NRDC WHITE PAPER

Identifying Near-Term Opportunities For Carbon Capture and Sequestration (CCS) in China

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Identifying Near-Term Opportunities For Carbon Capture and Sequestration (CCS) in China

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Table of Contents

Chapter 6: Planned CCS Projects and Potential Opportunities **39**

Executive Summary

After three decades of rapid industrialization fueled by coal, China is now the world's biggest emitter of carbon dioxide (CO_2)—the pollutant most responsible for global warming. To avoid the worst consequences of global warming, the world must limit average temperature increases to 2°C or less by reducing carbon emissions at least 50 percent below 1990 levels by the year 2050. Without a clean energy transformation away from coal and other fossil fuels, the detrimental effects of global warming will only intensify over the coming decades.

Improving energy efficiency and conservation, switching to renewable energy sources, and enhancing carbon sinks, such as forests, are widely recognized as the most desirable "no-regret" strategies for reducing carbon emissions. Yet, achieving the urgently needed emission reductions will require efforts beyond first-resort measures. Countries relying heavily on fossil fuels must pursue a wide range of carbon mitigation strategies that includes Carbon Capture and Sequestration (CCS). China is well positioned to be a global leader in the development and deployment of CCS technologies with broad support and engagement from the international community.

China's Energy Outlook

China's heavy reliance on coal and rapid economic growth has dramatically driven up China's CO_2 emissions. In 1994, China emitted 3.07 billion tons, or gigatons (Gt), of CO_2. A decade later, in 2004, China's CO_2 emissions stood 60 percent higher, at over 5 Gt a year.

But China is not standing idly. In recent years, the Chinese government has implemented policies to accelerate the development of low-carbon energy. China set a goal of increasing the share of renewable energy resources (hydro, wind, solar, and biomass) from 7.5 percent of primary energy consumption in 2005 to 10 percent in 2010, and 15 percent in 2020.

So far, China's progress in these areas looks promising. At the end of 2009, non-fossil energy sources provided 9.9 percent of China's total energy. The wind power target—30 gigawatts (GW) of installed wind power by 2020—will likely be achieved 10 years early. As a result, the government is reported to be contemplating raising the 2020 targets to 300 GW of hydropower, 150 GW of wind power, 30 GW of biomass power, and 20 GW of solar PV.

Alongside non-fossil fuel energy development, the Chinese government is making major efforts in energy efficiency. A recent assessment by Lawrence Berkeley National Laboratory found that China will likely meet or come close to meeting its 20 percent energy efficiency reduction target by the end of 2010.

In 2009, China announced that it would commit to cutting its domestic carbon intensity by 40 to 45 percent below 2005 levels by 2020. A recent NRDC analysis concludes that it represents a significant, additional commitment that goes beyond the energy intensity and renewable energy targets China set during the 11^{th} Five Year Plan.

Even with the measures described above, coal will likely remain a dominant energy source in China's economy for decades; therefore CCS will likely need to play a key role in reducing carbon emissions before low-carbon fuel resources can truly take the main stage. McKinsey & Company estimates that China could reduce its 2030 emissions by 46 percent below business-as-usual, with CCS providing 11 percent of this reduction. Researchers at the ERI believe that by 2050 CCS could reduce China's CO_2 emissions by 16.5 percent.

Existing Point Sources of CO_2 in China

CCS can be applied to a variety of carbon emission sources and fuels, including biomass (where net emissions could be negative), but by far the biggest need for CCS lies with coal-fired power generation. A joint research team by the Chinese Academy of Science's Institute of Rock and Soil Mechanics (IRSM) and the U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL) has identified 1,623 large point sources of CO_2 in China. The researchers estimate that these large sources, which are the facilities emitting 100,000 or more tonnes of CO_2 per year, emitted more than 3.89 Gt of CO_2 annually before 2005.

According to the IRSM/PNNL study, the largest source category of CO_2 emissions comprised 629 power plants, which accounted for 73 percent of the documented emissions. Cement production was the second largest CO_2 source, while iron and steel came in third.

Not surprisingly, China's most industrialized areas—its central and eastern coastal regions—are also home to the country's densest regions of large point sources of CO_2.

The industrial processes that produce high-concentration CO_2 waste streams can most readily be involved in CCS projects at a relatively low cost, because high-concentration CO_2 emissions streams greatly simplify, or eliminate the need for, the capture process. A recent joint study by Tsinghua University and Princeton University identified 398 facilities across China that generate or will generate high-concentration CO_2 once constructions are complete and operations begin. Of these facilities, the researchers have identified 43 coal-to-methanol plants, 12 ammonia facilities, and two coal-to-liquids facilities that have or will have net CO_2 emissions exceeding 1 million tonnes per year per facility. Together these large facilities will provide over 185 million tons of high-concentration CO_2 per year in the near future.

Capture Technology and Its Status in China

There are three main categories of capture technologies for avoiding CO_2 emissions while generating electricity from coal: *post-combustion capture*, *oxy-fuel combustion capture,* and *pre-combustion capture*.

China has a large installed capacity of coal-fired power plants—601 gigawatts by the end of 2008—as well as fast-growing heavy industries, which must be addressed if China is to reduce its carbon emissions meaningfully. Accordingly, development of post-combustion capture technology in China should be given high priority. In recent years, China has begun intensifying CCS research and considering pilot CCS projects as a potential additional emissions control measure. China has also exhibited a growing capability in coal gasification technology, which, while not being used for CCS per se, opens up the possibility for CCS in the future.

A number of Chinese universities and specialized research institutes are playing dynamic roles in fundamental research and applied technologies, especially in the area of CO_2 capture, but also on underground coal gasification.

A couple of state-owned utility companies are advancing capture technologies through pilot projects. For post-combutions capture, there are the well-known Huanneng's pilots in Beijing and Shanghai and another small facility in Chongqing by the China Power Investment

Corporation. For pre-combustion capture, China is building its first IGCC plant in Tianjin known as GreenGen that will capture CO_2. A number of more IGCC projects have been proposed, but not all intend to capture carbon and they are all pending central government's approval.

Manufacturing of chemicals from coal is widespread and growing rapidly in China and may soon reach 180 million tons annually. These processes ventilate high concentration CO_2 as waste gas. Sequestering high concentration CO_2 waste streams presents low-hanging fruit opportunities for CCS demonstration at low cost. For the technology to contribute meaningfully to emission reductions, integrated commercial projects are urgently needed to gain operational experience and drive down costs, which can be captured at very low incremental costs for sequestration.

CO_2 Geologic Storage Capacity in China

Overall, China's total theoretical CO_2 storage capacity in depleted oil and gas fields, deep saline formations, and unminable coal seams, as jointly estimated by researchers at China's Institute of Rock and Soil Mechanics (IRSM) and the Pacific Northwest National Lab (PNNL) in the U.S., could be about 3,120 billion tons—over 500 times China's total CO_2 emissions in 2004. Deep saline formations offer the largest potential storage capacity in China, accounting for approximately 99 percent of the country's total geologic storage resources, as we further outline below.

While China's sedimentary basins are large in number, they are also among the most complicated worldwide, and detailed localized studies and site characterization will be crucial to ensure successful CO_2 injection.

Summary of China's potential CO2 storage capacity (by type of storage option)[i]

	Deep saline formation ($MtCO_2$)	Oil fields by proved OOIP($MtCO_2$)	Gas fields by proved OGIP($MtCO_2$)	Unminable coal seams ($MtCO_2$)
Onshore	2,317,100	4,895	4,323	12,000
Offshore	776,700	189	898	
Total	3,093,800	5,084	5,221	12,000

[i] Data taken from Li, X. et al., 2009: CO2 Point Emission and Geological Storage Capacity in China, *Energy Procedia*, 1(1), 2793-2800; and Dahowski, R.T. et al., 2009: A Preliminary Cost Curve Assessment of Carbon Dioxide Capture and Storage Potential in China, *Energy Procedia*, 1(1), 2849-56.

