for Carbon Capture and Storage Demonstration and Deployment

Component B: Opportunities for CCS Deployment in PRC under Low Carbon Transformation Scenarios

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Opportunities for CCS Deployment in China under Low Carbon Transformation Scenarios

1 Introduction

Due to the energy-intensive 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 growth is a challenge to be met 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 and biomass with CCS. Though China has strong incentives for energy efficiency, renewable and other low-carbon technologies, coal is likely to remain a dominant part of China's energy mix in the near 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 has strong potential to be cost competitive in a low-carbon future not only in China, but also worldwide.

CCS (carbon capture and storage) from coal combustion is now widely viewed as potentially critical element of a strategy to stabilize the global climate. Given the central role of coal in China's energy system and the urgent need for cutting CO_2 emissions, CCS – currently the only available near-commercial system of technologies that can cut CO_2 emissions from fossil-fuel-based power plants to the atmosphere by 80%-90% – is an important emission reduction option for China. Although the ongoing CCS projects are making progress, 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. While 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 that the major impediment to CCS progress is not considered to be technical uncertainties but, rather, 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 long development periods. 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 report, we evaluate scenarios of CCS deployment depending on different global and national emission reduction targets. The focus is on coal-based power and poly-generation technologies utilizing CCS. In particular, we discuss the potential role of CCS on emission reductions under China's low-carbon transformation paths. Moreover, the impacts of CCS applications in China in terms of macro-economy, energy consumption structure, GDP growth, and industrial output are estimated in the report. These analyses are carried out by using two complementary, global energy-economic and integrated assessment modeling frameworks (C-GEM and MESSAGE). Each of these models is utilized because of its core strengths: C-GEM for its detailed coverage of the macro-economy, and MESSAGE for its detailed representation of energy technologies.

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 in the future; Section 3 briefly describes the two energy-economic models applied for investigating impacts of low-carbon policies on the development of CCS and the impact of CCS on the economy and emissions with Appendix A providing a more detailed description of the modeling tools; Section 4 describes the scenario design and the following Sections 5 and 6 lay out the results of the scenario analysis, where the scenarios are described in detail and the results are discussed; Section 7 summarizes the key insights.

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 Support

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 (STRACO$_2$), 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” Period

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 Methods and Tools

Two complementary global energy-economic and integrated assessment modeling frameworks have been utilized in this study: C-GEM and MESSAGE.

The China-in-Global Energy Model (C-GEM) is a multiregional, multisector, recursive–dynamic, computable general equilibrium (CGE) model of the global economy. The model is one of the major analysis tools developed 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. A particular strength of CGE models such as C-GEM is to account for sectoral impacts of climate policies (see list of sectors in Table 6). In addition, CGEs can be employed to analyze leakage effects due to trade in non-energy commodities (e.g., steel, aluminum, petrochemicals) which is particularly important in case of regionally fragmented approaches to mitigation which influences the competitiveness of individual countries and regions.

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is an integrated assessment modeling framework operated by the International Institute for Applied Systems Analysis (IIASA). MESSAGE combines a systems engineering energy model based on a linear programming (LP) optimization model used for medium to long-term energy system planning and policy analysis with an aggregated macro-economic model called MACRO that allows calculating price-induced changes of energy demand and aggregate macro-economic impacts of climate and energy policies. MESSAGE has a high technological resolution and represents many different energy supply routes from primary to final energy which allows analysing competition between alternative energy conversion technologies in detail. As a full-fledged integrated assessment model, MESSAGE also represents emissions of non-CO_2 greenhouse gases (GHGs) such as methane, N_2O and aerosols and can link emissions pathways to climate outcomes.

Table 1. Overview of CCS technologies represented in C-GEM and MESSAGE (see Table 7, Table 8, Table 13 for more details).

Sector	**Fuel**	**C-GEM**		**MESSAGE**	
		w/o CCS	**w/ CCS**	**w/o CCS**	**w/ CCS**
Electricity	Coal	X	X	X	X
	Natural Gas	X	X	X	X
	Biomass	X		X	X
Liquids/ Polygen.	Coal	X	X	X	X
	Natural Gas			X	X
	Biomass	X		X	X
Gas	Coal	X		X	X
	Biomass			X	X
Hydrogen	Coal			X	X
	Natural Gas			X	X
	Biomass			X	X

Table 1 provides an overview of the different CCS technologies represented in the C-GEM and MESSAGE models. The modeling tools are described in more detail in Appendix A. Based on the scenario design described in the following Section 4, the results of the coordinated scenario analysis performed with the two models will be presented in Sections 5 and 6.

4 Scenario Design

This section describes the general scenario design used in this study, including policies and assumptions about macroeconomic development (Section 4.1). Importantly, key socio-economic drivers for China (population and GDP) were harmonized between C-GEM and MESSAGE before running the same policy scenarios with both models. Section 4.2 then describes a set of sensitivity cases that were primarily performed with the MESSAGE model.

4.1 General scenario description and assumptions

4.1.1 Scenario description

To illustrate China's possible long-term emission reduction levels, we designed three scenarios – No Policy, Existing Efforts and Accelerated Efforts with early CCUS – to reflect different levels of policy effort. Under the mitigation scenarios, the impacts of CCS technologies are analyzed, in each of the following situations: without CCS technologies, with conventional CCS technologies, and with conventional CCS technologies and poly-generation with CCS technology (as shown in Table 2).

Table 2. Scenario Design.

	No Policy Scenario (NP)	**Existing Efforts Scenario (EE)**	**Accelerated Efforts Scenario with early CCUS (AE)**
No CCS	NP	EE-N	AE-N
Conventional CCS		EE-C	AE-C
Conventional CCS + Poly-generation-CCS		EE-P	AE-P

The key assumptions of No Policy Scenario, EE scenario and AE scenario are shown in Table 3.

4.1.1.1 "No Policy (NP)" Scenario

NP scenario is a reference scenario, under which there is no policy represented in the model. It reflects the situation without any policy intervention and gives an upper limit of the emissions and economic growth.

As a counterfactual reference for the other two policy scenarios, NP scenario demonstrates China's energy consumption and emissions trajectories where there is no energy or emissions policy constraints from 2010 to 2050. NP scenario does not exist in reality, and is just used as a reference to show the impact of policy intervention.

4.1.1.2 "Existing Efforts (EE)" Scenario

EE scenario is developed to reflect China's existing efforts, which will lead to the achievement of China's Copenhagen commitment. China has achieved a carbon intensity reduction of 21% over the Eleventh Five-Year Plan, and targets a further reduction of 17% over the Twelfth Five-Year Plan. As a result, if China can achieve a carbon intensity reduction of 3% per annum over the Thirteenth Five-Year Plan (2016-2020), it can accomplish a carbon intensity reduction of approximately 44% from 2005 to 2020, well meeting its Copenhagen carbon intensity commitment. In this context, we assume that China would maintain a carbon intensity reduction rate of at least 3% per annum from 2016 through 2050 under EE 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 EE scenario 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 160GW capacity by 2050, given the assumption that the development of nuclear energy would slow down after 2020 due to the security issues, 4) subsidizing renewable energy according to present level of benchmark electricity price (0.51-0.61 Yuan/kWh for wind power, 1-1.15 Yuan/kWh for solar power, and 0.75 Yuan/kWh for biomass electricity) by renewable energy surcharge imposed on terminal electricity consumptions, 5) an implicit carbon price to represent policies such as subsidy on industrial energy saving or subsidy on pollutions that have a direct or indirect impact on emissions reduction. In addition to the fossil resource tax and renewable feed-in tariff currently implemented in China, we assume there would be an implicit carbon price to maintain the Copenhagen pledge momentum after 2020 under EE scenario.

The policy environment outside of China will also have an impact on Chinese energy use and emissions over the next several decades. Therefore, the MESSAGE model also includes existing, major energy and climate policies for its other regions. The overall stringency of this “weak policy baseline” set-up (which was developed as part of a recent international model inter-comparison project; see Kriegler et al. (2014a)) is consistent with the scenario storyline envisaged in the “Existing Efforts” scenario for China.

4.1.1.3 “Accelerated Efforts with early CCUS (AE)” Scenario

AE scenario includes newly-announced measures set at the Plenum. Under AE scenario it is assumed that China is setting more aggressive targets for CO_2 emission mitigation and clean energy application than under EE scenario. Targets in AE scenario include: 1) a faster decrease of carbon intensity than EE scenario, 2) a faster increase in fossil fuel energy share compared to EE scenario, 3) carbon emission cap from 2020. In AE scenario, the level of fossil resources tax for oil and natural gas will be lifted from the current 5% to 7.5%. The coal resource tax is currently volume-based at a level of 8 Yuan per ton or $1.3 per ton, which is approximately 1.5% of the coal price. Coal has been the primary source of air pollutions and CO_2 emissions in China. Therefore a 10% of coal resource tax is assumed to accelerate coal substitutions and to better internalize the environmental externalities of coal uses under AE scenario. The capacity of hydro power is the same as in the EE scenario, while the capacity of nuclear energy is assumed to reach the potential 350 GW by

2050. It is also assumed that China would accept a higher electricity surcharge for renewable energies that is requested to implement the feed-in tariff policy compared with EE scenario. The Plenum has made an explicit directive for establishing a carbon Cap-and-Trade system in China. Therefore, it is assumed in AE scenario that there will be an economy-wide carbon price (implemented either as a carbon tax or via a cap-and-trade market), which is set at \$25/ton CO_2 in 2030 and rises thereafter (e.g., to \$66/ton by 2050). In MESSAGE, these carbon price levels are also applied globally to all regions.

4.1.1.4 "Peak 2030 Emission (P2030)" Scenario

In addition to the Existing and Accelerated Effort scenarios, a scenario with an emissions pathway that is consistent with the recently announced peaking of emissions in China around 2030 as part of the "U.S.-China Joint Announcement on Climate Change and Clean Energy Cooperation"[1]. In this scenario, the GHG intensity of the economy is reduced by about 4% per year between 2020 and 2050 while otherwise being consistent with the assumptions of the Accelerated Efforts scenario.

Table 3. Policy Assumptions for NP scenario, EE scenario and AE scenario.

	No Policy (NP)	**Existing Efforts (EE)**	**Accelerated Efforts (AE)**
I. Energy System Transformation Targets			
Carbon Intensity	--	At least 3% reduction per annum	Accelerated reduction
Non-fossil energy share	--	At least 15% in 2020	Accelerated increase

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[1] http://www.whitehouse.gov/the-press-office/2014/11/11/fact-sheet-us-china-joint-announcement-climate-change-and-clean-energy-c

Carbon emission cap	--	Not applicable	Applicable
II. Policy			
Carbon price	--	Implicit	Carbon price up to \$25/ton CO_2 in 2030
Fossil resource tax	--	Crude oil & Nature gas: 5% of the price Coal: 8Yuan/ton	Crude oil & Nature gas: 8% of the price Coal: 10% of the price
Feed-in tariff for wind, solar and biomass electricity	--	A 3.8% of surcharge rate on the electricity consumption to implement the policy	A 6.5% of 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.	The same as EE assumption
Nuclear power development policy	--	1) Achieving the existing nuclear development planning target of 40GW in 2015 and 58 GW in 2020; 2) With currently proved plants sites availability of 160GW;	1) Achieving the existing nuclear development planning target of 40GW in 2015 and 58 GW in 2020; 2) With projected plants sites availability of 400GW.

4.1.2 Demographic and macroeconomic assumptions

The population of China in 2010 was 1.34 billion. It is assumed that China's population peaks in 2030 with 1.43 billion, and falls 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.

Table 4. 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), counting 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 Sensitivity cases

A number of sensitivity cases were run with the MESSAGE model in order to better understand the impact of varying certain critical model assumptions. These assumptions can be interpreted as potential technological and policy levers, as will be discussed in the results section later in this report.

The first sensitivity focuses on CCS cost and availability. As a first step, a scenario without CCS (globally applied) was run as a benchmark. Then, in addition to the investment cost trajectories for coal-based technologies (pulverized coal w/ and w/o post-combustion CO_2 capture, IGCC w/ and w/o pre-combustion CO_2 capture, polygeneration facility w/ CO_2 capture) that are shown in Section A.2 of Appendix A, optimistic and pessimistic cost cases were also run. The cost data provided by C-GEM modelers was assigned to be the central estimate. These costs were then uniformly varied by +/-30% in all years in order to arrive at the pessimistic/optimistic cases, as shown in the figures below, and sometimes in addition by +/-15%. Note that because the costs of many other technologies in the model were related to these coal technologies based on simple scaling algorithms (see Appendix A, Section A.2), these sensitivities have a pervasive effect on technology costs throughout the system.

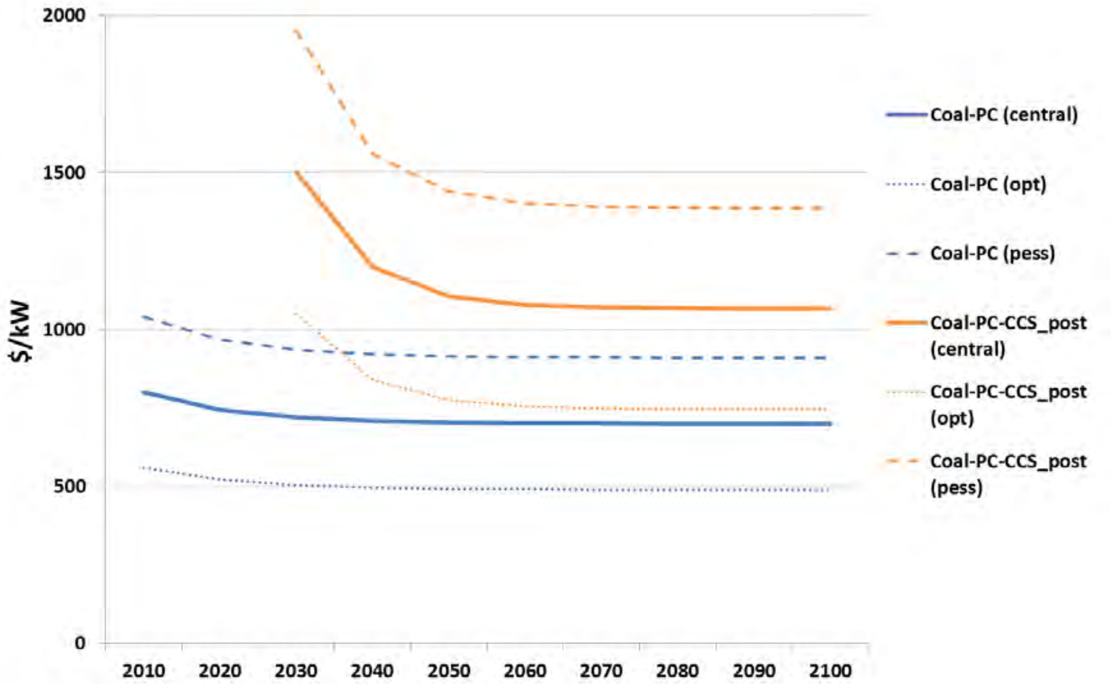


Figure 1. Investment costs assumed for pulverized coal power plant technologies (w/o and w/ CCS) in MESSAGE; both central estimates and optimistic/pessimistic sensitivity cases are shown.

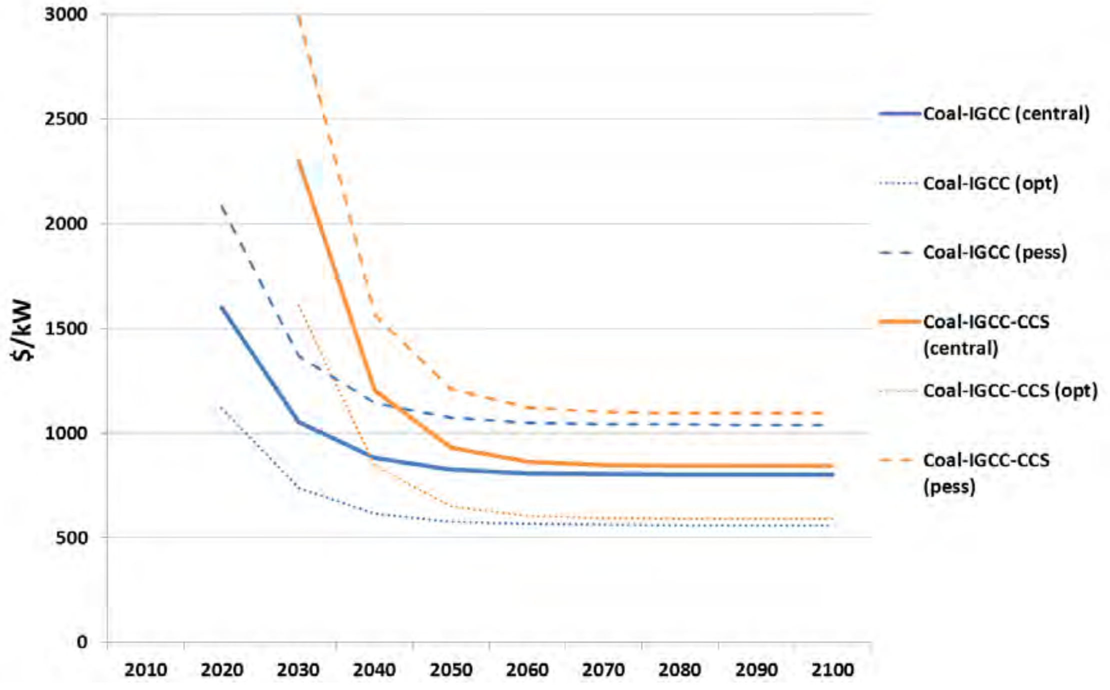


Figure 2. Investment costs assumed for IGCC coal power plant technologies (w/o and w/ CCS) in MESSAGE; both central estimates and optimistic/pessimistic sensitivity cases are shown.

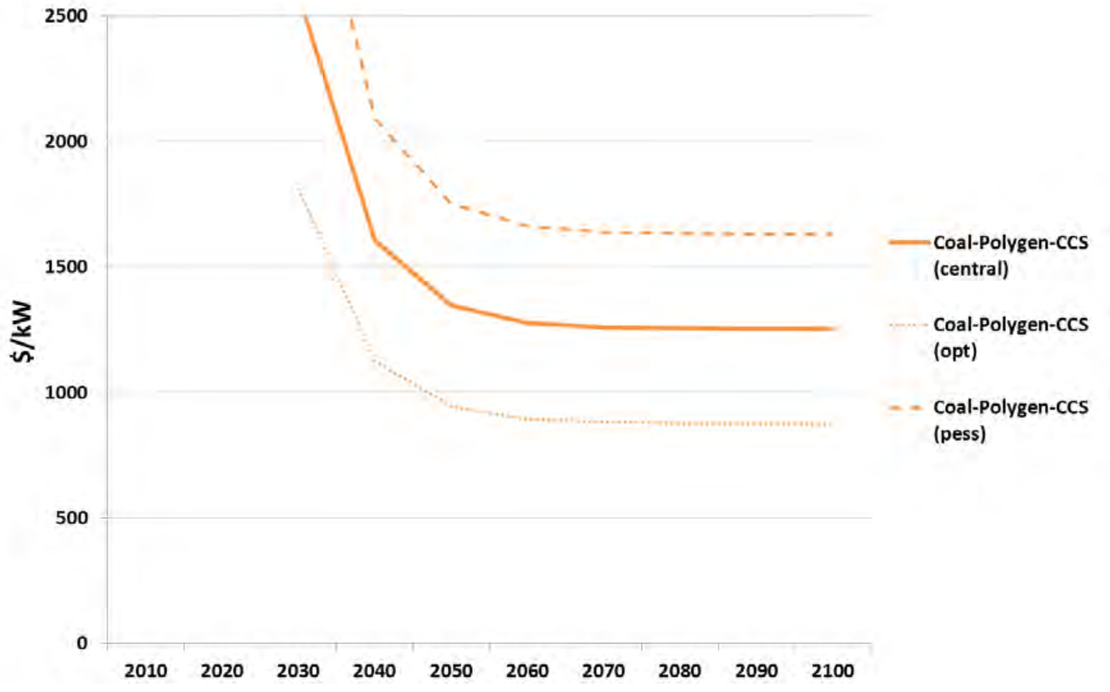


Figure 3. Investment costs assumed for coal poly-generation technologies (w/ CCS) in

MESSAGE; both central estimates and optimistic/pessimistic sensitivity cases are shown.