IRSM/PNNL joint research found that more than half of the 1623 large point sources of CO_2 in China are located directly above a potential geologic storage site, and more than 80 percent are within 80 kilometers from such a site. As a result, they estimate that the CO_2 emissions from 65 percent of the large point sources they identified can be transported and injected underground for less than $10 per ton (excluding capture costs).

As for high-concentration CO_2 source and site matching, 85 out of the 185 sources (46 percent) identified by co-authors of this report Li and Wei are located within 80 km of an oil or gas field. However, the Tsinghua/Princeton team has found that while 23 out of the 27 plants that emit over one million tonnes CO_2 per year are located less than 50 km from an onshore saline aquifer, only two are that close to an oilfield. The team estimates that the transportation and injection costs for plants within 10 kilometers of a sink range between $9 and $12.6 per tonne of CO_2.

Potential Opportunities for CCS Pilots in China

As no full-scale CCS projects have been carried out in China thus far, the first cluster of CCS demonstration projects will likely be smaller scale efforts that will allow China to gain experience in the technical, financial, regulatory, and social aspects of CCS.

We describe three areas that have oilfields or gas fields and are close to relatively large sources of CO_2 emissions. Excluding the saline aquifers deep underneath the sites, the storage capacities of those oil and gas fields are not very large, but they may still serve as convenient near-term pilot opportunities. We also profile four projects where CCS is already planned or might be possible: three IGCC plants in various stages of planning and with owners who have expressed their intent to capture CO_2 for sequestration, the widely reported Shenhua coal-to-liquid project.

These projects, intended as discussion examples only, and not the result of a systematic screening or assessment, include:

- *Daqing and Jilin oilfields in the Songliao Basin*
- *Jiangyou gas fields for possible co-storage of low-quality* CO_2
- *GreenGen IGCC project*
- *Langfang IGCC project*
- *Dongguan Taiyangzhou IGCC project*
- *Shenhua Direct Coal Liquefaction project*

Developing a CCS Regulatory Framework in China

To encourage further development and demonstration of CCS technology, China will need a regulatory framework that creates incentives while ensuring that CCS projects also protect human health and the environment.

In several industrialized countries, significant efforts have focused on developing a robust set of rules for appropriately selecting and operating a CO2 storage site, monitoring the CO2 stored, carrying out maintenance and corrective action if needed, and eventually decommissioning the site, while ensuring human health and safety as well as protection of the environment. As countries develop their regulatory infrastructure, there is a need for knowledge sharing and the documentation of CCS best practices.

The World Resources Institute (WRI) facilitated a stakeholder process with over 80 participants from industry, business, academia, governments, and environmental groups to establish CCS guidelines. These guidelines are now being used as a starting point for a Tsinghua University-WRI effort to develop CCS Guidelines for China. In this report, the co-authors with WRI summarize and analyze China's existing regulations and key players, as well as present the main components needed for a CCS regulatory framework.

Recommendations

Because CCS involves large-scale systems engineering and geologic expertise, international collaboration will be indispensable for accelerating CCS development and deployment in the countries that need the technology. For China, which still faces daunting development needs and has relatively limited technological, financial and regulatory capacities in some areas, international collaboration and assistance are all the more critical.

Near-term demonstration projects on CCS are a vital step toward widespread deployment of the technology. Demonstration projects can start on a smaller scale than will eventually be required over the long term. Further, to reduce project costs, CO_2 can be injected into depleted oilfields that have smaller storage capacities but will help develop CCS know-how, from design to construction and from monitoring to regulating. Full-size demonstration projects, especially those using deep saline reservoirs, are also an important next step with the main goal to drive down the costs of CCS and nurture a CCS industry.

Specifically to the international community, governments, and businesses, our recommendations are:

- Cooperation on financing early CCS opportunities
- Direct involvement in CCS demonstration projects in China
- Mutually beneficial transfer of technology and joint R&D and demonstration
- Assistance with development of regulations and policies on CCS

And to Chinese policymakers, priority is given to four key R&D and demonstration areas:

- Strengthening R&D and demonstration in CCS
- Timely development of a regulatory framework for CCS
- Building strong monitoring and verification capacities
- Incentivizing safe low-carbon energy systems

Despite China's commendable efforts to reduce coal's role in the country's energy supply, coal will remain a significant part of the energy mix for several decades. As a result, China is likely to need CCS as one of many important tools for CO_2 emissions mitigation. The future of CCS in China depends on the extent of international partnerships and the incentives that Chinese as well as international policymakers will adopt for reducing carbon emissions and developing a robust CCS industry. International cooperation in CCS is important for China and the rest of the world not only in terms of climate safety, but also shared benefits in technology advancement and economic competitiveness.

Chapter 1: Introduction

After three decades of rapid industrialization fueled by coal, China is now the world's biggest emitter of carbon dioxide (CO_2)—the pollutant most responsible for global warming.[1] This economic growth has lifted hundreds of millions of people out of poverty, and millions more could gain from further economic development. Yet continued reliance on coal-fired power threatens to create a climate catastrophe.

Scientific evidence has established that warming of the Earth's climate system is unequivocal.[2] The average atmospheric temperature near the surface has risen much faster over the past 150 years than during the thousands of years before, and over the last 50 years this warming trend has accelerated. During the last decade, the world experienced some of the highest average global temperatures in recorded history (see Table 1.1).[3]

Table 1.1 Top ten hottest years in recorded history

Rank	Year	Avg. global temperature
1	1998	14.52˚C
2	2005	14.48˚C
3	2003	14.46˚C
4	2002	14.46˚C
5	2004	14.43˚C
6	2006	14.42˚C
7	2007	14.40˚C
8	2001	14.40˚C
9	1997	14.36˚C
10	2008	14.31˚C

Source: Met Office Hadley Centre, 2009; Richard Black, 2009.

Without a clean energy transformation away from coal and other fossil fuels, the detrimental effects of global warming will only intensify over the coming decades. These negative trends will include rising sea levels, more extreme weather patterns, rapidly-melting glaciers, damage to ecosystems, and the resurgence and spread of diseases. Scientific models warn that a 2˚C to 4˚C increase in global average temperatures would likely trigger sudden and irreversible effects, including the submersion of large areas of coastline due to significant sea level rises, abrupt shifts in global ocean circulation patterns causing large-scale climate change, and the potential extinction of 40 to 70 percent of species worldwide.[4] Without significant global action, we may soon reach a tipping point upon which global warming begins to reinforce itself in hard-to-stop positive feedback cycles. For example, melting permafrost could unlock previously frozen greenhouse gases, which would accelerate and fuel the warming trend.[5]

To avoid the worst effects of this warming, the world must reduce emissions of CO_2 and other greenhouse gases by drastically reducing its reliance on fossil fuels. To this end, governments around the world are moving toward a consensus that we must not allow global average temperatures to rise by more than 2˚C above pre-industrial levels. This limit implies that the world as a whole must cut CO_2 emissions in half by 2050 compared to 1990 levels.[6]

To prevent a global warming disaster, China and other key countries must rapidly reduce CO_2 emissions. Improving energy efficiency and conservation, switching to renewable energy sources, and enhancing carbon sinks, such as forests, are widely recognized as the most desirable "no-regret" strategies for reducing carbon emissions. Yet several studies of global greenhouse gas abatement pathways and future scenarios have found that, for technical, economic, or political reasons, these strategies for CO_2 reduction would be insufficient alone or run a risk of not being deployed widely enough in time to keep temperature rise below the critical 2˚C threshold.[7] Thus, countries relying heavily on fossil fuels must explore interim measures to bridge the low-carbon clean energy economy of the future with the realities of the energy mix today.

This report assesses how one such technological approach—carbon capture and sequestration, or storage (CCS) (see Box 1.1)—can serve as a bridge to this future by reducing China's CO_2 emissions and meeting the country's internal energy and environmental goals. In particular, the report identifies China's "low-hanging fruit"—near-term, low-cost—CCS possibilities that could provide stepping-stones for broader deployment moving forward.

While CCS is not an optimal solution, it may be a necessary one. Significant cost improvements are expected, but the costs of CCS today are, in general, relatively high due to the capital and energy needed to capture, compress, transport, and inject CO_2 into deep underground reservoirs, except in specific cases which we examine in this report. Further, the application of CCS at coal-fired power plants will not displace coal mining and use, which create significant environmental problems beyond global warming. Still, until global energy production can fully abandon coal and other fossil fuels, CCS likely represents one of the necessary strategies to fight global warming. Of course, the applicability of CCS technology also extends beyond coal. In the case of biomass energy, for example, net emissions after CCS could actually be negative because production of biomass involves the removal of carbon from the atmosphere.

Given the dominance of coal in China's energy system and the urgent need to achieve significant CO_2 emissions reductions, China and the international community must consider CCS within a portfolio of climate protection strategies.

In the following chapters, this report discusses the potential and need for CCS in China by covering the country's energy challenges, CO_2 point sources, development of carbon capture technologies, potential storage capacity, case descriptions, and relevant regulations. Specifically:

- Chapter 2 details China's energy development plans and the potential role and importance of CCS in meeting China's environmental and energy goals.

- Chapter 3 maps China's large CO_2 emissions point sources and identifies the existing high-concentration CO_2 sources where capture would be possible at lowest cost.

- Chapter 4 reviews technologies that can be used to capture CO_2 from these large point sources and evaluates the current status of these capture technologies in China.

- Chapter 5 assesses China's geology to determine how and where China could best store captured CO_2.

- Chapter 6 evaluates five significant CCS projects in China that are either already under way or in their advanced planning stages, as well as two promising locations in China where future CCS projects may be economically attractive.

- Chapter 7 considers the regulatory frameworks needed to ensure safe and successful CCS implementation in China.

- Finally, Chapter 8 concludes with recommendations for the international community, businesses, and Chinese policymakers on how best to encourage and benefit from the implementation of CCS in China in the years ahead.

Box 1.1 Carbon Capture and Sequestration (CCS)

CCS is a 3-step process that involves CO_2 capture from large point sources, compression and transportation to an injection site, and geologic sequestration (or storage) in a suitable reservoir.

Step 1: Capture

The purpose of the "capture" stage is to isolate CO_2 into a nearly pure stream because large CO_2 point sources, such as power plants and some industrial facilities, do not usually produce high-concentration CO_2 streams directly. The volumes, costs, and energy involved in injecting a gas underground are significant; therefore, it is more cost-effective to inject high-concentration CO_2 than to inject the entire flue gas stream. There are commercially available capture technologies, but implementation of large-scale CCS will require further improvement in the efficiency and economics of these technologies.

Step 2: Compression and Transportation

After capture, high-concentration CO_2 is compressed into a supercritical, or dense, liquid-like phase, which is more suitable for transport and eventual sequestration. Both the compression of captured CO_2 and long-distance transportation in pipelines are mature technologies in use today.

Step 3: Sequestration

Sedimentary rocks present the best opportunities for geologic sequestration of CO_2. Depleted oil and gas fields, deep saline formations and, pending further proof, unminable coal seams, can permanently trap injected CO_2. The vast majority of storage capacity lies within deep saline formations, but enhanced oil and gas recovery using CO_2 offers an attractive near-term opportunity (albeit one that extends the availability of fossil fuels). Tens of millions of tons of CO_2 are already being injected for this purpose every year.

To ensure that injected CO_2 remains trapped underground, it is critical to establish robust short- and long-term monitoring, measurement, and verification systems. Adequate post-closure care for injection sites must also be an integral part of sound projects. Numerous technologies currently exist to monitor and model injected CO_2.

Chapter 2: China's Energy Outlook

Increasingly, China is investing in energy efficiency as well as renewable and low-carbon energy technologies (e.g., wind, solar, biomass, hydro, and nuclear) that could significantly reduce the country's climate impact. China should be commended for taking these measures.

Despite these efforts, however, China's total annual CO_2 emissions continue to grow. Even as China improves its energy efficiency, rapid economic growth is resulting in hasty construction of new power plants, most of which are fueled by coal. As is explained below, projections of energy demand further suggest that even if China continues to increase and incentivize low-carbon and renewable energy, coal will likely remain a major energy source through at least the middle of this century.

To avoid the worst effects of global warming, China—with help from the international community—must find ways to do more. This chapter discusses China's heavy reliance on coal, its efforts to promote cleaner energy, and the likely impacts of existing measures in addressing the country's greenhouse gas emissions.

This chapter also discusses the potential role of more expensive strategies like CCS in deflecting China from its current high emissions trajectory.

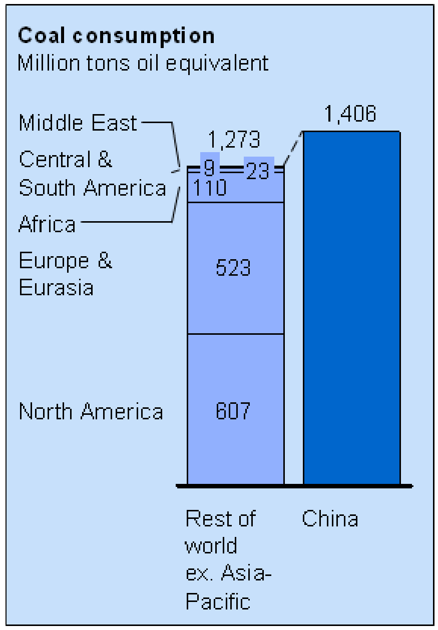
Heavy reliance on coal

Coal—the most carbon-laden of the three major fossil fuels (i.e., natural gas, crude oil, and coal)—supplies nearly 70 percent of China's energy. China's heavy reliance on this fuel is reflected by the fact that during the last five years the country has accounted for nearly four-fifths of the global growth in coal consumption.[8] In 2008, China consumed more coal than North and South America, the European Union, Russia, the Middle East, and Africa *combined* (see Figure 2.1).

Heavy reliance on coal has sharply driven up China's CO_2 emissions. In 1994, China emitted 3.07 billion tons, or gigatons (Gt), of CO_2. A decade later, in 2004, China's CO_2 emissions stood 60 percent higher, at over 5 Gt a year.[9] As a result, China's annual CO_2 emissions now exceed those of the United States.[10]

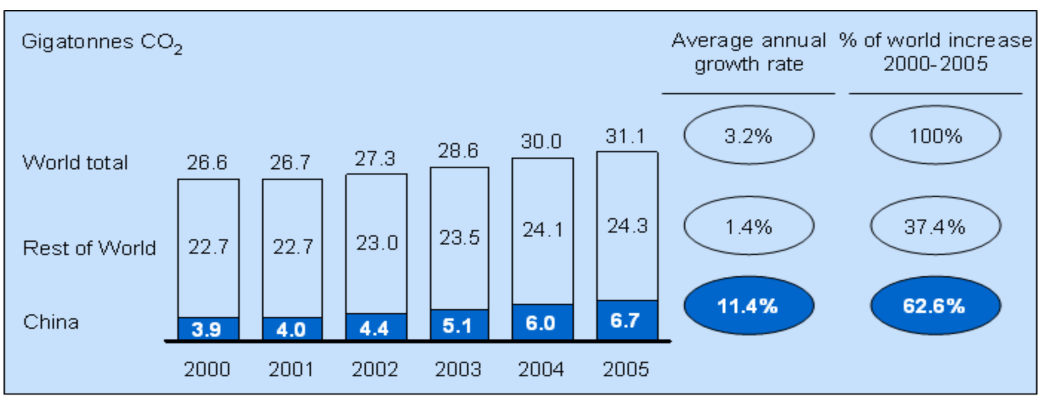
With its CO_2 emissions surging nearly eight times faster than in the rest of the world (see Figure 2.2), China has a pivotal role to play in the global effort to prevent the worst impacts of global warming from occurring.[11]

Figure 2.1 China's coal consumption compared to the rest of world in 2008



Source: BP Statistical Review of World Energy 2009.