Second, sensitivity analyses were performed where the plant-level capture rates of CO_2 were varied. This included four different capture rate levels between 85 and 100% and was applied to all CCS-relevant technologies in electricity generation and hydrogen production. Note that no variation of capture rates was made for poly-generation facilities given that a significant share of the input fuel carbon remains in the liquid fuel products.

Third, sensitivity cases were run to analyze the impact of co-firing biomass along with coal in power plants equipped with CCS. Because the biomass feedstocks in MESSAGE are assumed to contain zero fossil carbon, such co-firing can compensate residual fossil fuel emissions, including vented CO_2 emissions as well as upstream production of CO_2 and CH_4 (e.g., in coal mining). A maximum biomass co-firing limit of 25% has been assumed in consultation with engineers at Tsinghua University.

Finally, to also explore the impact of cost assumptions for competing low-carbon technologies on CCS deployment, a number of sensitivity cases that vary future cost development of nuclear power and several renewable energy technologies, including wind power, solar PV and Concentrating Solar Power (CSP), have been varied systematically. For nuclear power, we assume – as for CCS technologies – 30% higher or lower costs compared to the default assumptions documented in Appendix A, Section A.2.2. For wind power and CSP, costs are varied up and down by 20%-points and for PV by 30%-points.

5 Scenario Analysis of CCS Deployment in China with the C-GEM model

In this section, we apply the established China-in-Global Energy Model (C-GEM) to evaluate CCS technology application scenarios depending on different global and national emission reduction target. Section 5.1. discusses CCS technology's impact on emissions, energy and economy in different scenarios; Section 5.2. discusses the effect of introducing poly-generation technology with CCS.

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

5.1.1 Impact on Emissions

Our analysis shows that if implemented, the reform directives established at the Plenum will lead to a remarkable change in the trajectory of CO_2 emissions, and bring significant opportunities for clean energy applications in China. In NP scenario, China's CO_2 emission will keep increasing, from 5.9 Gt in 2007 to 21.1 Gt in 2050, while following the Copenhagen-pledge trajectory, China's CO_2 emission will peak at approximately 12.4 Gt in 2045, and fall back to 12.3 Gt in 2050. Along with the accelerated transformation path, however, China's CO_2 emission will reach the peak earlier, at approximately 10.3 Gt in 2030, and then decline to 8.5 Gt in 2050, as shown in Figure 4.

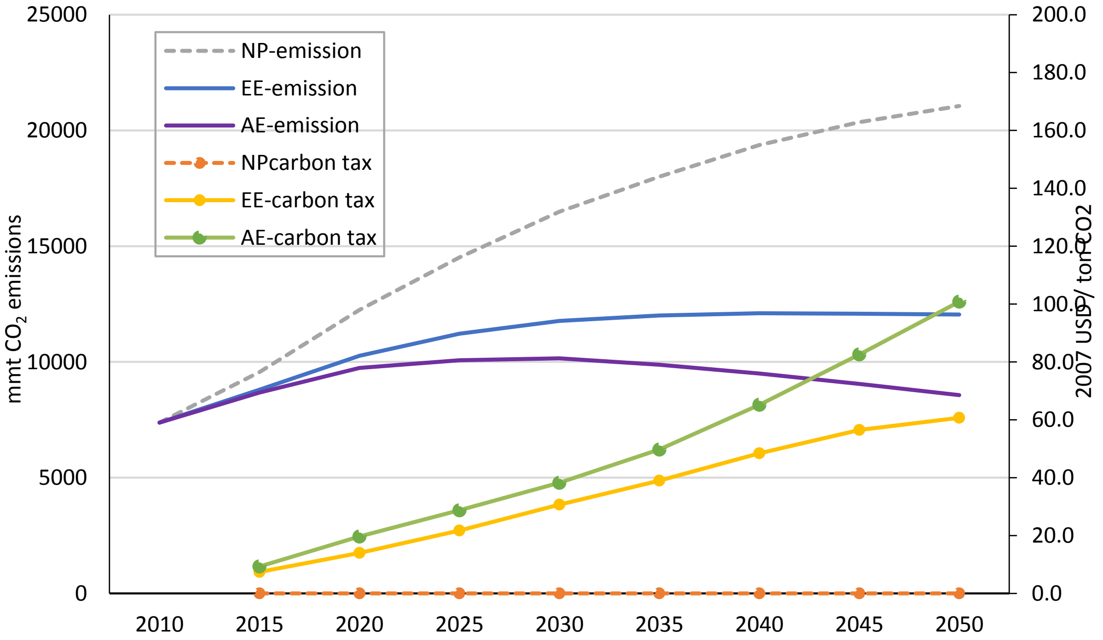


Figure 4. Trajectories of Total CO2 Emission and Carbon Price.

CCS technologies are playing an important role in emission mitigation in both EE scenario and AE scenario. In our analysis, CCS enters the market as a commercialized technology when carbon price exceeds $38/ton. As shown in Figure 5, in EE scenario, CCS emerges in 2030 and achieves a 1.4 Gt CO_2 emission reduction – contributing around 15% of the total CO_2 reduction compared to NP scenario – in 2050. As for in AE scenario, CCS technologies enter the market in 2030 and reduce CO_2 emission by 1.9 Gt – 0.5 Gt more than the emission reduction in EE scenario – in 2050.

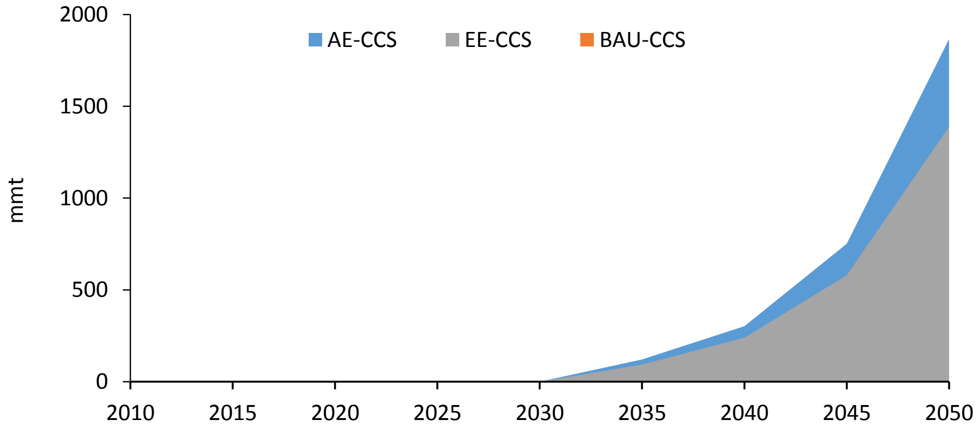
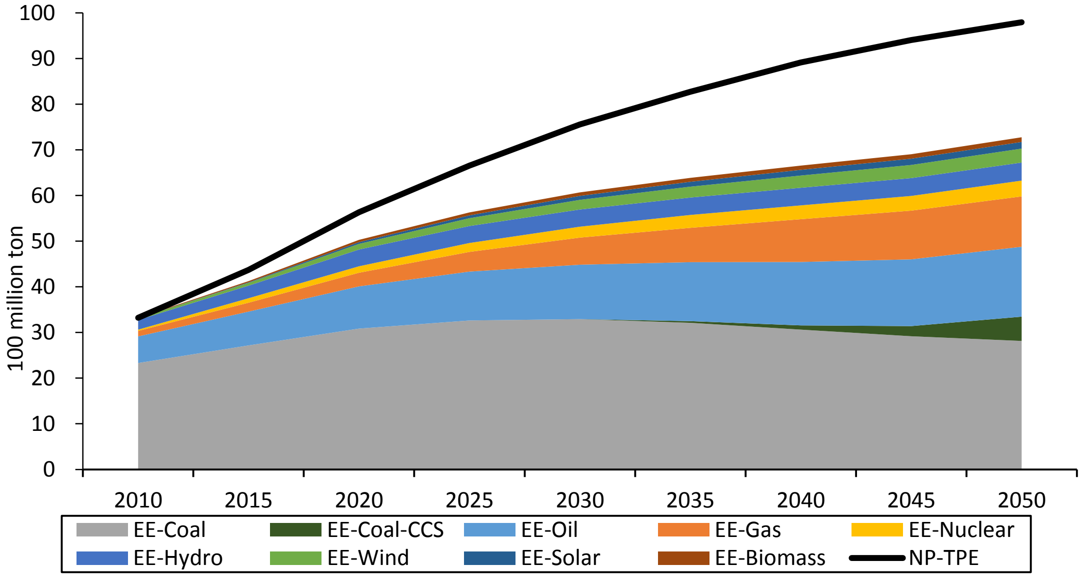


Figure 5. CO_2 Emission Reduction by CCS Technologies.

5.1.2 Impact on Energy System

Under AE scenario and EE scenario, China's energy consumption declines, while the energy structure also transforms at the same time. Under AE scenario, coal consumption in China reaches the peak during 2020-2025, with the value of approximately 2.85 Gtce, which is 0.45 Gtce less than that under the EE scenario. The decline after the peak value keeps a fast pace, as shown in Figure 6. Due to the better development of CCS technologies which results in more consumption of clean coal, natural gas in AE scenario shows characteristics of a transition energy. Natural gas in AE scenario keeps growing in a high rate before 2040, and declines gradually after 2040 due to the substitution by coal-CCS.



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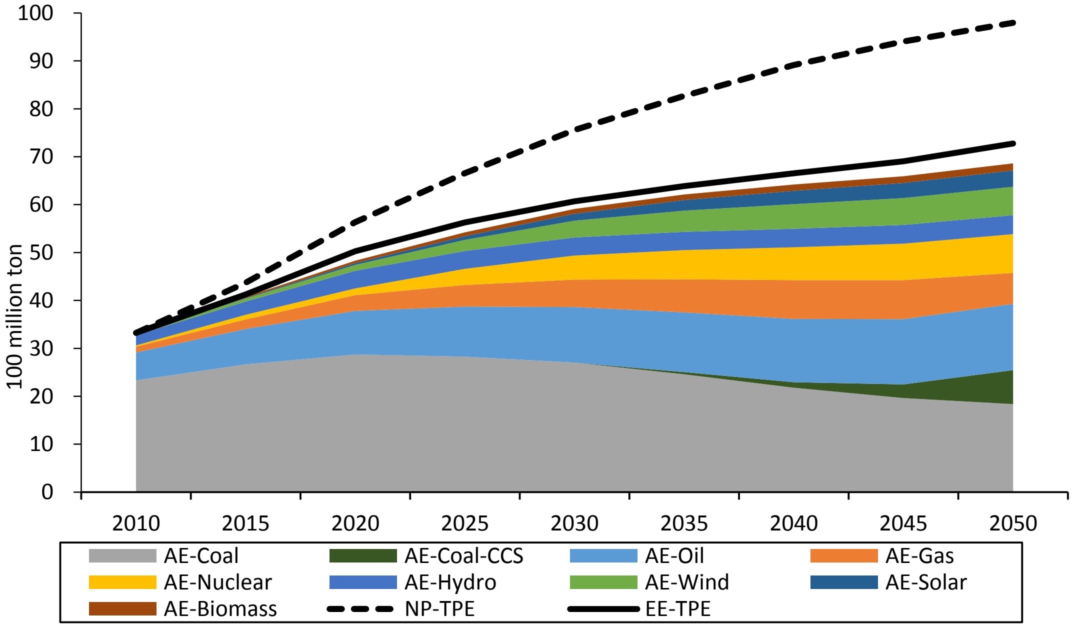

(b)

Figure 6. Primary Energy Structure from 2010 to 2050 in China.

5.1.3 Impact on Mitigation Cost

Under the same emission constraint, CCS technology is helpful to reduce the mitigation cost, especiall in the “deep cut” stage after 2040. As for No CCS scenario in EE-N scenario and AE-N scenario, there is a carbon price to enforce emission reduction. Shown in Figure 4.4, carbon price starts to rise in 2015, and reaches approximately $71/ton and $120/ton in 2050 respectively in EE scenario and AE scenario. CCS plays an important role in controlling the carbon price and further reducing CO_2 emissions after 2040. For EE scenario without CCS technologies, carbon price in 2050 will be up to $63.8/ton. Once introduced CCS technology in the EE scenario, carbon price is declined to $59.5/ton. The impact on carbon price of CCS technology is more significant in AE scenario. In AE scenario in 2050, carbon price is $123.3/ton and $100.3/ton without and with CCS technology respectively. The implementation of CCS technology brings a $4-$23 reduction in 2050's carbon price. The trajectories of carbon price with and without CCS technology from 2015 to 2050 in the two scenarios are shown in Figure 4.4. As the figures demonstrate, carbon price would be 7%-20% higher than it is in 2050 without the implement of CCS technology, which will result in a significant increase in social abatement costs. Higher carbon price also leads to higher electricity price. Without CCS, China's GDP is slightly lower – about 0.7% in 2050 in AE scenario. Comparing the two graphs in Figure 7 gives another implication – impact on abatement cost of CCS technology is more significant as the emission mitigation target becomes more stringent.

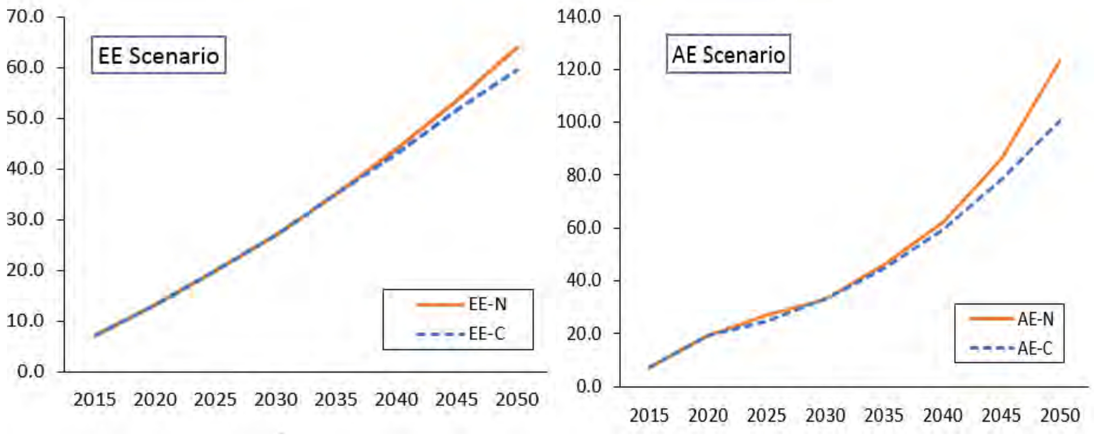

Figure 7. Impact of CCS on Carbon Price in AE Scenario.

5.1.4 Economic Impact

The carbon emission cap and other emission reduction measures result in an abatement cost which impacts the macro economy and causes a cumulative GDP drop of 0.6%. Implementation of carbon price mechanism and the high cost of clean energy increase the electricity price, as well as the cost of other energy resources in China, resulting in the decline of China's industrial competitiveness. International trade under AE scenario is 8% lower than that under EE scenario. Figure 8 shows China's GDP in EE scenario and AE scenario.

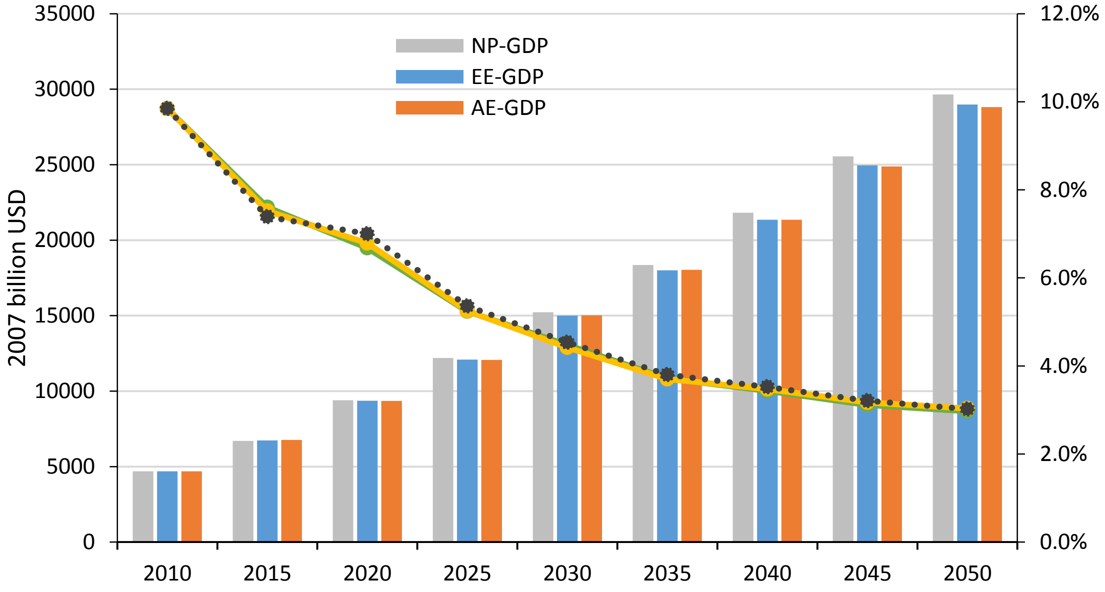

Figure 8. China's GDP in EE Scenario and the Scenario.

Under EE scenario, the electricity price is 14% higher in 2020, 30% higher in 2030, and 58% higher in 2050 compared to 2010 level. The electricity under AE scenario increases even faster, with 19% higher in 2020, 34% higher in 2030, and 76% higher in 2050 compared to 2010 level, as shown in Figure 9.

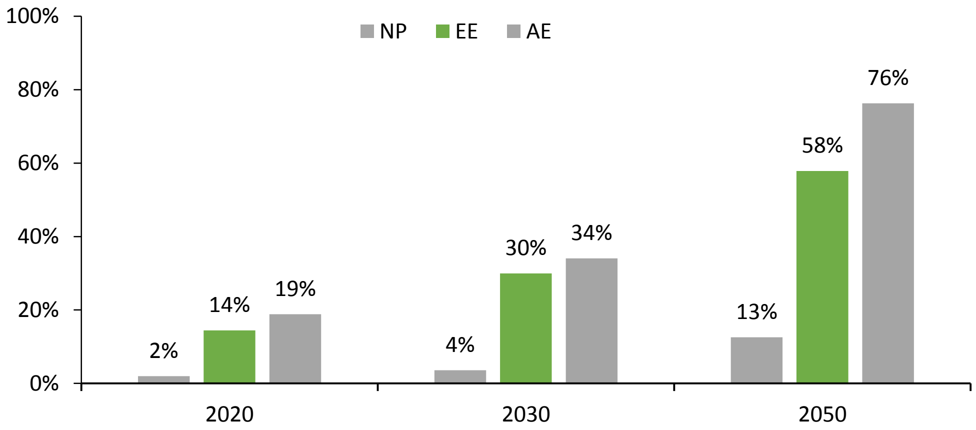

Figure 9. Electricity Price Growth from 2010 to 2050 in NP, EE, and AE scenarios.

Although the deployment of CCS and other emissions reduction technologies increases the energy price and results in the increase of related economic cost, but in a long-term perspective where emissions reduction is of growing importance, the implement of CCS lowers the mitigation cost compared to No-CCS scenario. CCS plays an important role in controlling the electricity price from 2040 to 2050, as shown in Figure 10. For EE scenario without CCS technologies, the electricity price in 2050 will be 58% higher than that in 2010. Once introduced CCS technology in the EE scenario, the electricity price in 2050 is 55% higher than that in 2010, which is a 3% drop compared to the 2010 level. The impact on the electricity price of CCS technology is more significant in AE scenario. In AE scenario in 2050, the electricity price is 87% and 73% higher than that in 2010 without and with CCS technology respectively. The implementation of CCS technology brings a 3%-14% (in 2010 level) electricity price reduction in 2050's carbon price.

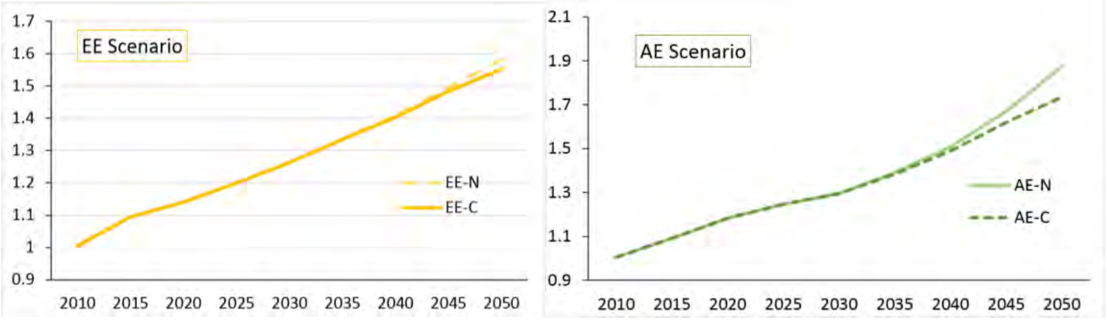

Figure 10. Impact of CCS on Electricity Price in EE scenario and AE Scenario.

5.2 Introducing Poly-generation Technology with CCS

According to relative technological studies, poly-generation technology with CCS has a lower cost than conventional CCS technologies. Due to the lower cost of poly-generation with CCS technology, part of the conventional CCS would be substituted by poly-generation with CCS (Figure 11).

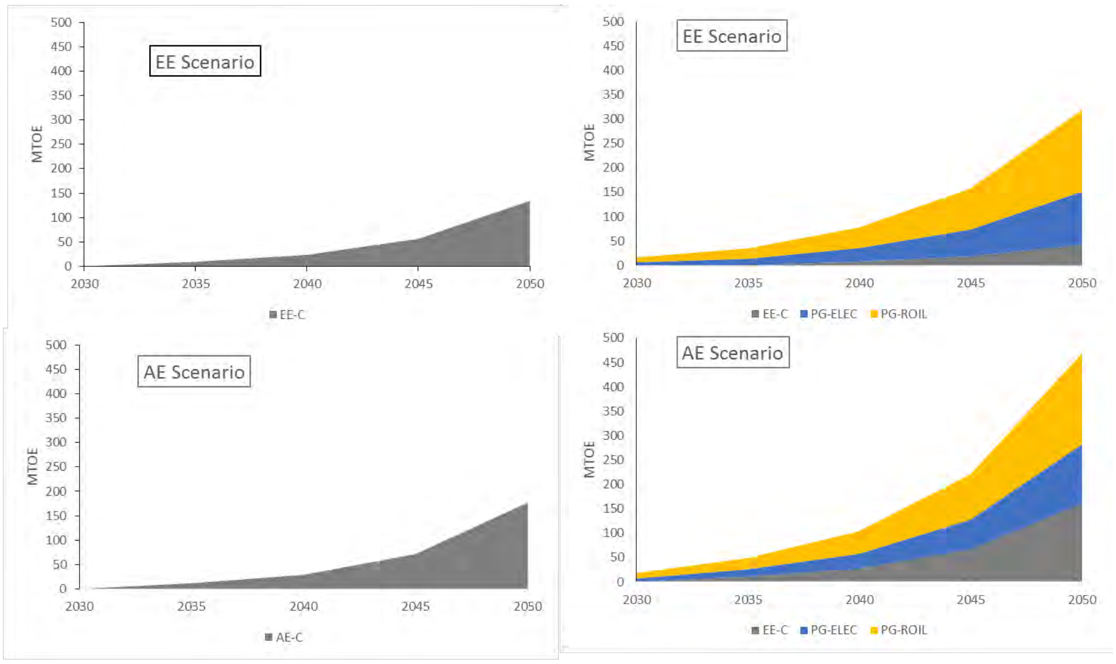

Figure 11. Electricity and Oil Production related to CCS and Poly-generation with CCS.

Introducing poly-generation technology with CCS can effectively lower carbon price and the abatement cost. The carbon price in AE scenario in 2050 decreases by $13/ton when poly-generation with CCS is implemented, and in EE scenario, carbon price in 2050 is $10/ton lower after poly-generation with CCS is introduced, as shown in Figure 12. Our analysis shows that due to its lower cost, poly-generation with CCS could achieve large-scale applications even under the scenario where the emission mitigation targets are not very stringent.

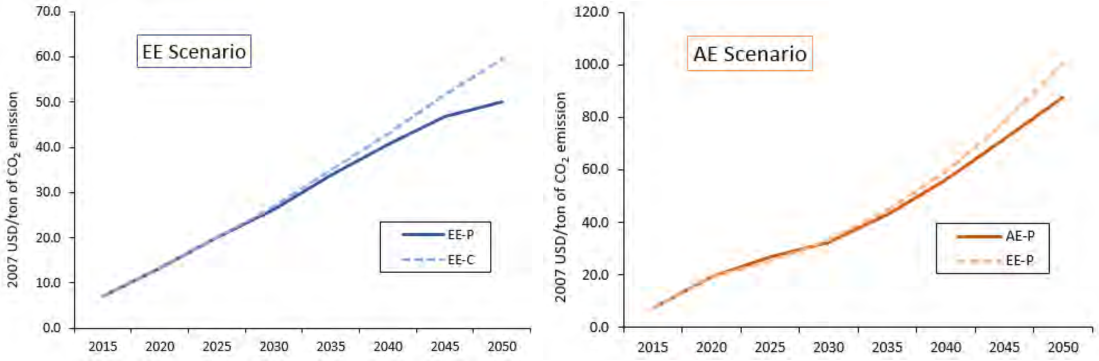

Figure 12. Impact of Poly-generation on Carbon Price in EE and AE Scenario.

While output from conventional CCS technologies is merely electricity from power plants, output from poly-generation technology is both electricity (40%) and oil (60%), see Figure 13. Oil produced by poly-generation technology substitutes for part of the crude oil's consumption, as shown in Figure 4.10. After introducing poly-generation with CCS, crude oil consumption in EE scenario in 2050 declines by 16% – 160 million tons, and that in AE scenario in 2050 declines by 19%, which is 190 million tons. If deployed in large scales, poly-generation with CCS may facilitate to guarantee China's energy security.

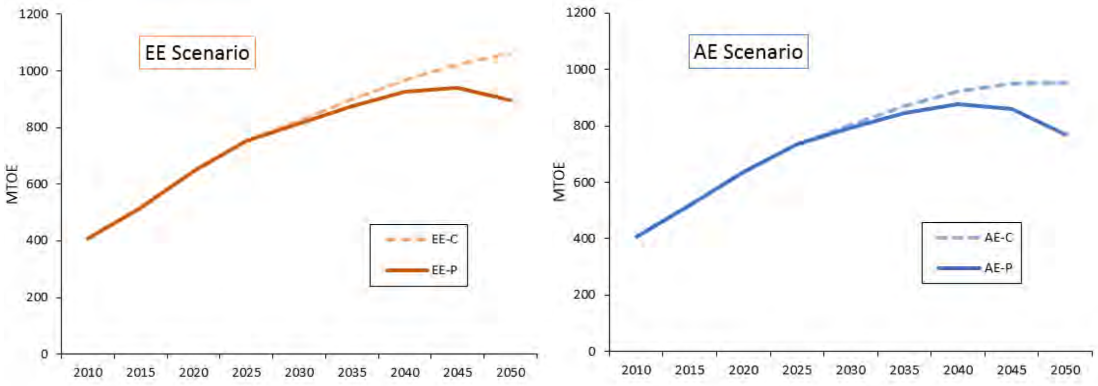

Figure 13. Impact of Poly-generation on Crude Oil Consumption in EE Scenario

6 Scenario Analysis of CCS Deployment in China with the MESSAGE model

This section summarizes results obtained from the MESSAGE model for the various policy scenarios and sensitivity cases described in Section 4.

6.1 Chinese energy use and CO_2 emissions in baseline and climate policy scenarios

As a result of China's projected socio-economic development and the policies depicted in the "Existing Efforts" (EE) scenario, the future energy and emissions picture in China is seen to change from the current situation. In terms of primary energy use, for example, Figure 14 shows (i) a slowdown and eventual peaking of coal, (ii) continued growth of oil and natural gas, with an eventual peaking of the former; and (iii) a moderate increase in nuclear and renewables. Notably, CCS deployment by mid-century is zero in this scenario, both for coal and natural gas. The above observations also apply to electricity use at the secondary energy level (Figure 15). Meanwhile, at the final energy level (Figure 16) the following trends are exhibited: (i) slowdown and eventual peaking of oil, (ii) rapid growth of natural gas and, especially, electricity, and (iii) moderate increase in fossil synfuels and solar thermal (distributed applications).

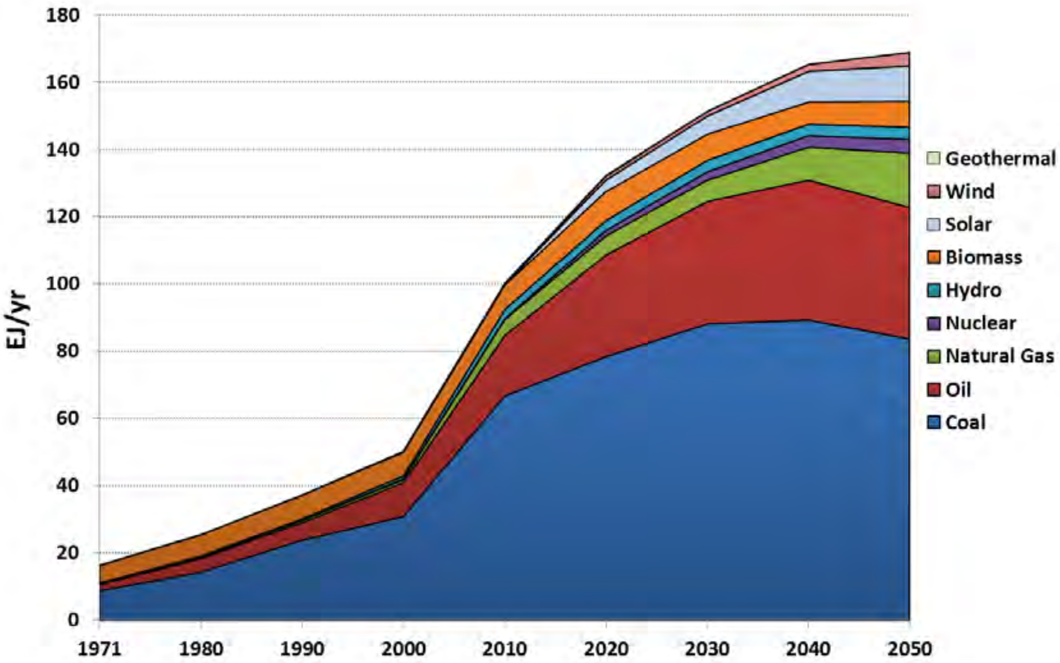

Figure 14. Primary energy supply to mid-century in CHINA+ in the Existing Efforts (EE) scenario.

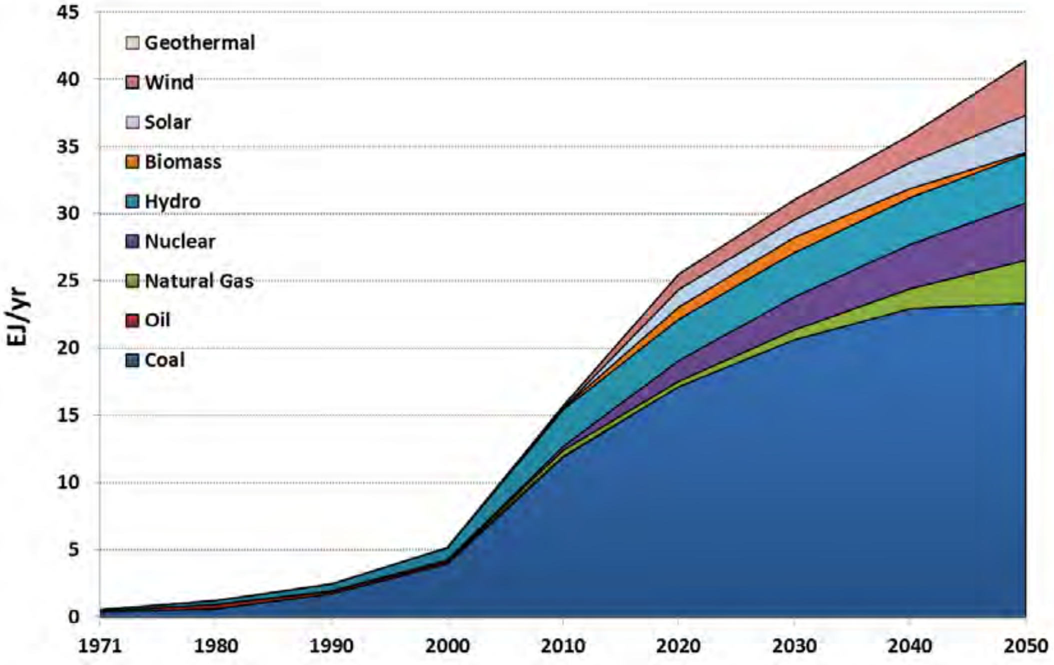

Figure 15. Electricity supply to mid-century in CHINA+ in the Existing Efforts (EE) scenario.

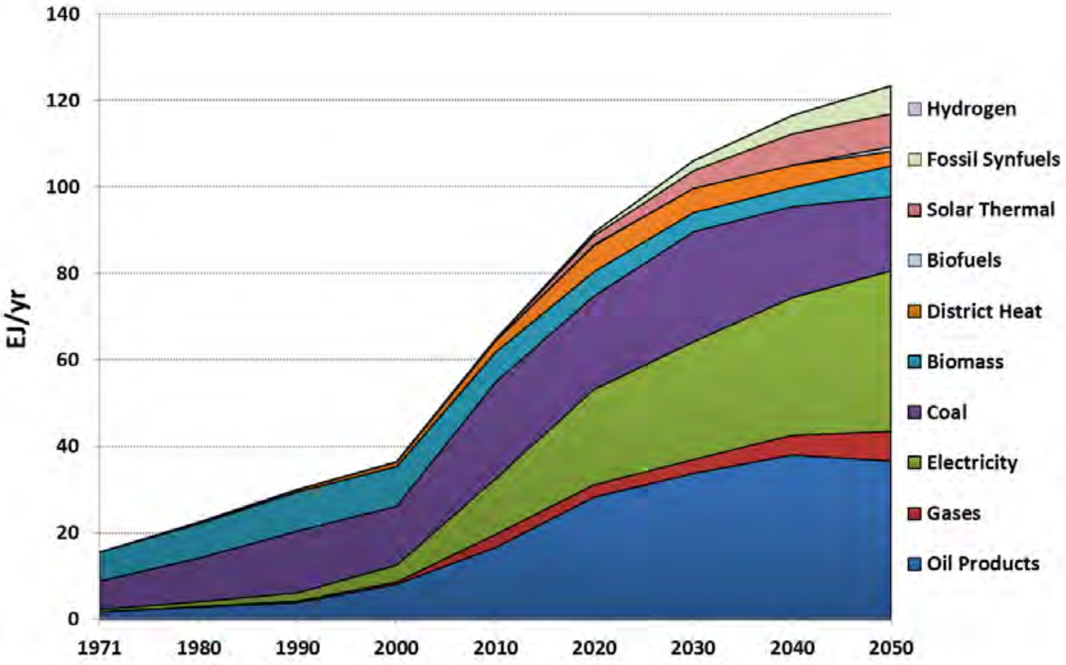

Figure 16. Final energy supply to mid-century in CHINA+ in the Existing Efforts (EE) scenario.

CO_2 emissions growth remains significant in the Existing Efforts scenario (though not at the same rapid rates experienced in China over the past 15 years), with emissions peaking by mid-century at around 12.7 $GtCO_2$/yr (note that this number is for the CHINA+ region of MESSAGE), as shown in Figure 17. The policies included in this scenario result in emissions levels that are considerably lower than they would otherwise be in a hypothetical no-policy baseline scenario (which assumes no climate action whatsoever and wherein CO_2 emissions growth in China remains strong throughout the century).

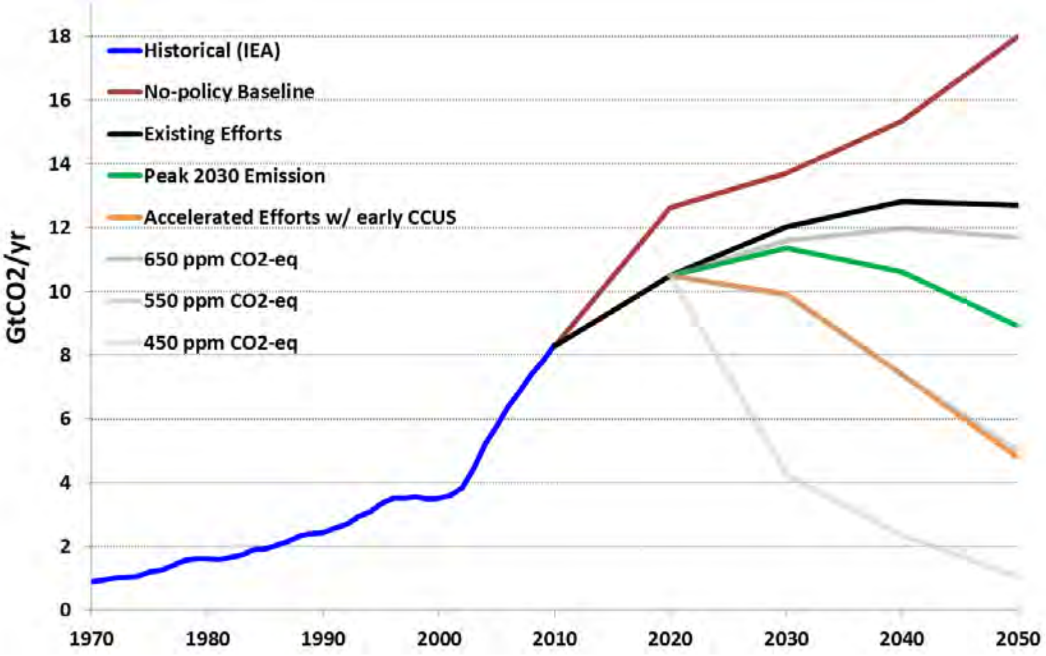

Figure 17. CO_2 emissions from fossil fuels in the CHINA+ region of MESSAGE across several climate policy scenario variants.

More stringent climate policies (relative to those in the EE scenario) have a pronounced effect on energy use and emissions in China over the next several decades. For instance, in the Accelerated Efforts with early CCUS (AE) scenario, fossil fuel CO_2 emissions in CHINA+ peak in 2020 at around 10.5 $GtCO_2$/yr and then fall to 4.8 $GtCO_2$/yr by 2050 (Figure 17). Such reductions represent 18% and 62% decreases from the EE baseline in 2030 and 2050, respectively. In other words, the AE carbon price scenario is consistent with a peaking of China's greenhouse gas emissions before 2030.