Figure 2.2 China CO_2 emissions compared to world emissions, 2000-2005



Source: EDGAR, 2009.

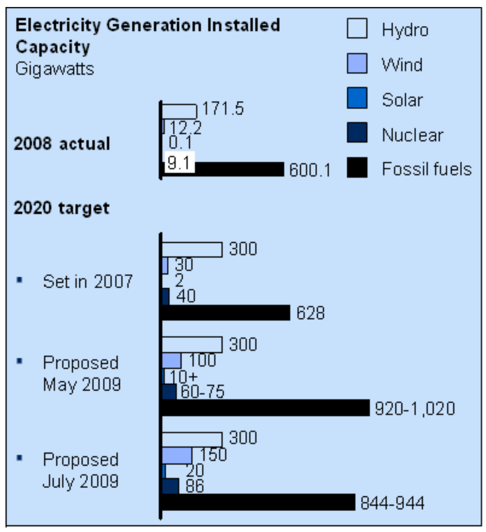
Low-carbon energy development

China is not standing idly by in the face of global warming and in addressing its own domestic energy security and environmental concerns, although the challenge is daunting.

Notably, in recent years, the Chinese government has implemented policies to accelerate the development of low-carbon energy, including renewable energy and nuclear power. China's 11th Five-Year Plan (2006-2010) for Renewable Energy Development and its 2007 Medium- and Long-Term Development Plan for Renewable Energy set a goal of increasing the share of renewable energy resources (hydro, wind, solar, and biomass) from 7.5 percent of primary energy consumption in 2005 to 10 percent in 2010 and 15 percent in 2020.[12] China has since converted its 15 percent by 2020 renewables target to a non-fossil energy target, which includes both renewables and nuclear power. Nuclear power provided less than 0.8 percent of China's energy in 2005 but should rise to 2 to 3 percent of the total by 2020, if national targets are met.[13]

So far, China's progress in these areas looks promising. At the end of 2009, non-fossil energy sources provided 9.9 percent of China's total energy.[14] Wind power development has been particularly successful. The 2007 Medium- and Long-Term Development Plan for Renewable Energy established a specific target of 30 gigawatts (GW) of installed wind power capacity by 2020. China will likely achieve this target in 2010—a full decade early.[15] As a result, the central government is reported to be contemplating raising the 2020 wind target to 150 GW or more of installed capacity.[16] China's nuclear and solar energy growth has also exceeded earlier expectations, leading to more ambitious target setting (see Figure 2.3).[17]

Figure 2.3 China's changing 2020 energy targets



Source: NDRC, 2007; Zheng, Lifei and Lijun Mao, 2009.

China's current draft plan for alternative energy development through 2020 calls for 300 GW of hydropower, 150 GW of wind power, 30 GW of biomass power, and 20 GW of solar PV, for a total of 500 GW of renewable power capacity by 2020. This represents almost one-third of the country's total expected installed power capacity of 1600 GW in 2020.[18]

Energy intensity reduction target

Alongside non-fossil fuel energy development, the Chinese government is making major efforts in energy efficiency. Under the 11th Five-Year Plan, China aims to reduce the energy intensity of its economy (the energy consumed per unit of GDP) by about 20 percent below 2005 levels by 2010.

In order to reach this goal, the government instituted and strengthened several energy efficiency programs and measures during the 11th Five Year Plan period, including:

- Ten Key Energy Conservation Projects, which aims to improve energy efficiency in ten broad areas in the industrial, building and power sectors;[19]

- The Top 1,000 Enterprises Program, which requires the 1000 most energy-consuming enterprises (accounting for 1/3 of total energy use) to increase their energy efficiency; building energy efficiency standards and programs;
- Closure of smaller power plants and industrial facilities in favor of larger, more efficient facilities;
- Measures to adjust China's economic structure to reduce the dominance of energy-intensive industry in the economy; and
- Appliance standards and efficiency labels.

A recent assessment by Lawrence Berkeley National Laboratory found that most of these programs were on track to meet their 11th Five Year Plan targets and that China will likely meet or come close to meeting its 20 percent energy efficiency reduction target by the end of the 11th Five Year Plan.[20]

Over the last five years, China's power generation sector has also deployed more efficient coal-fired power generation technologies, including circulating fluidized-bed combustion (CFBC) and supercritical and ultra-supercritical steam generation. China began researching and developing these technologies more than a decade ago. Thanks to these efforts and the growth of domestic manufacturing, the cost of these technologies has increasingly fallen.

Today, China is the world leader in CFBC technology, with 2,641 CFBC boilers installed through 2007.[21] It is true that around 80 percent of China's existing coal-fired power plants still use inefficient, antiquated subcritical steam parameter designs.[22] But in 2008, China's National Development and Reform Commission (NDRC) adopted a standard requiring that all new coal-fired power plants use state-of-the-art commercially available or better technology. As a result, today most of the world's new supercritical and ultra-supercritical power plants are being built in China.[23] On average, these new plants emit 20 percent less CO_2 than older plants.[24] In 2004, supercritical plants represented only 3 to 4 percent of China's total coal-fired power generation capacity, but by 2007 this percentage increased to 17.8 percent.[25] By the end of 2007, four 1,000 MW ultra-supercritical coal-fired power plants were online and as many as 100 more of this size may be under construction in China today.[26]

All of these plants, of course, still vent significant amounts of CO_2 into the atmosphere. And while China has closed down a large number of inefficient plants in recent years, many of the country's new more efficient plants add new generating capacity to the grid, creating new sources of emissions.

Carbon intensity reduction target

In 2009, prior to the United Nations climate change negotiations in Copenhagen, China's State Council announced that China would commit to cut its domestic carbon intensity (CO_2 emissions per unit of GDP) by 40 to 45 percent below 2005 levels by 2020.[27] A recent NRDC analysis of this target concludes that it represents a significant, additional commitment that goes beyond the energy intensity and renewable energy targets China set during the 11th Five Year Plan.[28] The analysis shows that if China were to fulfill only its previous commitments without extending its energy intensity policies beyond 2010, the country would only reduce its carbon intensity by 37 percent from 2005 levels by 2020. Therefore, China's 40 to 45 percent carbon intensity target represents a concrete new commitment when compared with the 37 percent reduction. Achieving the upper range of China's new target would require significant new efforts, and would be largely in line with the 47 percent reduction called for by the International Energy

Agency (IEA) in order to meet a 450 parts per million (ppm) atmospheric CO_2 concentration level and avoid the worse effects of climate change.[29]

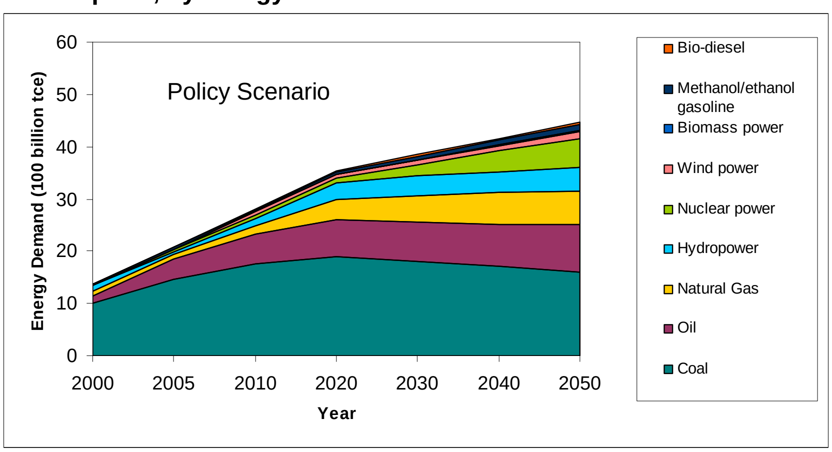
As with energy intensity, improved carbon intensity does not mean that China will reduce its net annual CO_2 emissions in the near future. In fact, with continued economic growth, China's emissions are still likely to rise beyond 2020. Improved carbon intensity will, however, reduce China's business-as-usual CO_2 emissions and begin to deflect the country from a higher emissions trajectory, which is an important step.