The “Peak 2030 Emission” (P2030) scenario presents a middle ground in between the EE and the AE scenarios with fossil fuel and industrial CO_2 emissions in 2030 at 11.4 $GtCO_2$/yr, i.e. about 650 $MtCO_2$ lower than in the EE scenario, and in 2050 at some 8.9 $GtCO_2$/yr, i.e. below current levels of CO_2 emissions.

To put these emissions reduction levels in context, Figure 17 also shows results for three global climate policy benchmark cases that were also run with MESSAGE (achieving 650, 550, 450 ppm CO_2-eq by 2100)[2]. The AE scenario is found to fall in between the 550 and 450 ppm CO_2-eq cases (though very similar to the 550 case) in terms of the emissions reductions required by 2050 (Figure 17). For comparison, the emissions levels achieved by 2050 in the AE scenario fall into the range of the Enhanced Low Carbon (ELC), but do not quite reach the level of the 2degree scenarios as presented in a previous ADB Technical Assistance Consultant’s Report (Beijing Jiaotong University 2014). The P2030 case ends up right between the 550 and 650 ppm cases, thereby not being compatible with the 2°C target adopted by the UNFCCC anymore.

To achieve reductions of this scale would require major improvements in energy efficiency and a massive upscaling of low-carbon energy supplies, including renewables (primarily solar, wind and biomass) and potentially nuclear power and carbon capture and storage. The specific role of the latter is discussed at length in the following sections.

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[2] The global climate policy scenarios assume cost-effective mitigation, i.e. mitigation measures are implemented when and where they are cheapest. The allocation of mitigation measures across regions by no means provides an indication of who should pay for them.

Box 1. Climate outcomes of MESSAGE scenarios

A scenario with a global carbon price growing at 5% p.a. and reaching 25 \$/tCO$_2$-eq in 2030 (66 \$/tCO$_2$-eq in 2050) is consistent with the long-term target of staying below 2 °C temperature rise over the 21st century.

Atmospheric CO$_2$-equivalent concentrations (including all GHGs and other radiative forcing agents) are about 520 ppm CO$_2$-eq in 2100 in the AE w/ early CCUS scenario. This approximately corresponds to an “as likely as not” (50/50%) chance of staying below 2 °C, according to other scenarios in the global pathways literature. Meanwhile, the policies implemented in the EE scenario, which assumes that all existing, major energy and climate policies are implemented throughout the world, lead to atmospheric CO$_2$ concentrations above 800 ppm CO$_2$-eq in 2100. Note that these climate change estimates depend on assumptions about climate policy in other parts of the world as well as on what happens beyond 2050 in China and other countries. Therefore, they are only indicative of global climate change corresponding to the level of climate policy ambition assumed in China.

6.2 The potential role of CCS in China

The potential of CCS to cost-effectively mitigate Chinese CO$_2$ emissions is significant, with captured emissions in the range of 2 GtCO$_2$/yr or more by 2050. The amount of CO$_2$ captured and stored represents a significant share of total mitigation: about one-quarter of CO$_2$ emission reductions relative to the Existing Efforts scenario. The following sections discuss the value of CCS (Section 6.2.1), the role of CCS in different sectors of the energy system (Section 6.2.2), as well as a number of important determinants for the success of CCS, including future costs, capture rates, the potential for co-firing biomass, niche market formation and the availability of geological CO$_2$ storage potential (Sections 6.2.3 to 6.2.7). Section 6.2.8 discusses, more generally, the co-benefits for air quality that can be attained in China via greater utilization of low-carbon technologies, such as CCS.

6.2.1 Value of CCS

A standard approach in the scientific literature to determine the value of CCS for the transformation toward a low-carbon economy is to exclude CCS from the portfolio of mitigation technologies (Edenhofer et al. 2010; Krey and Clarke 2011; Krey et al. 2014; Kriegler et al. 2014b; Riahi et al. 2014; Tavoni et al. 2012). As a result mitigation costs to achieve an identical mitigation goal increase, or – from an alternative perspective – the level of abatement at a given mitigation cost level or carbon price deteriorates.

Following this approach, we find that the absence of CCS technologies from the available mitigation portfolio has important economic implications. Both carbon prices and macro-economic losses (measured as percentage loss of GDP compared to GDP in the EE scenario) increase markedly. The AE w/ early CCUS scenario sees fossil fuel CO_2 emissions in the CHINA+ region of MESSAGE falling to 4.8 $GtCO_2$/yr by 2050. If CCS is removed from the technology portfolio (worldwide), a higher carbon price is needed to achieve a similar level of emission reductions. More specifically, an almost 25% increase in the carbon price by 2050 is required to achieve the same level of abatement as in the scenario with CCS technologies available (AE w/ early CCUS). The economic consequences of removing CCS from the technology portfolio is also associated with an additional 0.4 %-points loss in Chinese GDP in 2050 (Figure 18), largely due to the need for increasing the carbon price to achieve similar levels of mitigation as in the case where CCS is available.

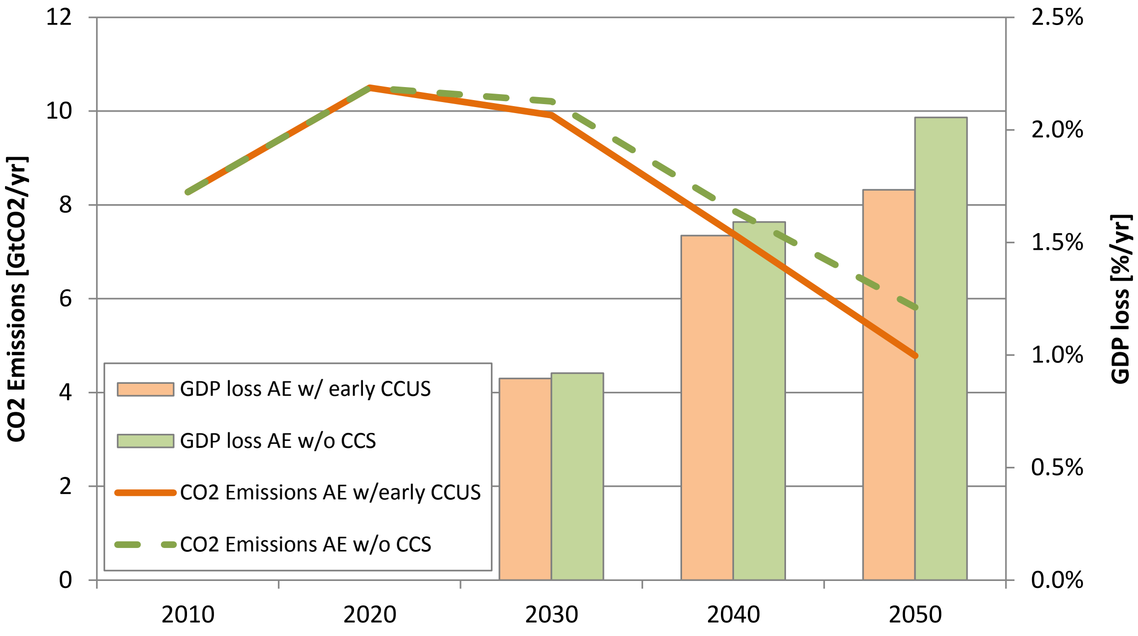

Figure 18. Fossil fuel and industrial CO_2 emissions (lines / left axis) and GDP losses (bars / right axis) in the CHINA+ region under the AE carbon price scenarios with and without CCS. Note that for the fixed carbon price trajectories, GDP losses are almost identical with and without CCS and therefore not shown separately.

The literature lists several reasons for this high value of CCS under stringent climate policy scenarios, (i) the ability to transition from the currently fossil fuel dominated energy system to a low-carbon energy system, (ii) the ability to apply CCS in various sectors including electricity generation, liquid fuel and hydrogen production, and industrial process emissions from, e.g., cement or steel production, and (iii) generating negative emissions in combination with biomass to compensate for delayed mitigation action as well as residual emissions from sources with high mitigation costs in the long-term (IPCC 2014; Krey et al. 2014).

6.2.2 Sectoral contribution of CCS

As mentioned in the previous paragraph, CCS is a versatile technology that can be applied in different sectors of the energy system (see Table 1 and Appendix A, Section A.2.2 for an overview of CCS technologies in the MESSAGE model). Our scenario analysis indicates that CCS technologies can be important contributors to climate mitigation in many sectors of the Chinese energy system, including electricity generation, liquid fuel production, hydrogen production and industrial applications (Figure 20).

The total amount of CO_2 captured from fossil fuels starts out at a level of a few $MtCO_2$ per year in 2020, mostly related to early opportunities in coal chemical and coal-to-liquids plants, growing to about 100 $MtCO_2$ by 2030 (central estimate; ADB 2015, Section V). Moreover, scenario analyses with MESSAGE indicate that by 2030 under the AE w/ early CCUS scenario, cost-effective CCS opportunities of about 50 to 230 $MtCO_2$ captured exist (Figure 19), depending on the costs of CCS. These sensitivity analyses, as well the importance of the costs of competing technologies (renewables, nuclear) and of niche market formation for the long-term potential of CCS, can be found in the following sections.

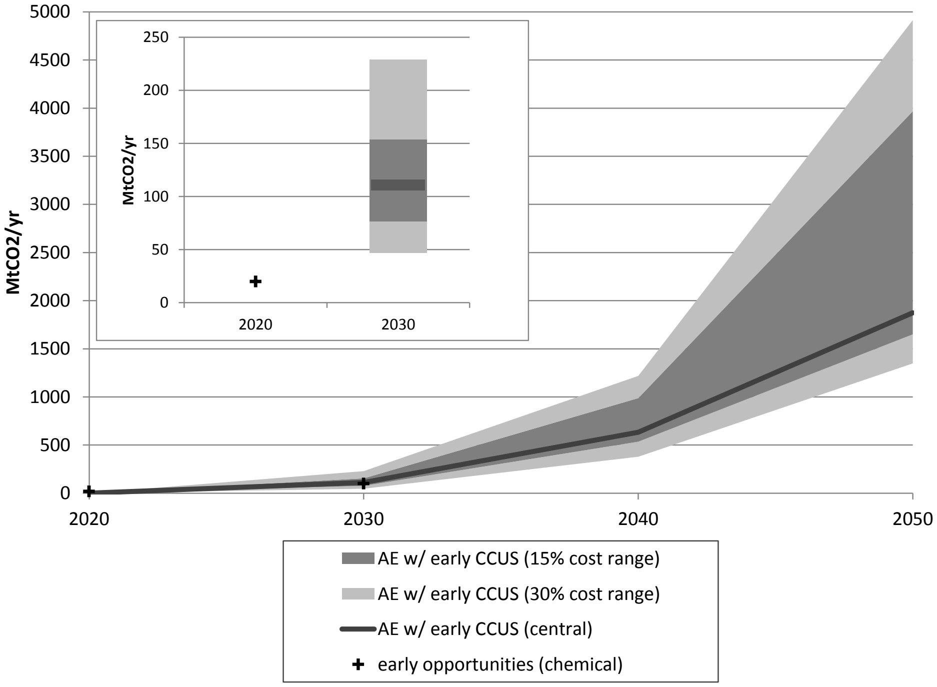

Figure 19: Development of annual CO_2 captured in CHINA+ in the AE w/ early CCUS scenario under different cost assumptions for CCS, compared to estimates of early opportunities for CCS deployment by 2020 and 2030.

Coal CCS technologies show significant market potential in the electricity sector in the AE w/ early CCUS scenario. Depending on future cost and performance development of coal power generation technologies with CCS by 2050, the CCS share of total electricity generation can reach 25% or more. It is noteworthy mentioning that coal CCS has important competitors in the electricity sector, because numerous low-carbon electricity generation technologies with high deployment potential exist (cf. Section 6.2.3), including nuclear energy and various forms of renewable energy (e.g., wind, solar PV and CSP). Therefore, competing low-carbon technologies, such as nuclear and renewables, contribute the majority of emission reductions in the electric sector in the central AE w/ early CCUS scenario.

CCS plays as bigger role in mitigating CO_2 emissions within the liquids, hydrogen and other energy conversion sector than it does within the electric sector in the AE w/ early CCUS scenario (see Figure 20). This is in part due to fewer and more costly alternatives for producing liquid fuels and hydrogen. In particular producing hydrogen from domestic coal using CCS can become an attractive option if hydrogen applications in energy end-use sectors (e.g., industrial applications such as hydrogen-based steel production, hydrogen fuel cell vehicles) become cost-competitive and a transmission and distribution infrastructure can be established.

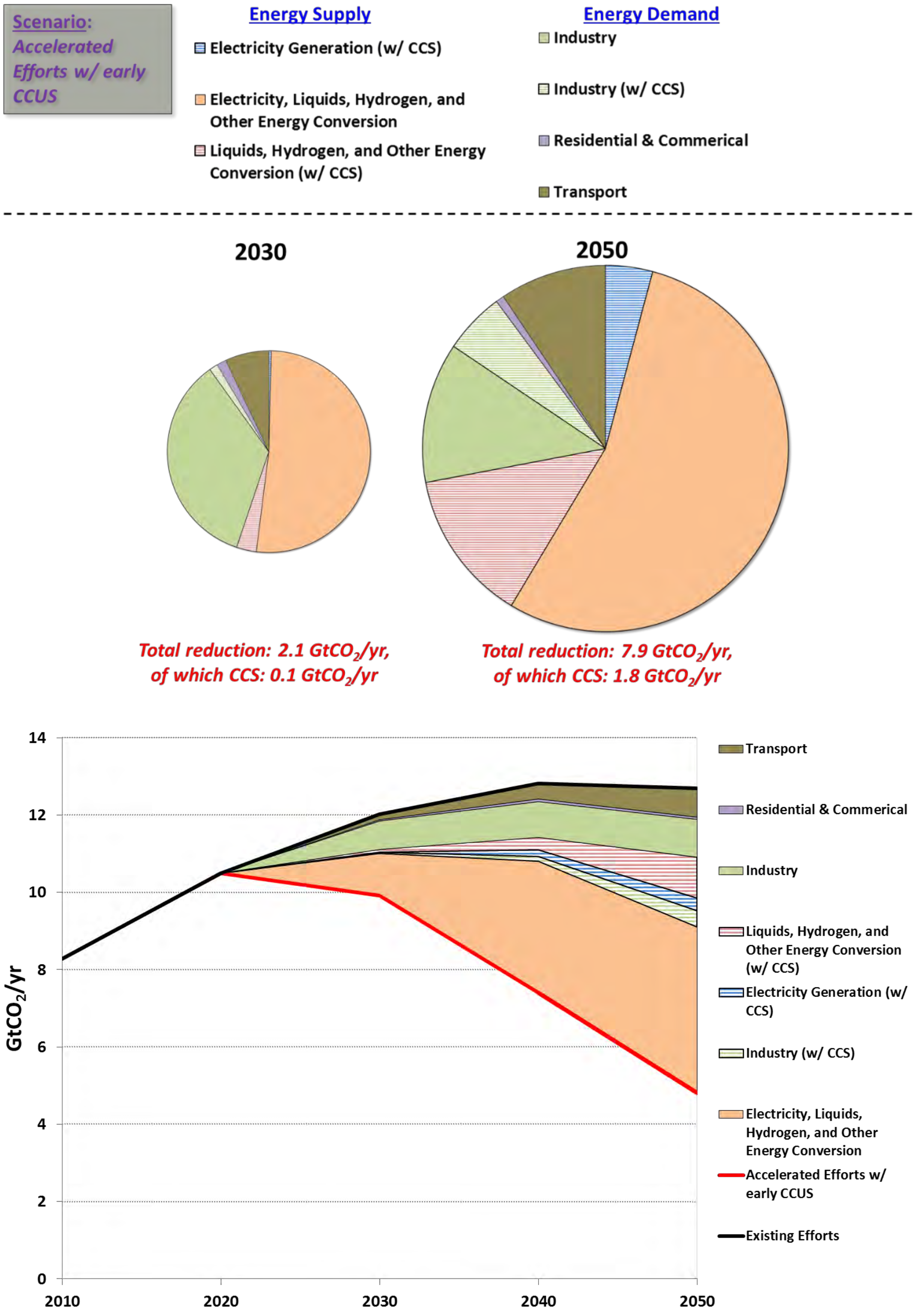

Figure 20. Reductions in CHINA+ CO2 emissions from fossil fuels and industry in the AE w/ early CCUS scenario, relative to the Existing Efforts scenario. CCS contributions within each sector (including both fossil- and biomass-CCS) are highlighted by shadings of similar, lighter color.

A commonality across all sectors where CCS can contribute to mitigation is that the overall role of CCS in reducing emissions shrinks when the 2050 carbon price rises to successively higher levels above that in the AE w/ early CCUS scenario. Looking past 2050 toward the end of the century, CCS appears to be a technology that experiences greater deployment under less stringent climate targets (e.g., 650 ppm CO_2-eq) than in the more stringent 450 ppm CO_2-eq and AE w/ early CCUS scenario (Figure 21). It is also the case that in the Peak 2030 Emissions scenario, which sits somewhere between the 550 and 650 ppm scenarios in terms of stringency, exhibits a considerable amount of CCS deployment as a part of its overall more modest mitigation portfolio (Figure 22), but the greatest level of deployment is reached after 2050.

Climate targets of greater stringency imply quite high carbon prices (exceeding 100 $/t$CO_2$-eq by 2050), which in turn puts a heavy penalty on residual (i.e., non-captured) CO_2 and non-CO_2 emissions (mostly CH_4) from upstream operations (e.g., coal mining and transportation). As an illustration of this observation, a 100 $/t$CO_2$-eq carbon price implies a cost penalty of 1 ¢/kWh_{el} for residual emissions of 100 gCO_2/kWh_{el} in electricity generation. According to the EDGAR emissions inventory database for 2010 (JRC/PBL 2012), CH_4 emissions from coal mining and transport in China amount to roughly the same contribution in terms of CO_2-eq emissions per kWh of electricity generated. At carbon prices in the range of 500 $/t$CO_2$-eq, which might ultimately be necessary beyond 2050 to stay below 2 °C maximum temperature increase over the century, the residual CO_2 emissions and the non-CO_2 fossil fuel supply chain emissions would thus yield a combined cost penalty in the range of 10 ¢/kWh_{el}. At these high prices, other low-carbon power alternatives become quite attractive relative to coal CCS.

On the other hand, the initially higher carbon prices of the more stringent scenarios help to accelerate CCS deployment in the near-to-mid term (2030-2050), followed by a “squeeze out” of the technology once even higher carbon prices are reached. In other words, coal-based CCS represents a “bridge” or “transitional” technology in the more stringent climate policy scenarios, with its importance peaking around mid-century.