China has not yet officially announced new targets for the next five years under its 12th Five Year Plan (2011-15). However, it is highly like that China will set a further energy intensity reduction target and continue to strengthen existing energy efficiency programs and measures in order to help reach its goal of reducing its carbon intensity by 40 to 45 percent by 2020.

Declining but lingering coal dominance

Even with the measures described above, coal will likely remain a dominant energy source in China's economy for decades. Researchers at China's Energy Research Institute (ERI) estimated that through implementing aggressive policies that encourage low-carbon energy use (without CCS), coal use in China might peak by 2020 (see Figure 2.4).[30]

Figure 2.4 China Energy Research Institute projection of China's primary energy consumption, by energy source



Source: Re-produced from Jiang, Kejun et al., 2008.

Under this aggressive *policy scenario*, coal's share in China's total energy mix would shrink to about 35 percent by 2050 from today's 69 percent. This still implies, however, that coal would remain a significant energy source through the middle of this century. Moreover, the ERI's study shows that under this scenario China's annual CO_2 emissions would only begin to level off after 2020 and would not decrease before 2050.[31] Such a non-declining projection in CO_2 emissions is based on the assumption that China's total energy demand will continue to rapidly grow and much of the growth will need to be met by oil and natural gas, neither of which are carbon free.

According to the same study, China's emissions would stabilize at around 7.7 Gt per year. This figure is 65 percent of the global permissible annual CO_2 emissions budget of 11.9 Gt in a halve-by-2050 scenario—the level considered necessary to maintain the average global temperature increase below 2°C.[32] If China maintains its current business-as-usual emissions trajectory instead, the country's CO_2 emissions could exceed 12 Gt per year in 2050, more than the total world budget.[33]

Projections by the U.S. Energy Information Administration (EIA) suggest that China's coal consumption could reach even higher levels. In 2007, energy conversion (e.g., power generation, coke making, and heating) and industrial production accounted for nearly 95 percent of China's coal consumption—totaling 1.7 billion tons of standard coal.[34] Coal demand in both categories is expected to continue growing rapidly. In electricity generation, the EIA projects that China's coal demand will grow by 3.5 percent per year through 2030, reaching 2 billion tons of standard coal annually.[35] Recognizing China's ongoing industrialization, the EIA also projects that coal demand from the industrial sector may increase by 1.9 percent per year over the next two decades, from 800 million tons in 2006 to 1.32 billion tons in 2030.[36]

An additional force that could drive China's demand for coal higher is the development of coal-based alternative fuels. In part because of China's relatively small indigenous supplies of oil and natural gas, coal-to-liquid fuel technologies have attracted the interest of many Chinese energy and chemical companies. Coal-to-liquid fuel processes are energy-intensive and coal-based transportation fuels would release almost twice as much CO_2 as petrol-based fuel, when analyzed on a life cycle basis.[37] China's NDRC has wisely restricted construction of coal-to-liquid plants three times since 2006. [38] One coal liquefaction project—in Inner Mongolia by the Shenhua Group—has been approved for construction. This project began operating in January 2009.[39] Only one other project—also by Shenhua—has been allowed to proceed with feasibility studies.[40]

The magnitude of the climate threat and the projections on China's energy outlook by ERI and the EIA, among others, suggest that CCS will likely need to play a key role in reducing carbon emissions before low-carbon fuel resources can truly take the main stage.

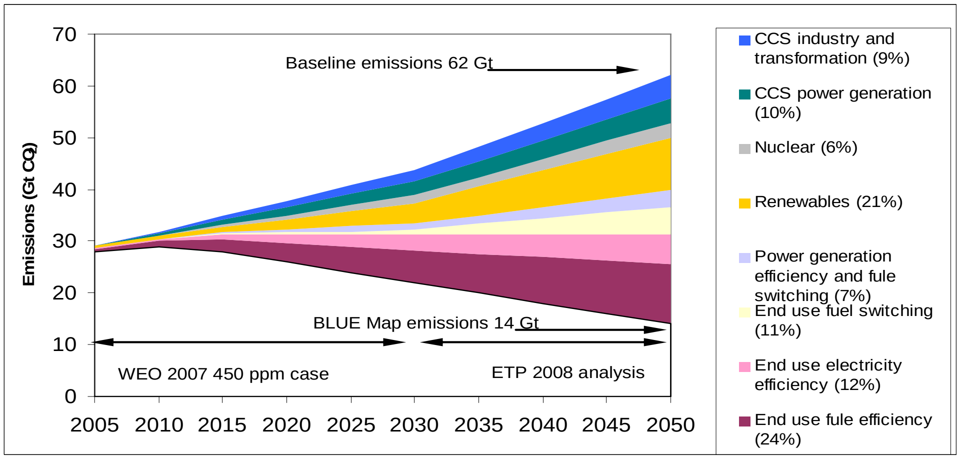
CCS in a portfolio of abatement options

The Intergovernmental Panel on Climate Change (IPCC) has identified CCS, among other options, as a key tool to help the world achieve the urgently needed deep cuts in CO_2 emissions before 2050.[41] CCS can be applied to a variety of carbon-intensive activities and fuels to reduce or eliminate emissions. For example, CCS can be used:

- With ethanol production;
- At refineries;
- At plants that produce and process cement, iron and steel, chemicals, fertilizer, and natural gas; and
- In power generation at facilities burning fossil fuels, such as coal, natural gas, and petroleum coke, as well as biomass (where net emissions after CCS could be negative).

McKinsey & Company estimates that China could reduce its 2030 emissions by 46 percent below business-as-usual, with CCS providing 11 percent of this reduction.[42] Researchers at the ERI believe that by 2050, CCS could reduce China's CO_2 emissions by 16.5 percent.[43] Overall, IPCC scenario analyses suggest that CCS could contribute 15 to 55 percent of cumulative global CO_2 emissions reductions needed through 2100.[44] In its analysis, the IEA assigns 19 percent of the needed CO_2 reductions by 2050 to CCS, with 10 percent coming from CCS at power plants and 9 percent by capturing CO_2 from other industrial processes (see Figure 2.5).[45]

Figure 2.5 IEA projection of impact on global CO_2 emissions, by mitigation strategy



Source: IEA, 2008.

Although further technical and economic advancements are needed before CCS can be deployed widely around the world, all of the technologies needed for CCS are already proven at large scale, and the first wave of commercial projects can be built and operated safely and effectively today. Existing large, integrated projects that demonstrate CCS technologies support these conclusions, and it is now widely recognized that CCS could provide an important and practical option for the world in CO_2 mitigation. Recognizing this, the G8 has committed to launch 20 large-scale CCS pilots by the end of 2010.[46]

Finally, while the cost of CCS is still high, the IPCC estimates that CCS technology could ultimately help reduce the global costs of stabilizing atmospheric CO_2 concentrations by 30 percent or more during this century.[47] In the following chapters, this report examines the factors that affect the potential of CCS to contribute to CO_2 emissions reductions in China.