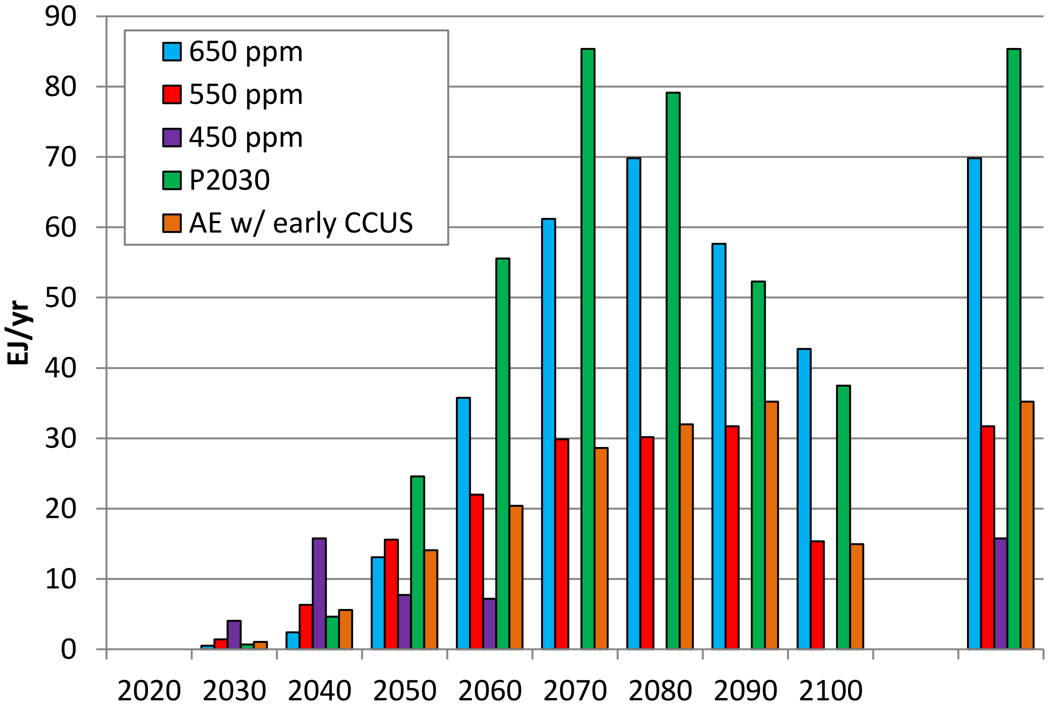

Figure 21. Coal primary energy deployment with CCS in CHINA+ in different climate policy scenarios. On the right side of the figure the maximum or peak deployment of coal with CCS over the 21st century is shown.

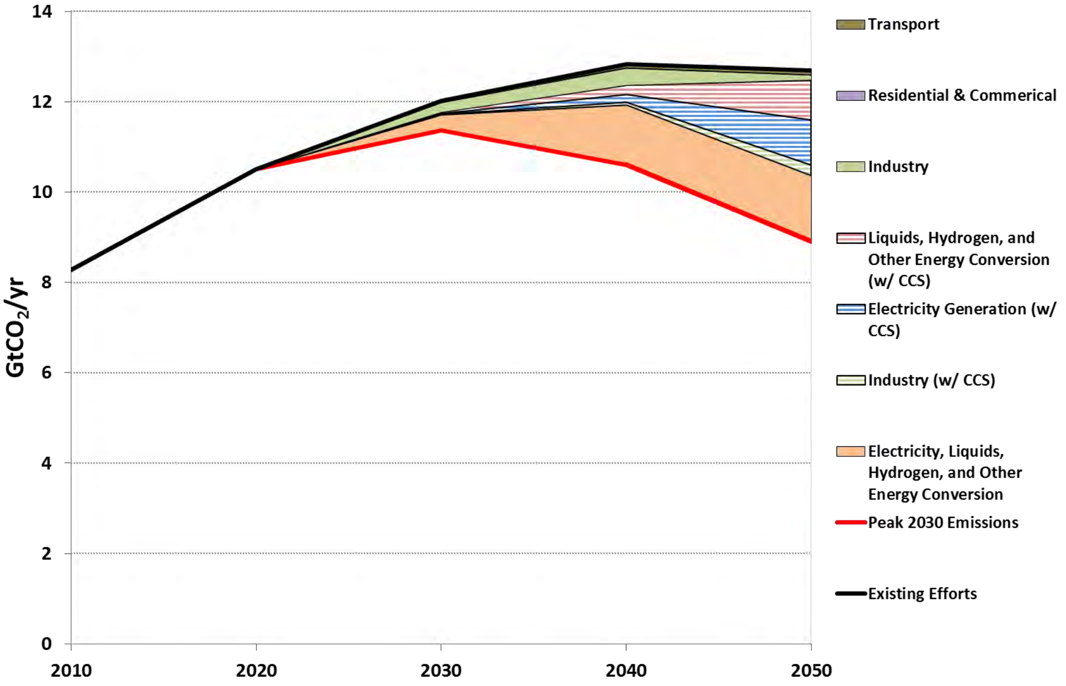

Figure 22. Reductions in CHINA+ CO2 emissions from fossil fuels and industry in the Peak 2030 Emissions scenario, relative to the Existing Efforts scenario. CCS contributions within each sector (including both fossil- and biomass-CCS) are highlighted by shadings of similar, lighter color.

Under a stringent climate mitigation regime, coal CCS is generally more suitable in the production of carbon-free energy carriers (e.g., electricity, hydrogen) than it is for producing liquid fuels (e.g., methanol, gasoline, diesel). Given that a significant share (30-40%) of the carbon contained in the coal feedstock remains in the liquid fuel product – carbon which ultimately ends up in the atmosphere – coal CCS for liquid fuels production is of particular interest while carbon prices are still relatively modest (<100 \$/tCO_2-eq). As carbon prices rise further, coal CCS for electricity and hydrogen production become the preferred options, because via these routes a much lower share (some 0-15%, depending on the realized capture rates) of the carbon contained in the coal feedstock is vented to the atmosphere.

Liquid fuel production based on coal with CCS may therefore play a larger role in the context of more modest global climate targets (in the range of 550 to 650 ppm CO_2-eq) and when domestic energy security concerns are a high priority. Given those conditions, polygeneration technologies become quite attractive because the synthetic fuels they produce (i) can substitute imports of crude oil and petroleum products, and (ii) are not significantly more carbon-intensive (on a life-cycle basis) than conventional oil.

As mentioned above, hydrogen production is a particularly interesting application for coal CCS because alternative methods of producing hydrogen either rely on more expensive fuels as feedstocks (e.g., imported natural gas) or require multiple, energy-intensive processing steps (e.g., wind/solar energy to electricity and finally to hydrogen via electrolysis).

6.2.3 Future costs of CCS and competing low carbon technologies

The scale of CCS deployment in China depends importantly on future costs of CCS technologies, as well as those of its low-carbon competitors (e.g., nuclear) across the different energy sectors.

In a series of sensitivity analyses (cf. Section 4.2), we varied the assumptions on capital and O&M cost projections for coal-based technologies (pulverized coal with and without post-combustion CO_2 capture, IGCC with and without pre-combustion CO_2 capture, polygeneration facility with CO_2 capture) in the MESSAGE model: +/- 15% and +/- 30% relative to the central cost estimates (see WP2, Table 4 and Section 4.2).

As shown in Figure 23, the future costs and performance of individual CCS technologies will have a significant impact on the deployment potential of coal-based electricity generation with CCS going forward. In particular under the optimistic future cost assumptions (-30% compared to the default assumptions), the deployment potential for coal-based CCS electricity generation significantly increases. Under given cost and performance assumptions, pulverized coal plants with post-combustion capture out-compete IGCC plants with pre-combustion capture under modest carbon prices (i.e., less than those seen in the AE scenario). Under higher carbon prices, the efficiency advantage and therefore the lower residual emissions of IGCC with CCS compared to post-combustion capture make IGCC similarly attractive. However, whether one or the other technology route is preferable will ultimately depend on realized cost reductions as well as performance. It should be emphasized that the gasification route to coal CCS (as in IGCC) could remain important for supplying hydrogen for end-use applications where electricity use is constrained (e.g., industrial processes and possibly some transport modes).

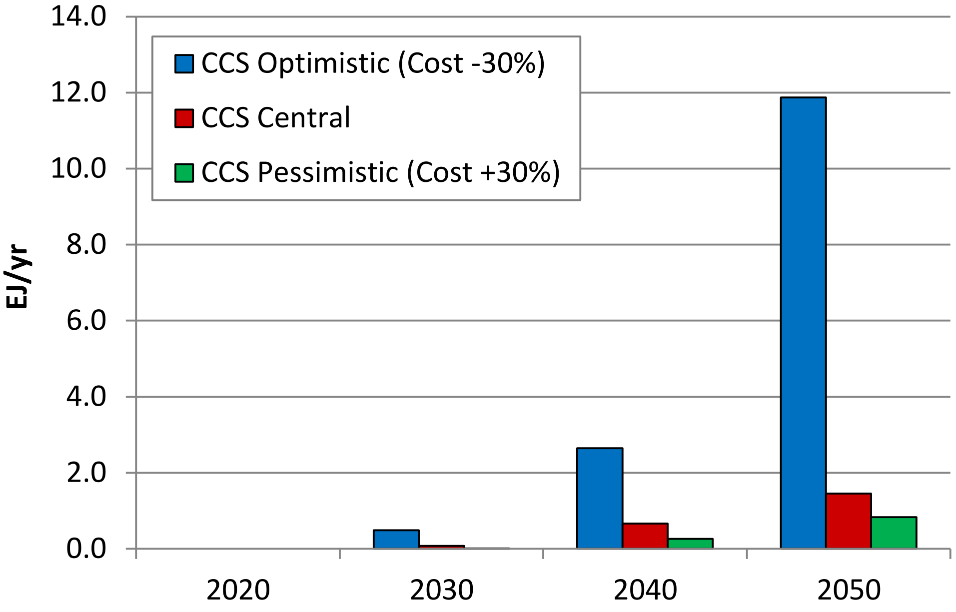

Figure 23. Deployment potential of coal-based electricity generation with CCS in CHINA+ across different sensitivity cases in response to varying cost projections for coal-based technologies (+/-30%). All cases are variants of the AE carbon price scenario.

Furthermore, in a separate sensitivity analysis we have varied the assumed cost projections for nuclear power (while continuing to apply the central estimates for all coal-based technologies). Given similar operational characteristics, nuclear energy can be regarded as a competitor to coal CCS in electricity generation because it is also low in carbon and provides base-load supply of power. Figure 24 shows that the future costs and performance of other low-carbon technologies like nuclear power may have an equally large impact on the future deployment potential of coal-based electricity generation with CCS.

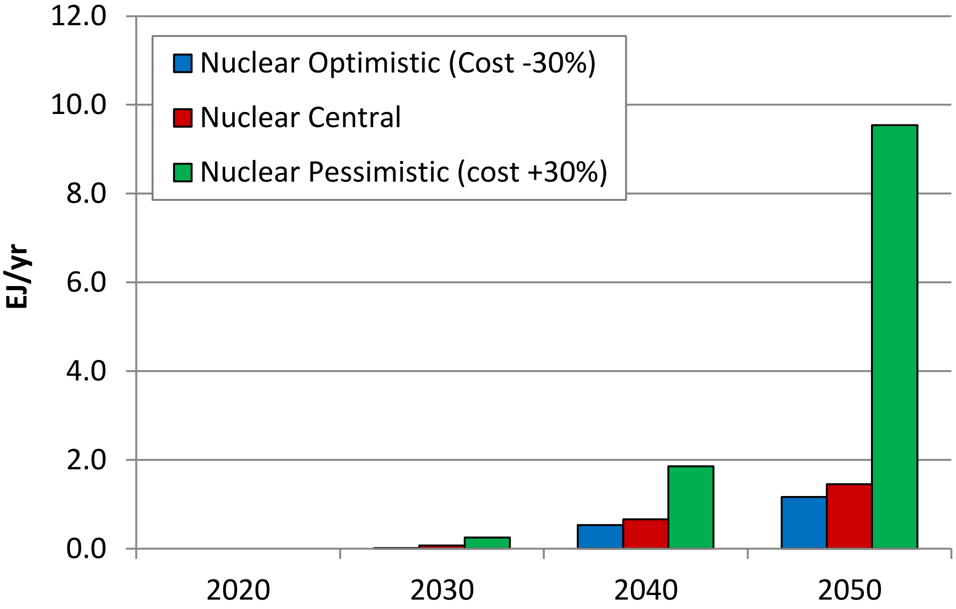

Figure 24. Deployment potential of coal-based electricity generation with CCS in CHINA+ across different sensitivity cases in response to varying cost projections for nuclear power. All cases are variants of the AE carbon price scenario.

The impact of varying cost assumptions for renewable electricity generation technologies on the deployment of coal-based CCS electricity generation is similar to that of varying assumptions on nuclear power, thus emphasizing the importance of taking the potential development of competing technologies into account when assessing the deployment potential of a technology. The influence of varying assumption about these competing low-carbon technologies is of the same order of magnitude as varying the cost assumptions for CCS technologies itself.

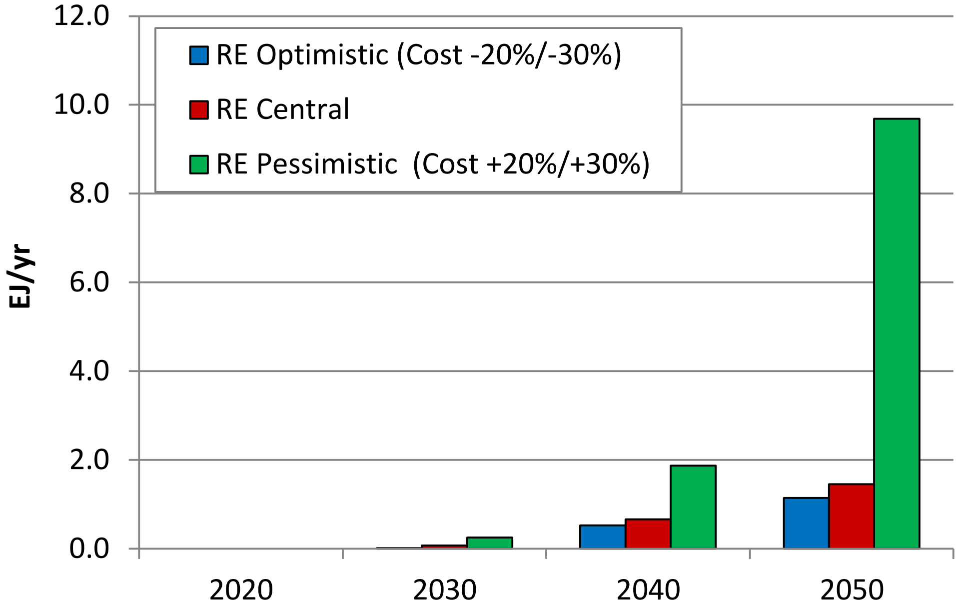

Figure 25. Deployment potential of coal-based electricity generation with CCS in CHINA+ across different sensitivity cases in response to varying cost projections for renewable electricity generation technologies, including wind and solar power. All cases are variants of the AE carbon price scenario.

An alternative view on the future role of CCS technologies is provided by the investments that go along with these deployment levels. Figure 26 shows investments between 2020 and 2050 associated with the deployment levels shown in Figure 23. Note that these investments only take into account the add-on costs for carbon capture and storage, not the full plant costs which might be a methodological difference to other studies. The range of investments turns out to be narrower than the range of deployment levels, because specific, plant-level investment costs are assumed to be 30% lower (higher) in the optimistic (pessimistic) case (see Section 4.2). It is worthwhile noting that investments into CCS technologies by 2030 are somewhat lower in our assessment compared to the earlier report, but the range of 2050 values encompass the investment level reported in (Beijing Jiaotong University 2014). We find some 0.2 to 1.6 billion USD by 2030 and 7 to 25 billion USD by 2050 compared to about 3.5 billion USD by 2030 and 12 billion USD by 2050 in that analysis.

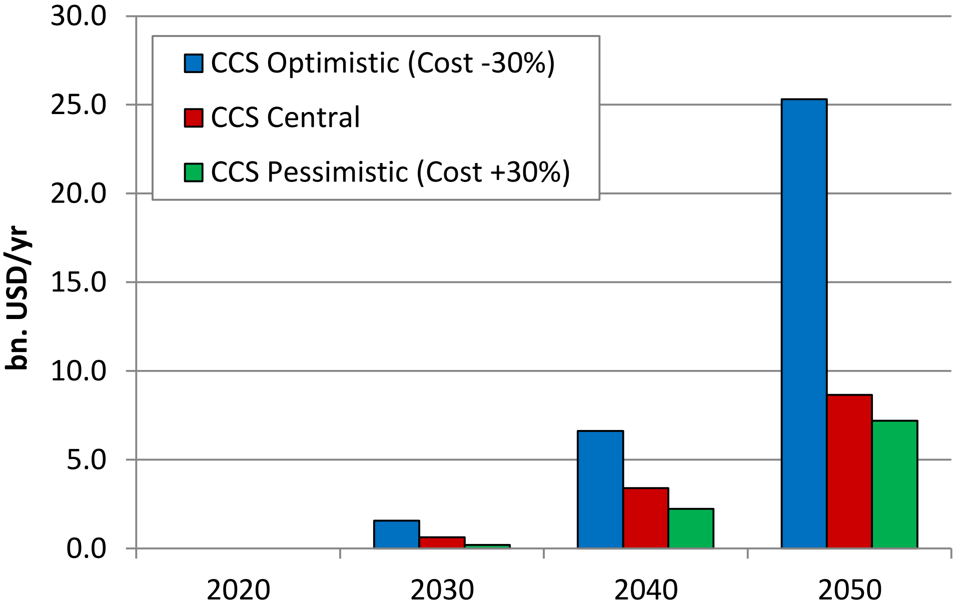

Figure 26: Annual investments into CCS technologies in CHINA+ in the AE carbon price scenario under different cost assumptions for CCS. Note that these investments only take into account the add-on costs for carbon capture and storage, not the full plant costs.

6.2.4 Capture rates

The competitiveness and deployment potential of coal CCS hinges critically on maximizing the fraction of plant-level CO_2 emissions that is captured, as opposed to vented to the atmosphere.

At high carbon prices, residual (i.e., non-captured) CO_2 emissions impose a considerable cost penalty on fossil CCS technologies. For coal-based electricity and hydrogen production in particular, CO_2 capture rates could become an important determinant of the competitiveness, and thus future market potential, of CCS vis-a-vis other low-carbon technologies.

The choice between post- and pre-combustion technologies for power plants on the one hand (PC vs. IGCC) and oxyfuel technologies on the other is especially important in this context. In a series of sensitivity analyses, we varied MESSAGE model assumptions on CO_2 capture rates for coal-based technologies between 85% and

100%. Higher capture rates in the range of 98-100%, as often associated with oxyfuel processes, can improve the competitiveness of coal CCS technologies under more stringent climate targets (in this case the AE carbon price scenario). Our analysis indicates that achieving capture rates in the range of 98-100% would increase the deployment potential of coal CCS in electricity generation multi-fold by 2050 relative to a scenario where 90% capture rates are the norm (see Figure 27). On the downside, oxyfuel technologies typically result in higher levels of impurities in the captured CO_2 which may require additional CO2 processing before transportation and storage (OFWG 2009; Wall et al. 2013). The latter could add to the costs of CCS.

A key technology and policy insight deriving from this finding is that under high carbon price scenarios, pushing the technology frontier with respect to CO_2 capture efficiencies may be equally important as, or even more than, reducing the costs of CCS technologies further.

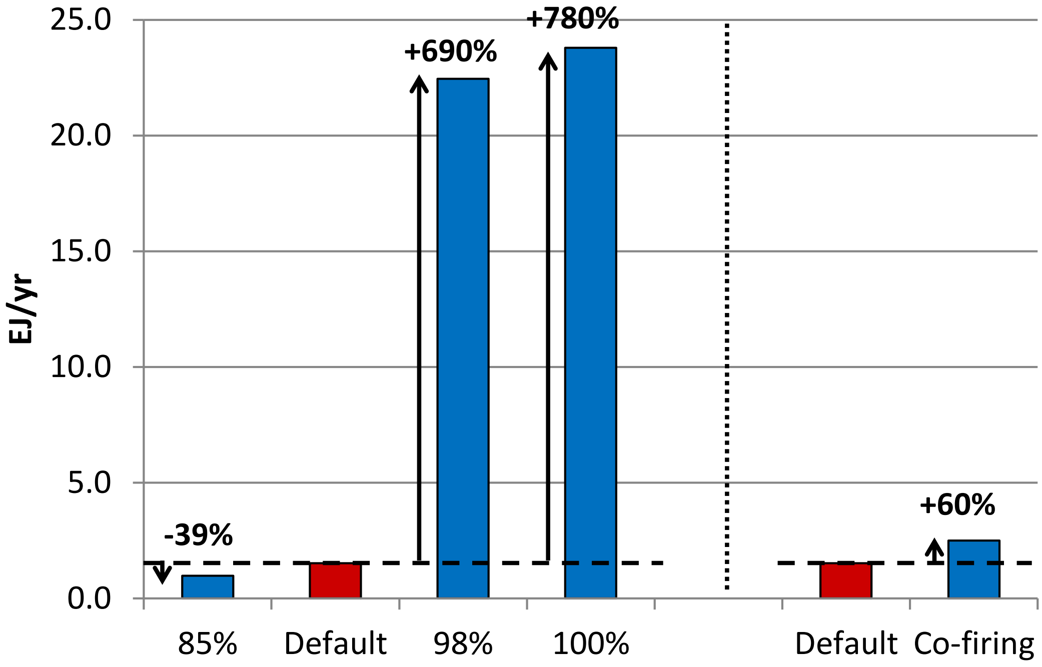

Figure 27. Deployment potential of coal-based electricity generation with CCS in 2050 in CHINA+ across different sensitivity cases: varying CO_2 capture rates (left), and without/with biomass co-firing (right). All cases shown are variants of the AE carbon price scenario.

6.2.5 Co-firing with biomass

The competitiveness and deployment potential of coal CCS in China can be improved through co-firing of biomass. Utilization of biomass along with coal as a feedstock for energy conversion can help to compensate residual CO_2 and non-CO_2 emissions from coal CCS technologies – both at the plant level and from upstream processes in the supply-chain. Thus, “biomass co-firing” could be a cost-effective measure for improving the competitiveness of coal CCS technologies vis-a-vis other low-carbon technologies such as nuclear power or non-biomass renewable energy technologies.

In a series of sensitivity analyses, we varied MESSAGE model assumptions on the possibility for coal-based electricity generation technologies to co-fire with biomass (up to 25% of energy input). As indicated by Figure 27, the option to co-fire with biomass increases the deployment potential of coal CCS by 2050. With growing carbon prices, higher levels of co-firing are preferable but generally require pre-treatment of the primary biomass feedstock. Pre-treatment technologies should therefore be developed in parallel to coal CCS technologies themselves (van Loo and Koppejan 2008). In addition, there may be limits to the amount of biomass that can be sourced locally in the surrounding area of a given coal CCS facility.

6.2.6 Niche market formation

The long-term market potential of CCS is closely linked to a successful niche market formation and demonstration phase to 2030. To which extent CCS technologies will be able to contribute to mitigation efforts by 2050 will therefore, among other things, critically depend on the creation of niche market over the next couple of decades. Reaching coal CCS electricity generation deployment in CHINA+ in the range of 20 (10-30) GW by 2030 would be crucial for allowing a meaningful contribution of CCS by mid-century. Such a finding is particularly relevant in light of the role of coal CCS as a “bridge technology” (see above). In case of delayed niche market formation, the potential for a significant contribution of CCS remains low. On the other hand, under a more successful niche market formation with higher deployment levels around 2030, the ultimate market potential of CCS could also be significantly higher compared to the levels described in this study. In addition, the ability to deploy CCS more quickly may allow reducing emissions further at the same carbon price level.

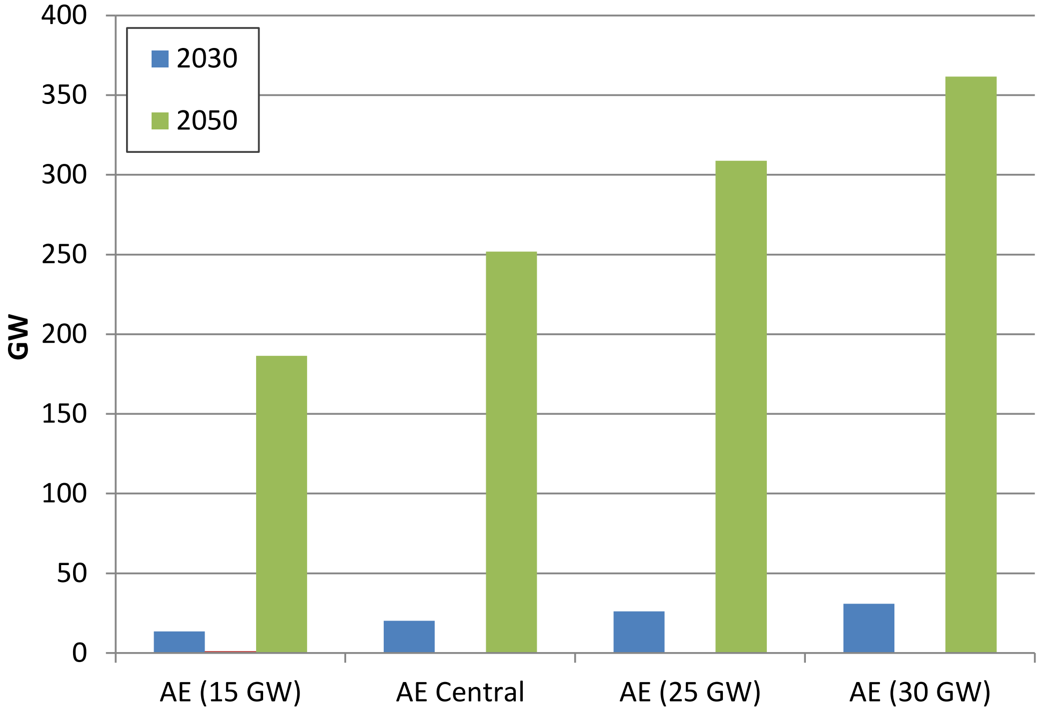

Figure 28. Deployment potential of coal power capacity with CCS in CHINA+ by mid-century as a function of niche market size in the AE carbon price scenario. Values along horizontal axis correspond to niche market size in 2030.

6.2.7 CO_2 storage

Previous studies (e.g., McCollum et al. (2014)) have called attention to the possibility that in the long term, under scenarios with significant quantities of CO_2 being stored in underground reservoirs, certain regions of the world could eventually bump up against limits to the geological storage base. However, according to the scenarios developed in this study, the gross potential of CO_2 storage in underground reservoirs in China does not appear to be a limiting factor for CCS deployment over the course of the 21st century. In the AE w/ early CCUS scenario, the cumulative amount of required CO_2 storage is 17 $GtCO_2$ by 2050 and 200 $GtCO_2$ by 2100. The Peak 2030 Emissions scenario, on the other hand, sees more CO2 storage being needed: 16 $GtCO_2$ by 2050 and 290 $GtCO_2$ by 2100. This is because the climate policies envisioned in the latter scenario are less stringent. Moreover, across all scenarios and sensitivity cases run with MESSAGE, the cumulative amount of required CO_2 storage reaches a maximum of 42 $GtCO_2$ by 2050 and 423 $GtCO_2$ by 2100. These CCS deployment levels are generally within the range of CO_2 storage potential estimates (in underground reservoirs, China-wide) that can be found in the literature, including global analyses by the International Energy Agency and Global Energy Assessment and China-specific assessments by Prof. Li Xiaochun of the Institute of Rock and Soil Mechanics (personal communication). These literature estimates range from 181 to 1445 $GtCO_2$, which on the high end equates to levels ~3.5x greater than the maximum storage requirements by 2100 of the scenarios (Figure 29).

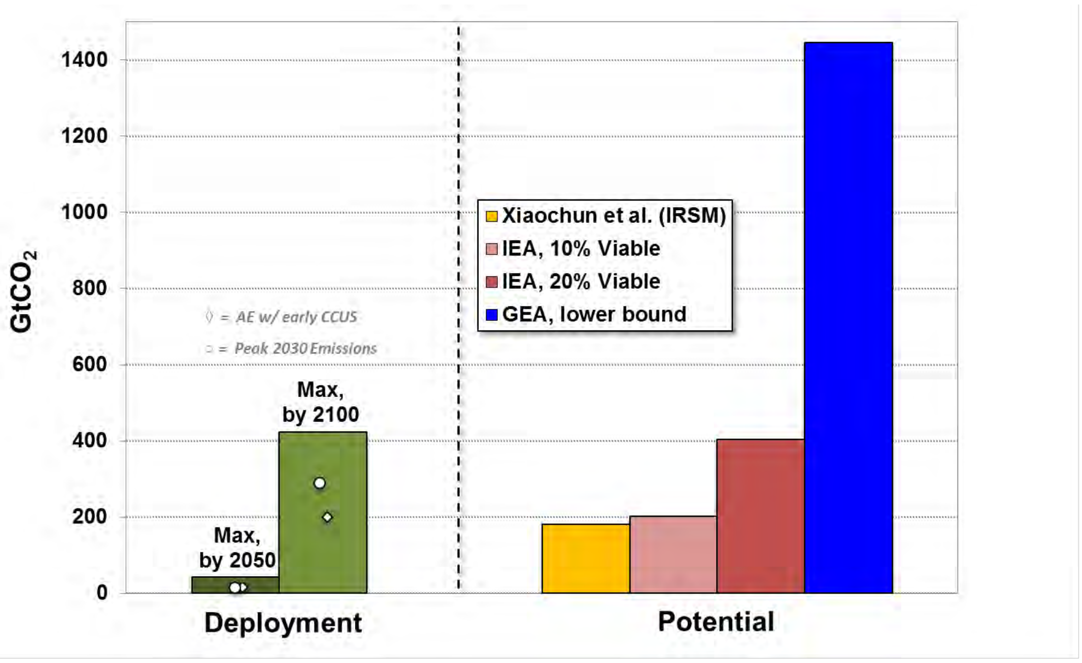

Figure 29. CCS deployment by 2050/2100 in the AE w/ early CCUS scenario and across all other sensitivity cases (cumulative, maximum) vs. literature estimates of CO_2 storage potential in underground reservoirs in China.

6.2.8 Co-benefits of climate change mitigation for air quality

Climate change mitigation can be an important entry point for achieving China's other objectives for energy sustainability, namely improved air quality in the country's many urban centers. Mitigation necessitates decarbonization, and low-carbon technologies also yield low levels of air pollutant emissions (e.g., sulfur and nitrogen oxides). This is true for renewables and nuclear power, as well as for advanced fossil fuel conversion plants equipped with CCS.

Figure 30 illustrates the magnitude of these co-benefits in both 2030 and 2050 in CHINA+. First, one sees that in the absence of climate policy, and assuming that the current suite of air quality policies in China remain the same going forward (i.e., no new air quality policies are designed, but those already planned are enacted successfully), SO_2 emissions are estimated to come back down to 2010 levels by 2030. Greater reductions are foreseen by 2050. Meanwhile, NO_x emissions increase by 2030 before falling by 2050. (Note that in this scenario these dynamics occur within a context of increasing GDP, energy use and carbon emissions in China over this timeframe.) Second, Figure 30 shows that China's currently planned climate mitigation policies (i.e., the Existing Efforts scenario) would lead to important reductions in SO_2 and NO_x by 2030/2050, relative to the no climate policy baseline, while the country's goal of peaking CO_2 emissions by 2030 would yield additional air quality co-benefits. Far greater reductions in air pollutant emissions are possible, however, through enacting more stringent climate policies, as in the AE w/ early CCUS scenario: >30% reductions in SO_2 and >25% in NO_x by 2030, relative to a baseline scenario without any climate policies whatsoever in China. By 2050, these reductions could be even greater: >75% and >65% for SO_2 and NO_x, respectively.

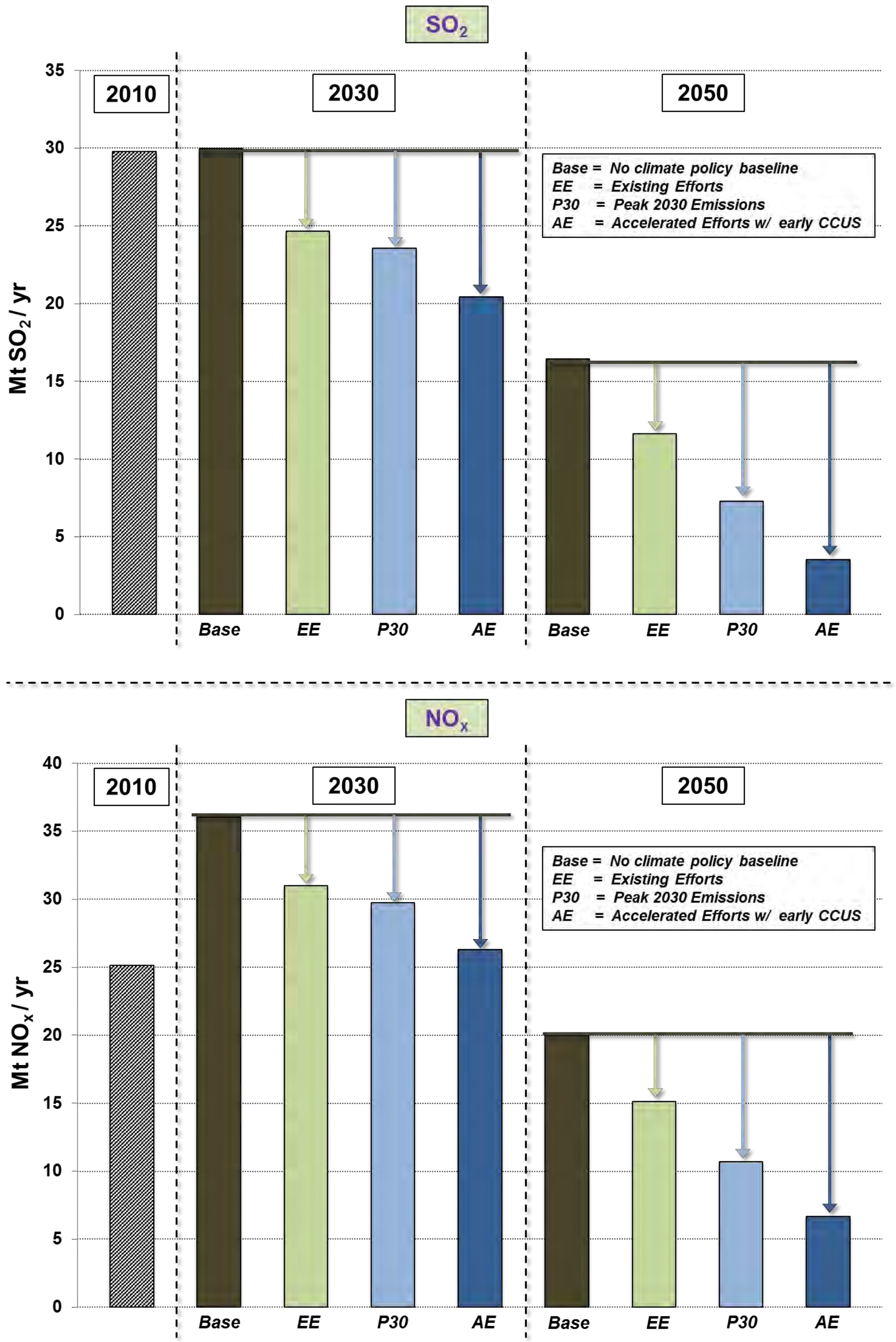

Figure 30. Co-benefits of climate change mitigation for air quality in CHINA+. Top panel: SO_2, bottom panel: NO_x. Co-benefits stemming from climate policy scenarios

are shown as absolute reductions from the 2030/2050 emission levels estimated in the no climate policy baseline.

7 Conclusions

CCS is considered to be a cost-competitive solution for a low-carbon future in China, while its deployment largely depends on China's future mitigation scenario and targets. In this report, we evaluated the application of CCS in scenarios developed with two different energy economic modeling frameworks (C-GEM and MESSAGE), depending on different national emission reduction targets. We calculated the impact of CCS on emission reductions and assessed the effects of CCS applications in China in terms of macro-economy, energy consumption structure, GDP growth, and industrial output. Impacts of the application of CCS in different sectors of the energy system, including electricity generation, liquid fuel and hydrogen production and poly-generation CCS are also discussed. Below, the key conclusions drawn from this analysis are summarized.

(1) A clear long-term mitigation target is crucial to the development of CCS. Comparing the two different mitigation scenarios we designed, emissions are more constrained under the Accelerated Efforts w/ early CCUS (AE) scenario than under the Existing Efforts (EE) scenario after reaching the peak value in 2030; hence, CCS develops faster in the AE scenario. In the EE scenario, the C-GEM model shows CCS emerging in 2030 and achieving a 1.4 Gt CO_2 emission reduction in 2050 – contributing around 15% of the total CO_2 reduction compared to NP scenario. In contrast, in the EE scenario the MESSAGE model does not show CCS contributing to CO_2 mitigation until the second half of the century (i.e., 0 Gt CO_2 in 2050). In the AE scenario, both models show CCS technologies entering the market in 2030. Across the C-GEM and MESSAGE models, CCS helps to reduce CO_2 emissions by approximately 2 Gt CO_2 in 2050.

(2) Coal CCS deployment tends to increase as the mitigation target becomes more stringent, but only up to a point. Under more stringent climate targets (e.g., 450 vs. 650 ppm CO_2-eq), coal CCS deployment actually declines due to the heavy penalty put on residual (i.e., non-captured) CO_2 and non-CO_2 emissions from upstream operations (e.g., coal mining and transportation). This is particularly true when looking toward the long term (post-2050). In other words, coal-based CCS represents a “bridge” or “transitional” technology in the more stringent climate policy scenarios, with its importance peaking around mid-century.

(3) As a high-cost mitigation option, CCS will not be widely deployed until 2030, when the mitigation constraints are more stringent and low-cost mitigation resources become rarer so that CCS begins to become a cost-competitive option. CCS technology is helpful to reduce the mitigation cost in the “deep cut” stage after 2040. In our analysis, CCS enters the market and starts to be deployed in a large scale after 2030. More specifically, in the C-GEM model CCS is deployed when the carbon price exceeds \$38/ton. The carbon price would be 7%-20% higher than it is in 2050 without the implementation of CCS technology, which will result in an increase in social abatement costs. Analysis with the MESSAGE model indicates similar economic impliciations if CCS is not assumed to become available. Specifically, in the AE w/ early CCUS scenario, the removal of CCS from the technology portfolio is found to lead to an additional 0.4%-point loss in Chinese GDP in 2050, largely due to the need for increasing the carbon price by some 25% to achieve similar levels of mitigation as in the case where CCS is available.

(4) Carbon capture and storage technologies can help yield important co-benefits for air quality in China. Numerous studies have shown that climate change mitigation can be an important entry point for achieving China’s other objectives for energy sustainability, namely improved air quality in the country’s many urban centers. Mitigation necessitates decarbonization, and low-carbon technologies also result

in low levels of air pollutant emissions (e.g., sulfur and nitrogen oxides). This is true for renewables and nuclear power, as well as for advanced fossil fuel conversion plants equipped with CCS. Our analysis finds that large reductions in air pollutant emissions are possible through enacting stringent climate policy in China, as in the AE scenarios: >30% reductions in SO_2 and >25% in NO_x by 2030, relative to a baseline scenario without any climate policies whatsoever in China. By 2050, these reductions could be even greater: >75% and >65% for SO_2 and NO_x, respectively.

(5) The scale of CCS deployment in China depends importantly on future costs of CCS technologies, as well as those of its low-carbon competitors. It is important to note that beyond the future development of costs and performance of CCS technologies, also the progress made with other low-carbon energy supply technologies such as nuclear power will have a significant impact on the market potential of CCS. As shown through a sensitivity analysis in which cost projections for nuclear power were varied, In particular nuclear power can be regarded as a competitor to coal CCS in electricity generation because it is also low in carbon and provides base-load supply.