Chapter 3: Existing Point Sources of CO_2 in China[a]

If CCS is to contribute meaningfully to the fight against global warming in China and other countries, the technology must be implemented at large point sources of CO_2 where it can have the greatest impact, such as coal-fired power plants and certain other industrial facilities. Thus, the first step must be to assemble information on the location of China's large point sources of CO_2 and their annual emissions amounts.

Also important—especially for early projects when the cost of CCS technology will be at its highest—is to identify high-concentration sources because their waste streams require less processing during the capture phase to arrive at the pure CO_2 needed for transport and sequestration.

This chapter describes the findings of the most recent study on large point sources of CO_2 in China by a joint effort between researchers from the Chinese Academy of Science's Institute of Rock and Soil Mechanics (IRSM) and the U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL).[48] Another joint study by Tsinghua University and Princeton University on high-concentration CO_2 sources in China is also mentioned.[49]

Characteristics of large CO_2 point sources

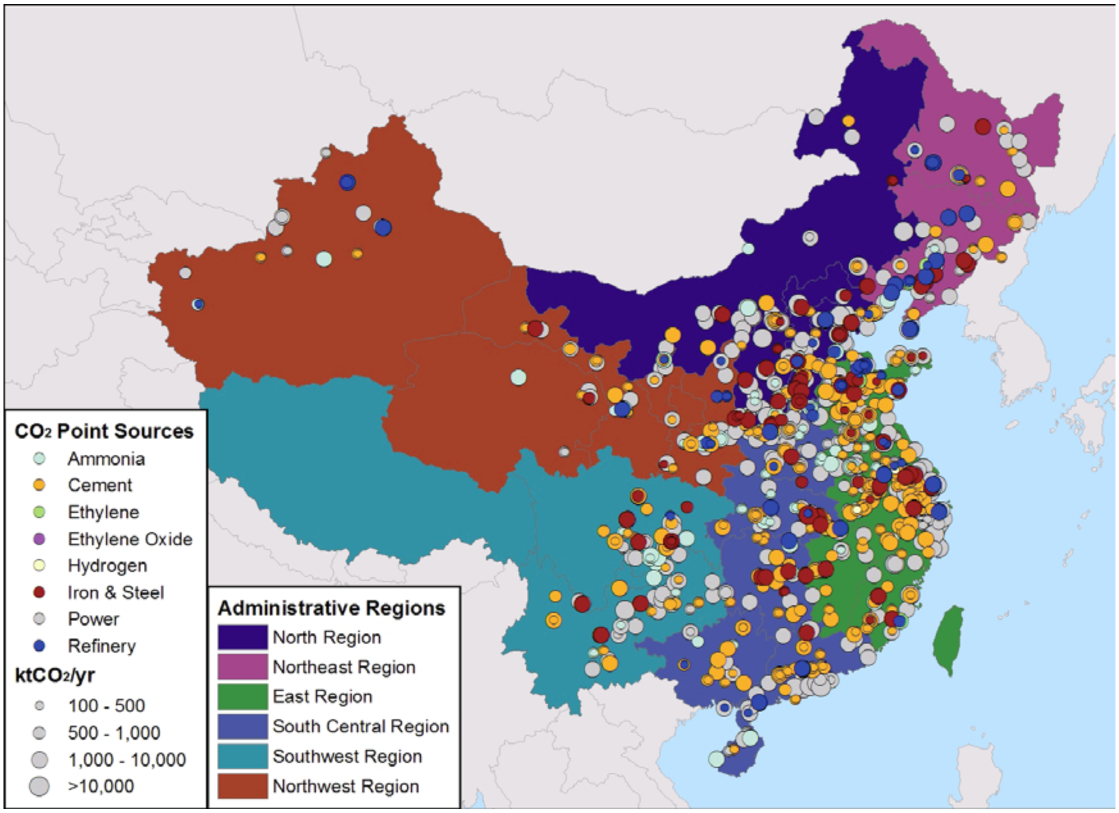
The joint IRSM/PNNL team identified 1,623 large point sources of CO_2 in China. These large sources, which the team defined as facilities emitting 100,000 or more tonnes of CO_2 per year, are estimated to have emitted more than 3.89 Gt of CO_2 annually before 2005.[50] Because the researchers had to rely on publicly available data, much of which dated from 2005 or earlier, total emissions from China's large point sources are likely higher today, given recent growth in China's energy-intensive, high carbon-emitting sectors such as power generation and the production of cement, iron, and steel.

Looking at Figure 3.1, it is not surprising to see that China's most industrialized areas—its central and eastern coastal regions—are also home to the country's densest regions of large point sources of CO_2. The joint IRSM/PNNL team identified other dense, though smaller, clusters of large point sources in the southwestern Sichuan-Guizhou area and the southern province of Guangdong. China's northeastern region also contains many large point sources.

According to the joint IRSM/PNNL study, the largest source category of CO_2 emissions comprised 629 power plants, which collectively accounted for 73 percent of the documented emissions; 994 sources in other sectors accounted for the rest (see Figure 3.2).[51] Cement production was the second largest CO_2 source, while iron and steel came in third. In total, the top three sectors produced 93 percent of China's total CO_2 emissions from large point sources.

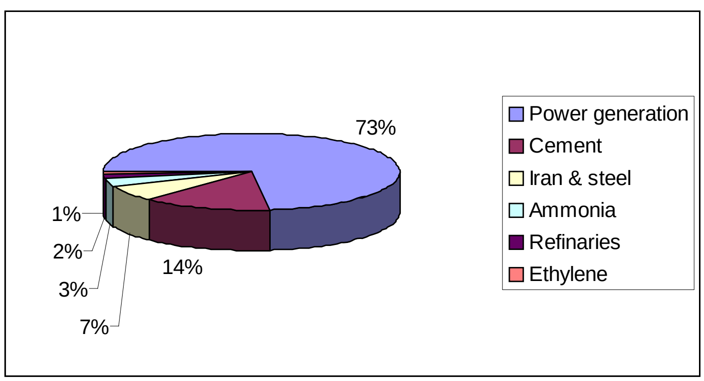
[a] Xiaochun Li and Ning Wei from China's Institute of Rock and Soil Mechanics are the main contributors to this chapter with most of their information drawn from their joint publications with the U.S. Department of Energy's Pacific Northwest National Laboratory.

Figure 3.1 Distribution of large CO_2 point sources by type and amount of emissions



Source: Dahowski, R.T. et al., 2009a.

Figure 3.2 Share of CO_2 emissions by sector



Source: Dahowski, R.T. et al., 2009a.

Table 3.1 reveals that the majority of large point sources and associated CO_2 emissions come from a small number of regions. While the IRSM/PNNL team collected data from 31 provinces, autonomous regions, and municipalities with provincial status, just twelve—Zhejiang, Guangdong, Inner Mongolia, Henan, Shanxi, Liaoning, Hubei, Anhui, Shanghai, Shandong, Jiangsu, and Hebei—produced 70 percent of all emissions from large point sources. The three highest emitters—Shandong, Jiangsu, and Hebei—accounted for a quarter of all emissions.