(6) The competitiveness and deployment potential of coal CCS in China hinges critically on maximizing the fraction of plant-level CO_2 emissions that are captured, as opposed vented to the atmosphere. In particular under high carbon prices, residual (i.e., non-captured) CO_2 emissions impose a considerable cost penalty on fossil CCS technologies. The choice between post- and pre-combustion technologies for power plants on the one hand (PC vs. IGCC) and oxyfuel technologies on the other is especially important in this context. A key technology and policy insight deriving from this finding is that in high carbon price scenarios, pushing the technology frontier with respect to CO_2 capture efficiencies may be equally important as, or even more than, reducing the costs of CCS technologies further.

(7) The competitiveness and deployment potential of coal CCS in China can be improved through co-firing of biomass. Utilization of biomass along with coal as a feedstock for energy conversion can help to compensate residual CO_2 and non-CO_2 emissions from coal CCS technologies (both at the plant level and from upstream processes in the supply-chain). Thus, “biomass co-firing” could be a cost-effective measure for improving the competitiveness of coal CCS technologies vis-a-vis other low-carbon technologies. Higher levels of co-firing are preferable but generally require pre-treatment of the primary biomass feedstock. Pre-treatment technologies should therefore be developed in parallel to coal CCS technologies themselves. In addition, there may be limits to the amount of biomass that can be sourced locally in the surrounding area of a given coal CCS facility.

(8) Development of CCS exerts certain impact on energy consumption, especially coal consumption. Under the mitigation scenario, coal consumption will be well-controlled by 2025, and reaches the peak value during 2020-2025, while in the longer term due to the development of CCS, clean coal utilization grows in the later period. Under AE w/ early CCUS scenario, coal consumption in China reaches the peak during 2020-2025, with the value of approximately 2.85 Gtce, which is 0.45 Gtce less than that under the EE scenario. While due to the large development of CCS technologies, coal consumption may turn to increase after 2040.

(9) CCS technologies can be important contributors to climate mitigation in different sectors of the Chinese energy system, including electricity generation, liquid fuel production, hydrogen production and industrial applications. The MESSAGE AE w/ early CCUS scenario, in particular, show that while coal CCS technologies can play an important role in the electricity sector, they could play an equally large, if not larger, role within the liquids and hydrogen production sectors.

(10) Under a stringent climate mitigation regime, coal CCS is generally more suitable in the production of carbon-free fuels (e.g., electricity, hydrogen) than it is for liquid fuels production (e.g., gasoline, diesel). This is due to the fact that a significant share (30-40%) of the carbon contained in the coal feedstock remains in the fuel product – carbon which ultimately ends up in the atmosphere; in contrast, for electricity and hydrogen these shares are 0-15%, depending on realized capture rates. That said, when mitigation targets and carbon prices are relatively modest, CCS technologies can contribute throughout their application to poly-generation schemes, which has lower cost compared to conventional CCS technologies. Poly-generation with CCS technology is expected to have a great impact even when the carbon price and emission mitigation targets are at a low level. Due to the lower cost of poly-generation with CCS technology, part of the conventional CCS would be substituted by poly-generation with CCS. Our analysis shows that poly-generation with CCS could see large-scale application when emission mitigation targets are not very stringent, due to its relative lower cost. Furthermore, as the output from poly-generation technology is both electricity and oil, by substituting part of the crude oil consumption with its output, poly-generation technology contributes to the maintenance of national energy security in China.

(11) At the national scale, the gross potential of CO_2 storage in underground reservoirs in China does not appear to be a limiting factor for CCS deployment over the course of the 21st century. However, the economics of CCS will depend on the distances that CO_2 will have to be transported, from its point of production to suitable storage reservoirs.

A Appendix: Modeling Tools

This appendix describes in some detail the two modeling frameworks that were utilized in this study, C-GEM and MESSAGE. Further information on the modeling tools can be found in numerous publications which are referred to in the sections below.

A.1 China-in-Global Energy Model (C-GEM)

A.1.1 Overview

The China-in-Global Energy Model (C-GEM) is a multiregional, multisector, recursive–dynamic, computable general equilibrium (CGE) model of the global economy. The model is one of the major analysis tools developed 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 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 models are now well-established tools used to undertake quantitative analysis of the economic impacts of energy and environmental policies (Böhringer et al. 2003; Sue Wing 2004).

The CGE model simulates the circular flow of goods and services in the economy, as shown in Figure 31 below.

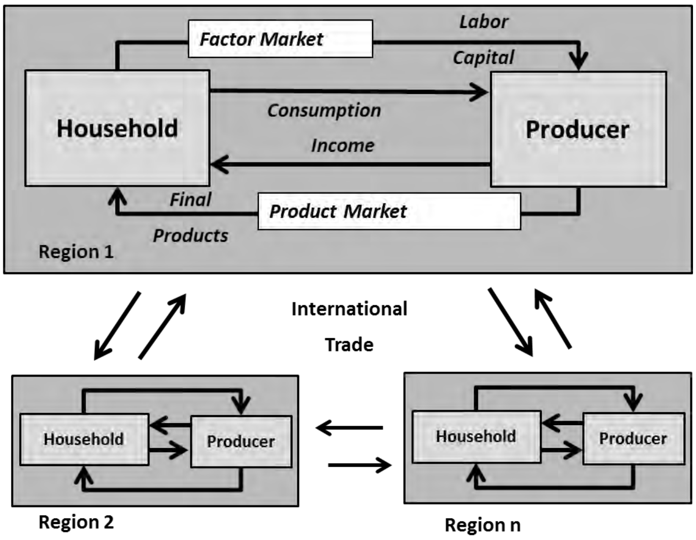

Figure 31. Economy-wide circular flow of goods and services in the C-GEM.

The arrows in Figure 31 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 mobile across regions. The international capital flows that account for the trade imbalance between regions in the base year are assumed to gradually disappear.

A.1.2 Model structure

The C-GEM disaggregates the world into 19 regions and 20 sectors, as shown in Table 5, Table 6 and Figure 32 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 (IMF 2012). 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 5. 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.

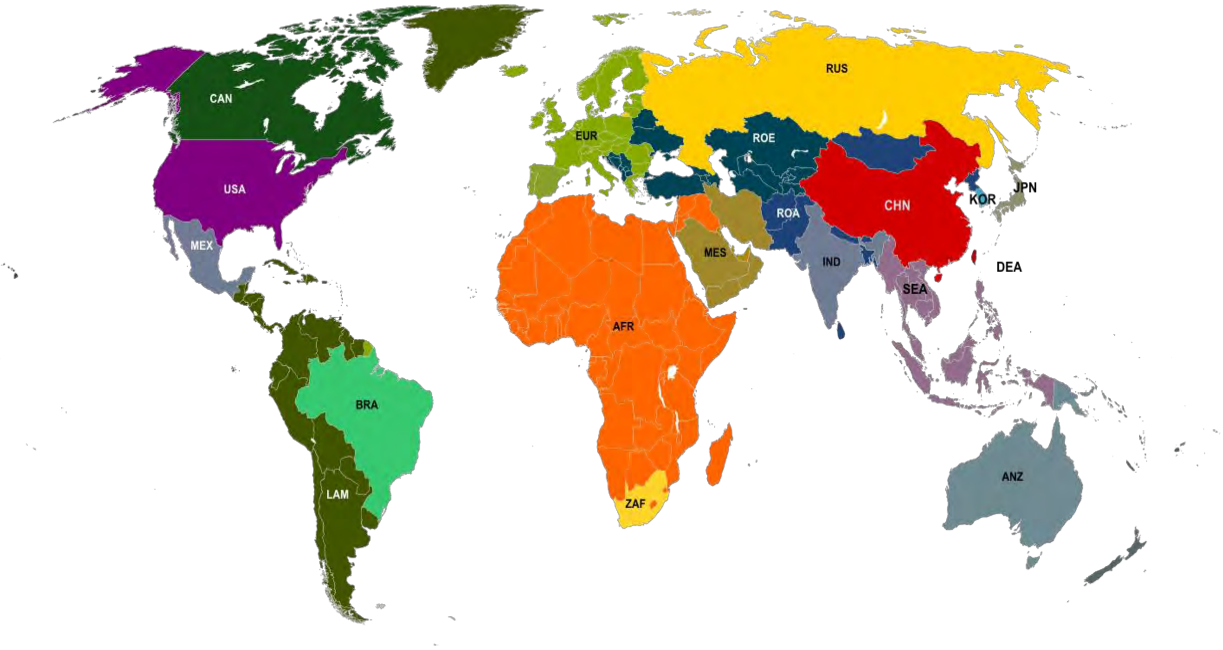

Figure 32. Regions in the C-GEM.

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 intensive industries. As shown in Table 6 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 6. 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 quantifies the 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 et al. 2012a). 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 et al. 1992). The C-GEM keeps track of the physical flows of carbon-based fuels and resources in the economy through 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 et al. 2012b). 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.

A.1.3 Model 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 33 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).

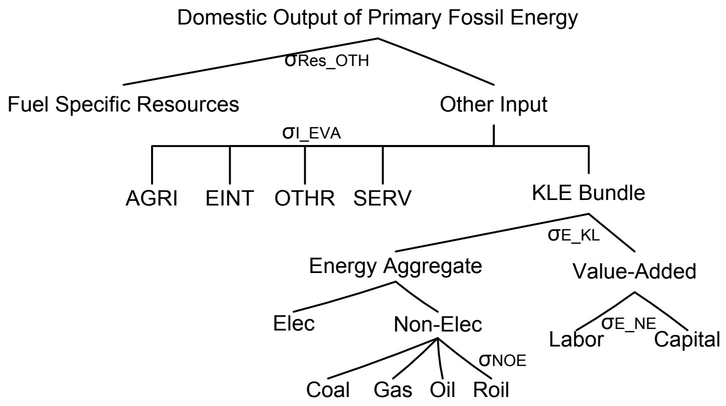

Figure 33. The structure of the primary fossil energy sectors in the C-GEM.

The structure of the electricity sector is shown in Figure 34. The top two nests permit substitution among various generation technologies. Twelve types of power generation technologies are represented in the base version of C-GEM as listed in Table 7, 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 34 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.

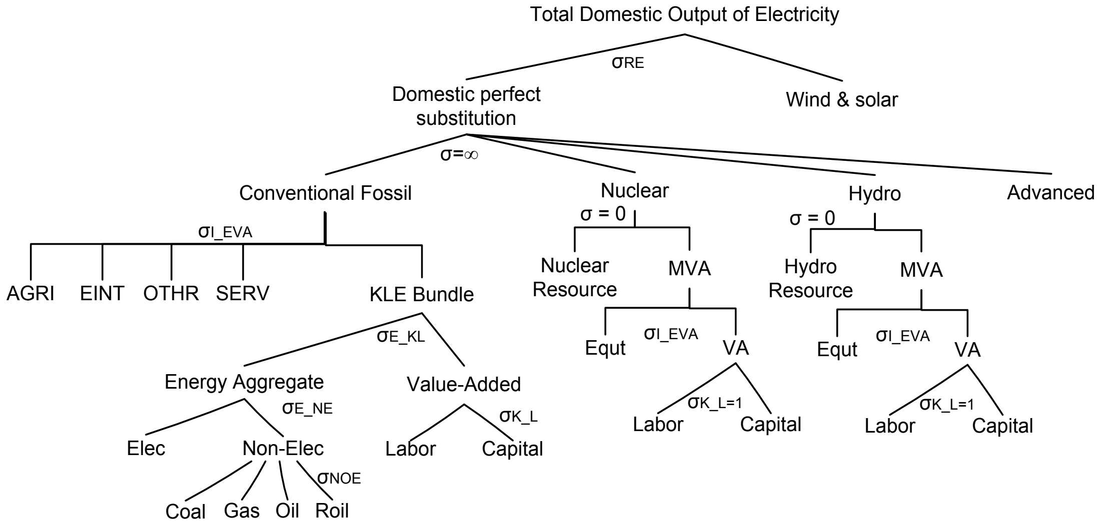

Figure 34. Structure of the electricity sector in the C-GEM.

Table 7. 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 Figure 35. We use consumption (excluding savings) as a consistent measure for welfare accounting.[3] 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.

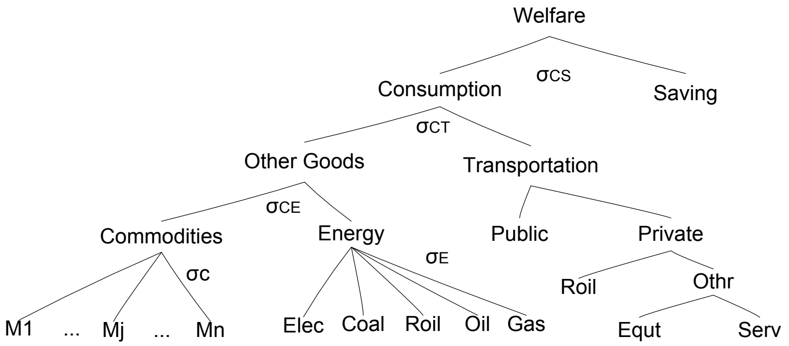

Figure 35. The nested structure of the consumption function in the C-GEM.

Production and consumption in each region in the C-GEM are linked through bilateral trade. Capturing this links allows the model to forecast how policy impacts propagate 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

---

[3] 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.

oil in the C-GEM is modeled as homogeneous good with a single global price. The Armington CES structure is shown in Figure 36. The top level nest captures the tradeoff between domestic and imported goods, including imported goods that are comprised of imports from different regions. Bilateral trade flows, which include export taxes, import tariffs, and international transport costs, are represented in the C-GEM.

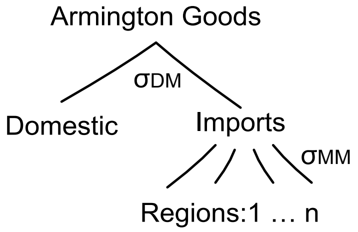

Figure 36. The nested Armington structure consisting of domestic and imported goods in the C-GEM.

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 adopts the same nested CES as household consumption.

Investment in the C-GEM is represented by a sector that produces an aggregate investment good using inputs of inventories by sectors which 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 the 2006 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_2 emissions 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).

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.

A.1.4 Technology Details

The C-GEM also includes a full suite of advanced "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 in Table 8. 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 8. List of new technologies in the C-GEM.

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

substitute for natural gas

The CES production structure for coal gasification technology is shown in Figure 37. Coal, equipment, and a value-added bundle enter as a Leontief structure at the top of the level of the production structure.

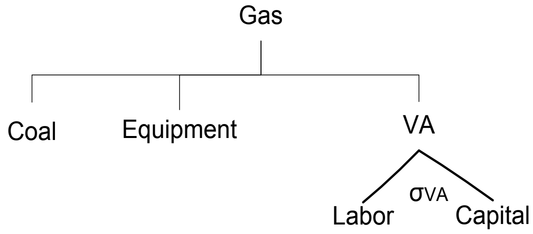

Figure 37. CES production structure for coal gasification.

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 Table 9, 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 3.3.3.

Table 9. 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

A.1.5 Detailed representation of CCS in the Model

A.1.5.1 Represent the CCS technology in the model

C-GEM has designed detailed production structures for both conventional CCS and poly-generation with CCS, as shown in Figure 38. In Figure 38, the structure without the dashed square represents the production structure of conventional CCS. In the structure, the cost of transmission and distribution (T&D), and 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 priced or otherwise 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 allows deployment 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.

In the model, IGCC with CCS and NGCC with CCS are considered conventional CCS technologies, from which the major energy output is electricity. Poly-generation with CCS shares the similar basic production with conventional CCS technologies, while its output include not only electricity, but also refined oil, as shown in Figure 38, including the dashed square. The proportions of electricity output and oil output from poly-generation technology are about 40% and 60%.

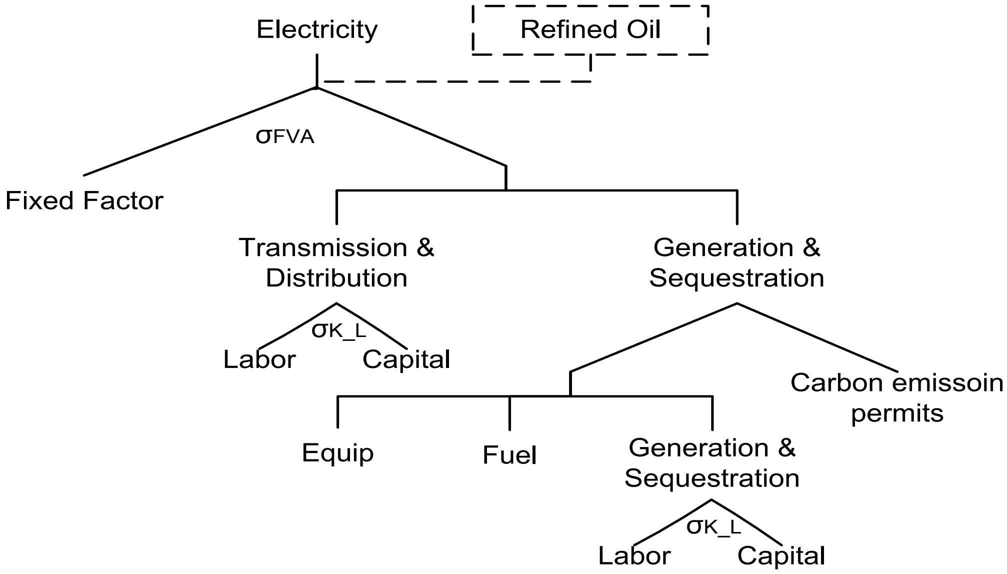

Figure 38. CES production structure for CCS.

A.1.5.2 Calibration of CCS parameters

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). 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 10 concludes the variables, assumptions, and results of some capture cost studies in China.

Table 10. Cost Analysis of Carbon Dioxide Capture in China.

Author	Huang Bin (Huang et al. 2010)	Xiong Jie (Xiong et al. 2009)	Xiong jie (Xiong et al. 2009)	Yan Shuiping (Yan et al. 2008)	Wang Yun (Wang 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	297.4436 MW	297.4436MW		558MW	574.1MW	295.1MW	824.3MW		

Efficiency	295g/kWh				5632t/ d	40.28%	38.15%	43.9%		
Utilization hours		8000	8000	5500	6000	85%	85%	85%		
CO_2 emissions	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		232.9436 MW	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		28.18t/h	28.18t/h		0.23	125.5g/k	133.6	98.2	95.44	196 g/kWh

emissions					kg/kWh	Wh	g/kWh	g/kWh	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 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	￥170/t			￥137.6/t						

cost	(O&M cost only)			(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.

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 both conventional CCS and poly-generation CCS technologies, as shown in Table 11.

Table 11. Calibrated Cost of CCS.