Table 3.1 Estimated Annual CO_2 Emissions From Major Industries by Province (2005)

(Thousands of tons per year)

Provincial evel region	Power plant	Cement	Ammonia	Ethylene	Hydrogen	Iron & Steel	Refinery	Ethylene oxide	Total
Shandong	270279	53077	15256	3871	206	17331	8300	0	41168
Jiangsu	227088	30284	6474	2859	899	17295	6329	113	31413
Hebei	190198	11334	2873	0	103	36691	2210	0	26235
Zhejiang	144302	21356	2034	0	652	4193	3504	0	23003
iuangdong	179037	7379	1169	3430	549	8649	8037	0	22735
Inner Mongolia	201723	27661	3067	0	0	13237	0	0	22484
Henan	177959	26480	6652	869	0	11404	2656	0	22089
Shanxi	193812	32628	6875	0	0	11863	0	0	21992
Liaoning	95146	75346	6317	6632	995	43665	12702	0	17679
Hubei	87008	10226	4258	1830	0	21504	1205	0	14346
Anhui	84728	1681	7904	0	103	10770	0	0	13613
Shanghai	82322	6820	1604	8118	532	14350	6154	0	11476
Guizhou	101102	11078	2000	0	0	2286	0	0	10926
Shaanxi	71891	3881	8166	0	0	4286	1927	0	94463
leilongjiang	66381	8192	4259	2607	343	1715	6723	0	87829
Hunan	52427	5802	6132	0	257	9887	1095	0	85744
Fujian	56368	6489	1556	1372	0	8225	876	0	83595
Sichuan	48060	15945	8897	1830	0	12041	153	0	81206
Gansu	49553	11546	4015	1006	0	2035	3504	0	71192
Jiangxi	50596	15198	2819	0	0	8573	1095	0	71116
Yunnan	51005	15785	6328	0	0	2398	0	0	69937
Chongqing	39389	251	2654	0	0	6834	0	0	66666
Tianjin	55060	10207	0	869	0	3200	0	0	63896
Guangxi	44698	1850	2454	0	0	0	219	0	63157
Jilin	37000	8034	2643	2927	0	5579	2628	0	62324
Beijing	28673	17788	667	4904	103	3669	4161	0	48921
Ningxia	33321	6745	2102	0	0	0	1478	0	38752
Xinjiang	19881	4766	4039	503	0	0	3176	0	34087
Qinghai	9298	0	1259	0	0	572	0	0	12168
Hainan	6716	1040	2622	0	0	0	0	0	9589
Tibet	0	0	0	0	0	0	0	0	0
Total	2755021	448873	127093	43627	4741	282251	78133	113	373985

Source: Co-authors X. Li and N. Wei compiled from multiple references as explained in Dahowski, R.T. et al., 2009b.

High-concentration CO_2 point sources

As described in more detail in the next chapter, activities producing high-concentration CO_2 waste streams can most readily be used in CCS projects at a relatively low cost because high-concentration CO_2 emissions streams greatly simplify, or eliminate the need for, the capture process. Table 3.2 lists the production processes that generate high-concentration CO_2 streams as well as other processes for comparison. As can be seen from the table, the processes for manufacturing ammonia, methanol, liquid fuels, hydrogen, and ethylene oxide from coal can create very high-concentration CO_2. Ammonia production has been the largest source of high-concentration CO_2 in China and generated about 117 million tonnes CO_2 per year before 2005.[52] Combining this category with hydrogen and ethylene oxide productions, the amount adds to about 130 million tonnes of CO_2 per year.[53]

Table 3.2 Range of CO_2 Concentrations from Emission Sources by sector

Industry	CO_2 Concentrations* in waste stream
Power generation	3-15%
Cement	15-25%
Iron & steel	15-20%
Refinery	3-18%
Ethylene	12%
Ammonia (based on coal gasification	100%
Coal to methanol	100%
Coal to liquid fuels (indirect and direct methods)	100%
Hydrogen	100%
Ethylene oxide	100%

* Scientifically speaking, a component's share in a gas mixture should be represented as "partial pressure". Here we use the term "concentration" for the general audience, even though not accurate.

Source: Co-authors X. Li and N. Wei and Zheng Z. et al., 2010.

However, China's coal-to-chemicals capacities have been expanding rapidly in recent years. A study published earlier this year by Tsinghua University and Princeton University found that coal-to-methanol will soon become the largest source of high-concentration CO_2 in China, emitting 172 million tonnes per year when all the under construction methanol plants go online.[54] The Tsinghua and Princeton team identified 398 Chinese facilities that generate high-concentration CO_2. Of these facilities, 43 coal-to-methanol plants, 12 ammonia facilities, and two coal-to-liquids facilities that have net CO_2 emissions exceeding 1 million tonnes per year per facility.[55] Most of the mega-tonne level coal-to-methanol plants and all of the coal-to-liquids plants are under construction, while most of the ammonia production facilities are already operating.[56] The researchers based their calculations on estimated production once all phases of a plant are operating. The large ammonia facilities emit 14.7 million tons of CO_2, while the two coal-to-liquids plants will ultimately release 21.8 million tons.[57] Together these large facilities will provide over 185 million tons of high-concentration CO_2 per year in the near future.

The distribution of high-concentration CO_2 sources is similar to the overall picture for large point sources, with the over one million-tonne facilities clustered in the central northern region of China.[58]

Chapter 4: Capture Technology and its Status in China[b]

Because it requires high-cost equipment and a significant quantity of energy, carbon capture generally takes up the lion's share of the total cost of CCS—except in some industrial cases where a high-concentration CO_2 waste stream already exists. Experts, however, believe that through active research and by scaling up the commercial capacity of CCS these capital and energy requirements can be considerably reduced in approximately the coming decade. .[59]

China has been engaged in capture technology research over the past five years and is making notable progress in certain key areas although implementation of CCS in China remains in its early stages. This chapter begins with an overview of CO_2 capture technologies, and then discusses their current status in China, including research and pilot projects.

CO_2 capture technologies

There are three main categories of capture technologies for avoiding CO_2 emissions while generating electricity from coal: post-combustion capture, oxy-fuel combustion capture, and pre-combustion capture.[60]

Post-combustion capture

As the name implies, post-combustion capture entails capturing CO_2 from a waste stream after coal—or another fossil fuel—has been burned to release energy. When coal is fully combusted, the resulting exhaust gas mixture contains roughly 12 to 13 percent CO_2 by volume, which must then be separated from other gases before compression, transport, and storage.

There are different approaches to capturing CO_2 from the waste gas stream, including well-established conventional technologies, such as cryogenic distillation, adsorption and absorption, and newer innovative ideas such as membrane separation and algal processes. Cryogenic distillation and chemical adsorption have been used for many years in the chemical industry to make hydrogen, oxygen, and nitrogen. Although technically mature, these approaches consume large amounts of energy, especially in the case of cryogenic distillation. Most recent CCS research has focused on improving the efficiency of chemical absorption and membrane separation. Chemical absorption is most commonly achieved by using amine-based aqueous solvents to scrub the exhaust gas. This technology is similar to flue gas desulfurization scrubbers, already used in the power generation industry, including in China. The greatest energy requirement for the amine scrubbing process is the thermal energy required to regenerate the solvents, which currently could amount to 25 to 30 percent of the energy output of a typical post-combustion coal-fired power plant.[61]

Post-combustion capture technology could be particularly important for China due to two key advantages: it is possible to retrofit existing coal-fired power plants with post-combustion capture technology, and this technology can also be adapted to other industrial facilities, such as cement kilns and parts of the iron and steel production process.[62] China has a large installed capacity of coal-fired power plants—601 GW by the end of 2008—as well as fast-growing heavy industries, which must be addressed if China is to reduce its carbon emissions meaningfully.

[b] S. Ming Sung, Mike Fowler, and Jingjing Qian made significant contributions to this chapter.

Accordingly, development of post-combustion capture technology in China should be given high priority.