	IGCC (/kWh)	**IGCC capturing CO_2 (/kWh)**	**Poly-generation (/MJ)**
Capital ($/kW)	2200	2950	1650
Efficiency	0.46	0.38	0.45
Operating Cost Coefficient	0.04	0.04	0.06
CRF	0.12	0.12	0.12
Fuel Price (￥/kg)	0.6	0.6	0.6
Calorific Value of Coal (MJ/kg)	26.71	26.71	26.71
Annual Operating Time Ratio	0.68	0.68	0.68

Plant Life	30	30	30
Total Electricity Generated (kWh)	178704	178704	643334.4
Coal Consumption (kg)	52360.7	63383.9	53524.2
Cost per kW			
Equipment Cost	13860	18585	10395
Fuel Cost	31416	38030	32115
Capital	54636	73262	40977
Labor	16632	22302	18711
Cost per kWh / per MJ			
Equipment Cost	0.078	0.104	0.0162
Fuel Cost	0.176	0.213	0.0499
Capital	0.306	0.410	0.0637
Labor	0.093	0.125	0.0291
CO_2 Emission (kg/kWh)	0.85	0.05	0.142
Total Cost (￥/kWh)	0.652	0.852	0.1589
Cost Structure			
Equipment Cost	0.119	0.122	0.102
Fuel Cost	0.270	0.250	0.314
Capital	0.469	0.481	0.401
Labor	0.143	0.147	0.183
Share of Transport & Storage Cost in Total Cost Structure	20%	—	20%

A.2 MESSAGE model

MESSAGE (Model for Energy Supply Strategy Alternatives and their General

Environmental Impact) is an integrated assessment modeling framework operated by the International Institute for Applied Systems Analysis (IIASA). Here we provide a brief summary of the main features of the model; further details can be found in the literature (Messner and Schrattenholzer 2000; Messner and Strubegger 1995; Rao and Riahi 2006). The text below contains a description of the modeling concept and main data sources, as well as a brief description of the emissions mitigation options that our analysis considers.

A.2.1 Model structure and approach

The systems engineering energy modeling component of MESSAGE is a linear programming (LP) systems engineering optimization model used for medium to long-term energy system planning and policy analysis. The model minimizes total discounted energy system costs, and provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, and inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. In addition to the core energy model, MESSAGE is soft-linked with air pollution and agriculture and forestry models.

MESSAGE runs from 1990 to 2100 in 10-year time steps (5-year steps from 1990 to 2010). It has global coverage comprised of 11 world-regions (Table 12 and Figure 39). For the purposes of this study, the “CHINA+” region of MESSAGE is used as a proxy for China alone. While this grouping includes a handful of countries in addition to China (e.g., Mongolia, Cambodia), the discrepancies remain small because China accounts for the overwhelming majority share of economic and energy activity in the region. For example, in 2010 Chinese population and GDP comprised 90.9% and 96.9%, respectively, of the CHINA+ totals; and for primary energy and fossil fuel CO2 emissions, the shares were 96.6% and 97.4%. Hence, the conclusions drawn from the MESSAGE modeling work for its native CHINA+ region are entirely valid for the country of China.

Table 12. Listing of 11 MESSAGE regions and countries within them.

11 MESSAGE regions	**Definition** *(list of countries)*
NAM	**North America**
	(Canada, Guam, Puerto Rico, United States of America, Virgin Islands)
WEU	**Western Europe**
	(Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom)
PAO	**Pacific OECD**
	(Australia, Japan, New Zealand)
EEU	**Central and Eastern Europe**
	(Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia, Estonia, Latvia, Lithuania)
FSU	**Former Soviet Union**
	(Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan)
CPA (CHINA+)	**Centrally Planned Asia and China**
	(Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam)
SAS	**South Asia**
	(Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka)
PAS	**Other Pacific Asia**
	(American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa)
MEA	**Middle East and North Africa**

(Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen)

LAM **Latin America and the Caribbean**

(Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela)

AFR **Sub-Saharan Africa**

(Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe)

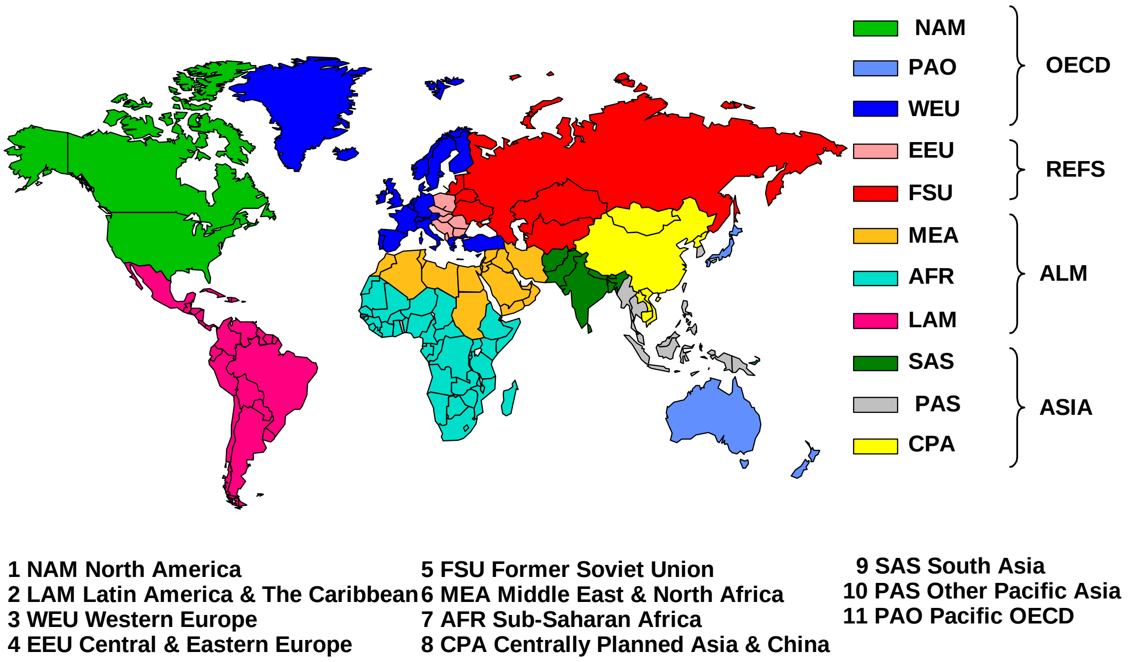

Figure 39. Overview of the 11 MESSAGE regions.

A typical MESSAGE model application is constructed by specifying performance characteristics of a set of technologies and defining a Reference Energy System (RES) that includes all the possible energy chains that MESSAGE can make use of. In the course of a model run MESSAGE determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints, while minimizing total discounted energy system costs. A simplified illustration of the MESSAGE Reference Energy System is shown in Figure 40.

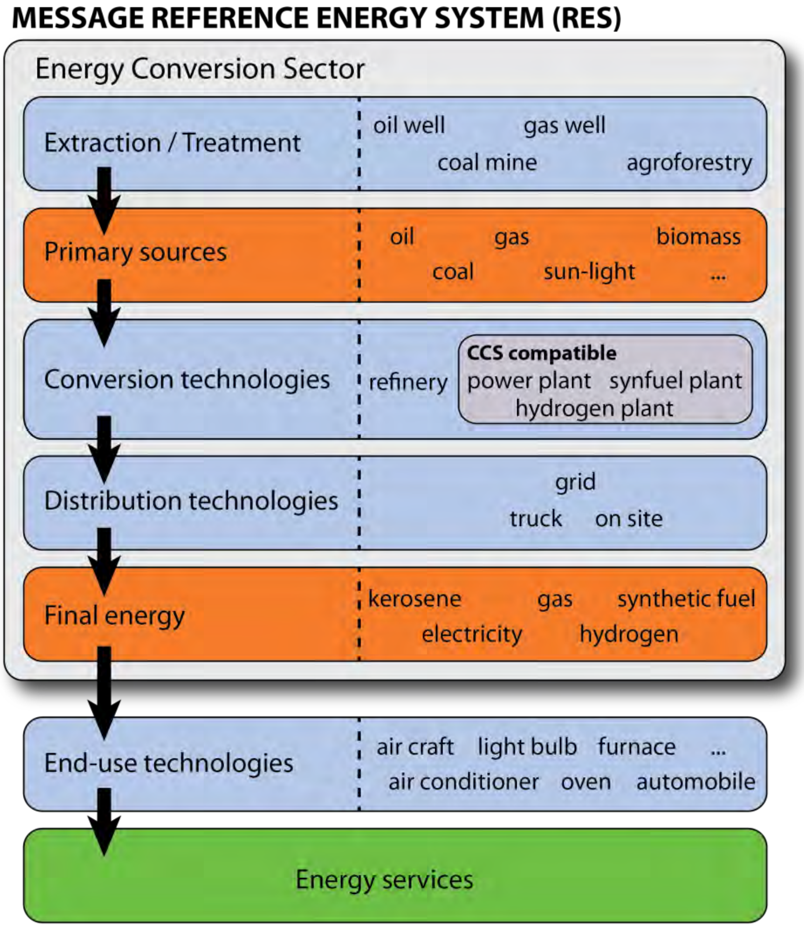

Figure 40. Overview of the MESSAGE Reference Energy System (RES). Blue fields indicate energy technologies, orange fields energy carriers, and green fields energy services.

The representation of the energy system includes vintaging of the long-lived energy infrastructure, which allows for consideration of the timing of technology diffusion and substitution, the inertia of the system for replacing existing facilities with new generation systems, clustering effects (technological interdependence) and possible phenomena of increasing returns (i.e., the more a technology is applied the more it improves and widens its market potentials). Combined, these factors can lead to “lock-in” effects (Arthur 1989; Arthur 1994) and path dependency (change occurs in a persistent direction based on an accumulation of past decisions). As a result, technological change can go in multiple directions, but once change is initiated in a particular direction, it becomes increasingly difficult to change its course.

A.2.2 Technology representation

Important inputs for MESSAGE are technology costs and technology performance parameters. For the scenarios included in this study, technical, economic and environmental parameters for over 400 energy technologies are specified explicitly in the model. Costs of technologies are generally assumed to decrease over time as experience (measured as a function of cumulative output) is gained. In general, assumptions concerning the main energy conversion technologies are from (Riahi et al. 2007) and (Nakicenovic and Swart 2000) with updates for regional costs from (IEA 2008) and for biomass technologies from (America's Energy Future Panel on Alternative Liquid Transportation Fuels et al. 2009). Moreover, specifically for the purposes of this study, the investment and fixed O&M costs of CCS-relevant technologies in China in MESSAGE were harmonized with the assumptions in the C-GEM model. For pulverized coal power plants (w/o and w/ post-combustion CO_2 capture), IGCC coal power plants (w/o and w/ pre-combustion CO_2 capture), and coal poly-generation facilities (w/ CO_2 capture), the cost values were transferred directly to MESSAGE. For a variety of other energy conversion technologies with similar componentry (e.g., hydrogen and biofuels plants utilizing gasification systems and/or gas turbines), costs were varied based on simple scaling algorithms. The motivation for doing the latter was to preserve the internal consistency of the scenario storyline, in this case in terms of relative differences in the incremental costs of technologies over time. For instance, it stands to reason that if the cost of gasifiers declines over time due to technological progress, this would have an impact on the overall costs of not only coal IGCC plants but also coal-to-hydrogen plants and biomass-to-liquid plants utilizing Fischer-Tropsch technologies. Table 13 lists the CCS-relevant technologies that are currently included in MESSAGE. The investment values assumed for a subset of these and other technologies are shown in Figure 41.

Table 13. List of CCS technologies included in MESSAGE.

Sector	**Fuel Source**	**Technology**	**Co-generation**
electricity	coal	PC supercritical with post-combustion capture	heat
electricity	coal	PC ultra-supercritical with post-combustion capture	heat
electricity	coal	IGCC with pre-combustion capture	heat
electricity	natural gas	steam cycle with post-combustion capture	heat
electricity	natural gas	CC with pre-combustion capture	heat
electricity	biomass	IGCC with pre-combustion capture	heat
liquids	coal	Fischer-Tropsch (FT) coal-to-liquids with CCS	electricity
liquids	coal	coal methanol-to-gasoline (MTG) with CCS	electricity
liquids	natural gas	Fischer-Tropsch (FT) gas-to-liquids with CCS	-
liquids	biomass	Fischer-Tropsch (FT) biomass-to-liquids with CCS	electricity
gases	coal	coal gasification with CCS	-
gases	biomass	biomass gasification with CCS	-
hydrogen	coal	coal gasification with CCS	electricity

hydrogen	natural gas	steam methane reforming with CCS	-
hydrogen	biomass	biomass gasification with CCS	electricity
industry	cement	capture of CO2 emissions from calcination process	-

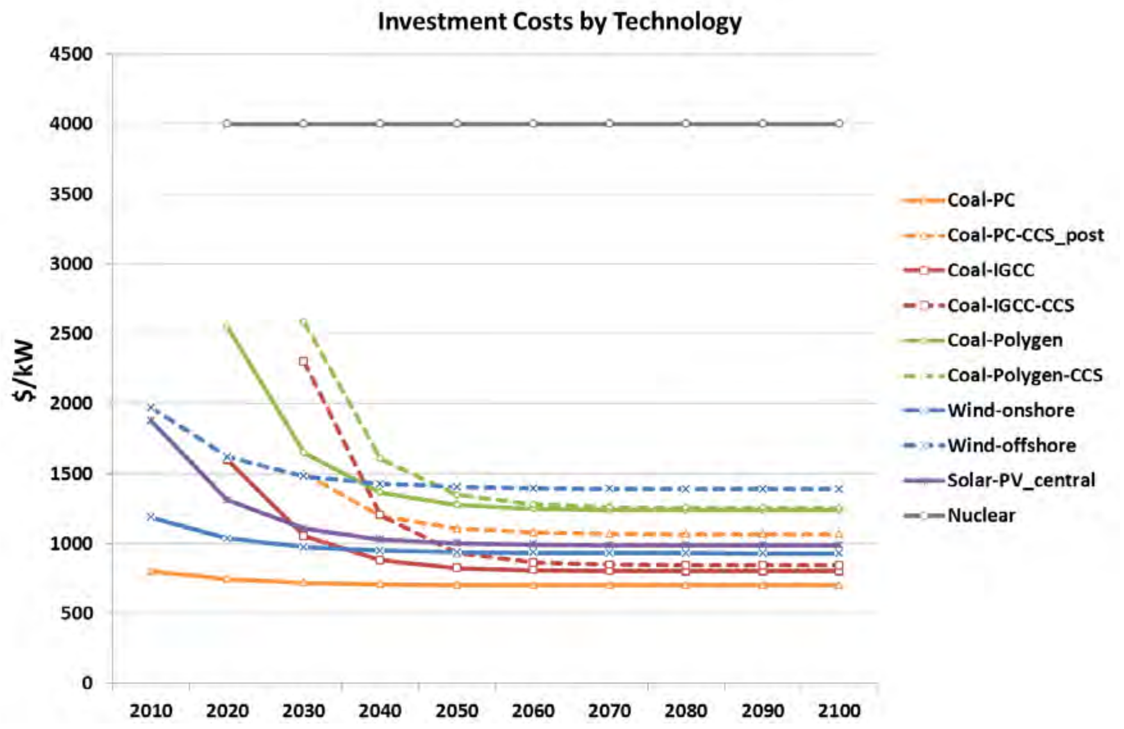

Figure 41. Investment costs assumed for a variety of energy conversion technologies in MESSAGE.

Other important input parameters for the modeling are fossil fuel resource estimates and potentials for renewable energy. For fossil fuel availability the model distinguishes between conventional and unconventional resources for eight different categories of oil, gas, or coal occurrences (Rogner 1997). With regards to volumes we follow by and large the quantitative assumptions adopted for the IPCC B2 scenario of the SRES report (Nakicenovic and Swart 2000). For renewable potentials we rely on spatially explicit analysis of biomass availability and adopt the assumptions discussed in (van Vuuren et al. 2009).

A.2.3 Macro-economic modeling

Price-induced changes of energy demand are calculated through iterations of MESSAGE with the macro-economic model MACRO. In the form used here, MACRO has its roots in a long series of models by Manne and Richels, the latest of which is MERGE 5.1 (Manne and Richels, http://www.stanford.edu/group/MERGE/). MACRO's objective function is the total discounted utility of a single representative producer-consumer (for each of its 11 world-regions). The maximization of this utility function determines a sequence of optimal savings, investment, and consumption decisions. In turn, savings and investment determine the capital stock. The capital stock, available labor, and energy inputs determine the total output of an economy according to a nested constant elasticity of substitution (CES) production function. Energy demand in two categories (electricity and non-electric energy) is determined within the model, consistent with the development of energy prices and the energy intensity of GDP. When MACRO is linked to MESSAGE, internally consistent projections of GDP and energy demand are calculated in an iterative fashion that takes price-induced changes of demand and GDP into account. This is achieved through iterations between the two models, in which demand, energy system costs and energy prices are exchanged until the solution of both models converge. For details of the iterative model linkage, see (Messner and Schrattenholzer 2000).

A.2.4 Emission species and climate

The modeling framework considers a number of GHG abatement options in the energy, industry, agriculture, and forestry sectors. These range from CO_2 emissions reductions due to structural changes of the energy system and replacement of carbon-intensive fossil fuels by cleaner alternatives (such as a switch from coal to natural gas, or the enhanced use of nuclear and renewable energy) to price-induced changes on the demand side geared towards energy conservation and efficiency improvements. Options in the power generation sector include the full suite of renewable technologies (biomass, solar, wind, geothermal) as well as nuclear. In addition the model provides alternative conversion processes for producing carbon-free liquid fuels, e.g., from biomass (ethanol or hydrogen) as well as hydrogen from renewable electricity. In addition, the capturing of carbon during energy conversion processes with subsequent storage in geological formations (CCS) provide an add-on, end-of-pipe approach for the decarbonisation of fossil fuels that enables their continued use with low CO_2 emissions to the atmosphere. Besides fossil CCS, the model allows for the application of CCS to bioenergy-conversion processes (e.g., during electricity or hydrogen production). Bioenergy in combination with CCS (BECCS) permits – if the biomass is grown sustainably – the supply of energy at negative CO_2 emissions. Another important option for CO_2 emissions reduction encompasses the enhancement of forest sinks through afforestation and reforestation activities.

In addition to these options to reduce CO_2 emissions, our analysis considers also the full basket of non-CO_2 gases. These gases comprise CH_4, N_2O, and F-gases. MESSAGE considers CH_4 emissions from the energy sector, like the extraction and transportation of coal, natural gas, and oil, and non-energy-related sources, like livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning. The major source of N_2O emissions considered is from agricultural soils. To a smaller extent, N_2O emissions also stem from animal manure, sewage, industry, automobiles, and biomass burning. Finally, F-gases are emitted predominantly from industrial sources. We consider bottom-up, technology-based mitigation options for the majority of the above sources. For emissions sources with particularly large uncertainties, such as emissions from rice cultivation or agricultural soils, we use more aggregated information given by regionally specific marginal abatement cost curves (MACs). For details on the mitigation technologies, their costs and the methodology used for accounting non-CO_2 sources see (Rao and Riahi 2006).

Parameterization of the mitigation potentials and costs of agricultural MACs was further updated based on (Beach et al. 2008) and (van Vuuren et al. 2006).

MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change), version 6.0, has been used in this study to estimate the climate system impacts of the varying greenhouse gas emission trajectories of the scenarios in the ensemble. MAGICC is a reduced-complexity coupled global climate-carbon cycle model, in the form of a user-friendly software package that runs on a personal computer (Meinshausen et al. 2011; Wigley 2008). In its standard form, MAGICC calculates internally consistent projections for atmospheric concentrations, radiative forcing, global annual-mean surface air temperature, ice melt, and sea level rise, given emissions trajectories of a range of gases (CO_2, CH_4, N_2O, CO, NO_x, VOCs, SO_2, and various halocarbons, including HCFCs, HFCs, PFCs, and SF_6), all of which are outputs from MESSAGE. The time horizon of the model extends as far back as 1750 and can make projections as far forward as 2400. The climate model in MAGICC is an upwelling-diffusion, energy-balance model, which produces output for global- and hemispheric-mean temperature and for oceanic thermal expansion. Climate feedbacks on the global carbon cycle are accounted for through the interactive coupling of the climate model and a range of gas-cycle models.

For further reading on MESSAGE, note that detailed background information on the model set-up and mathematical formulation of the modeling framework is available in (Messner and Strubegger 1995) and (Riahi et al. 2012). The model’s representation of technological change and learning is presented and discussed in (Rao et al. 2006; Riahi et al. 2004; Roehrl and Riahi 2000).

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