Table 4.1 Operational and some planned post-combustion capture power plants worldwide

Project	Country	MW	$MtCO_2/y$ captured[i]	Startup
Trona	USA	35	0.3	1978
Lubbock	USA	100	0.35-0.4	1982[ii]
Bellingham	USA	320	0.1-0.12	1991
Warrior Run	USA	180	0.055	2000
AEP Mountaineer	USA	1300	0.1	2009
Statoil Mongstad	Norway	630 CHP	0.1/ 3-Jan	2010/ 2014
Plant Barry	USA	2567	0.1-0.15	2011
AEP Northeastern	USA	450	1.5	2011
Sargas Husnes	Norway	400	2.6	2011
Naturkraft Kårstø	Norway	420	1.2	2011-12
SSE Ferrybridge	UK	500	1.7	2011-12
Antelope Valley	USA	450	1	2012
Brindisi (ENEL 1)	Italy	660	1-1.5	2012
Aalborg V.Fall	Denmark	470	1.8	2013
Teeside	UK	800	5-Apr	2013
HECA	USA	390	2	2014
Huerth RWE	Germany	450	2.8	2014
Rotterdam CGEN	Nether-lands	450	2	2014
Belchatow BOT	Poland	858	1.7	2015
Williston	USA	450	1	2009-15
Union Fenosa	Spain	800	1	2016-17
Huaneng Gaobeidian	China		0.003	2008
Huaneng Shidongkou	China	660	0.1	2009-10

Sources: IEA GHG, 2009; Cohen et al., 2009; MIT, 2009; ZEP, 2009; Herzog, 1999; Xu, 2008.
[i] Some plants only capture a fraction of CO_2 from the flue gases produced.
[ii] Shut down in 1984.

Still, this technology presents some unknowns and complications that will need to be addressed. For one, post-combustion capture has not been demonstrated on as large a scale as other technologies, such as those involved in pre-combustion capture. The largest post-combustion capture installation currently operating is in Trona, California, and captures only 900 metric tons of CO_2 per day (0.3 $MtCO_2$ per year).[63] Several pilot scale demonstration projects are, however, in process as are preparations to construct larger demonstrations (see Table 4.1).[64] A second issue is that the current post-combustion capture process is relatively inefficient , and retrofits would incur pronounced operation and maintenance costs in addition to capital costs. Additional development work on advanced solvents and systems as well as large-scale pilots are needed to increase the efficiency of this technology.[65]

Oxy-fuel combustion with CO_2 capture

Oxy-fuel combustion capture is a special type of post-combustion capture that involves burning coal in a mixture of oxygen and re-circulated exhaust gas, rather than in normal air. This ensures that the exhaust gas contains nearly pure CO_2, as well as water, and eliminates the need to separate CO_2 at the end from other gases.

Although considerable laboratory and pilot projects are being carried out in Europe and the United States, there is little industrial scale experience with oxy-fuel combustion capture available yet. In 2008, the Swedish power company Vattenfall began operating a 30 MW experimental oxy-fuel combustion capture facility in Germany, and the results appear promising so far.[66] Additional pilot facilities have been completed and others are in the planning stages or approaching construction (see Table 4.2). Overall, however, the technology has yet to be proven at an industrial scale.

Table 4.2 Some planned oxy-fuel combustion power plants worldwide

Project	Country	MW	$MtCO_2/y$ captured[i]	Startup
Total Lacq[i,ii]	France	30	0.075	2009
Callida-A Oxyfuel	Australia	30	0.03	2010
Kimberlina	USA	50	0.25	2010
Compostilla Endesa	Spain	400	2.75	2015

Source: IEA GHG, 2009; MIT, 2009; ZEP, 2009.
[i] Not necessarily processing all flue gas for CO_2 capture.
[ii] Using heavy oil as the feedstock.

Because oxy-fuel combustion capture requires the production of almost pure oxygen at very large scale for combustion, it is also energy intensive and expensive to run. Retrofitting the technology to existing power plants presents further challenges although two retrofit pilot projects were reported in 2009 in France and the United Kingdom.[67]

Initial research suggests that oxy-fuel combustion capture may be able to be adapted to capture CO_2 emissions from non-power industrial facilities as well as coal-fired power plants, and may have the capacity to offer some cost advantages over post-combustion carbon capture.[68]

Pre-combustion capture

A third form of capture technology—pre-combustion capture—involves converting coal to a synthetic gas (known as "syngas") in a reducing environment (i.e., an environment with no significant supply of oxygen), and removing CO_2 before utilizing the resulting gas for fuel. Coal gasification requires high temperatures and pressures as well as the presence of water to provide hydrogen. Raw syngas is composed primarily of carbon monoxide (typically around 50 percent by molecular weight) and hydrogen (30 to 40 percent), with less than 20 percent CO_2.[69] Depending on the purpose of the process, some or all of the carbon monoxide in the syngas can be further oxidized to CO_2 through a so-called "shift reaction."

To separate CO_2 from the syngas, the gas is put in contact with a solvent that captures CO_2 through either chemical absorption or physical adsorption. The solvent then goes through a regeneration process, which releases pure CO_2. The CO_2 can also be separated from syngas by using specially designed membranes, which only allow CO_2 molecules to pass through them.

The main advantage of pre-combustion capture is that syngas contains a much higher concentration of CO_2 (especially after carbon monoxide is converted to CO_2) than does flue gas from post-combustion processes. This allows the use of physical solvents, which have lower regeneration costs and energy needs than chemical solvents, to capture the CO_2.

Pre-combustion capture is conceptually more complicated than other forms of capture, yet gasification and CO_2 separation are standard practices in the petrochemicals industry, which uses syngas to produce hydrogen, methanol, ammonia, and other intermediary chemicals.

For power generation, gasification can also be coupled with gas and steam turbines, known as Integrated Gasification Combined Cycle (IGCC) technology, to generate power more efficiently than a conventional coal-fired power plant.[70] Syngas from coal gasification can be used directly in a gas turbine to generate electricity; however, if the goal is to reduce CO_2 emissions, the syngas must first go through the CO_2 removal process described above. After CO_2 removal, only hydrogen remains, which can then be burned in gas turbines.

Millions of tons of CO_2 are separated from syngas each year at facilities around the world. One example from the United States is the Dakota Gasification Company plant located in Beulah, North Dakota. There, brown coal (lignite) is gasified and the resulting syngas is converted to synthetic natural gas (SNG), by-product CO_2, and other products. The SNG is sold into the interstate pipeline system, while the CO_2 is transported hundreds of kilometers away to the Weyburn area in Canada, where it is used for enhanced oil recovery. Currently, 8,800 tons of CO_2 are sequestered every day at the Weyburn site.[71]

Because syngas has higher concentrations of CO_2 than exhaust gas from conventional coal combustion, and because IGCC technology offers relatively high efficiency power generation, there has been much interest in promoting IGCC for new coal-based power plants. Thus far, the high capital costs associated with this technology have delayed rapid development, but many IGCC projects are planned for the next few years, and some of these will incorporate CO_2 capture technology (see Table 4.3).

Table 4.3 Some planned pre-combustion capture power plants worldwide

Project	Country	MW	$MtCO_2/y$ captured[i]	Startup
ZeroGen	Australia	80/ 300	0.42/ TBD	2012/ 2017
GreenGen	China	250/ 650	0.03/ TBD	2012-13/ 2017
Powerfuel Hatfield	UK	900	5	2012-14
Nuon Magnum	Nether-lands	1200	2-2.5	2013
Kedzierzyn PKE	Poland	250[ii]	2.4	2014
TCEP	USA	600	3	2014
RWE Goldenbergwerk	Germany	450	2.3-2.8	2014-15
Rotterdam ESSENT	Nether-lands	1000	4	2016

Source: IEA GHG, 2009; MIT, 2009; ZEP, 2009.

[i] Some plants will only capture a fraction of CO_2 from the syngas produced.

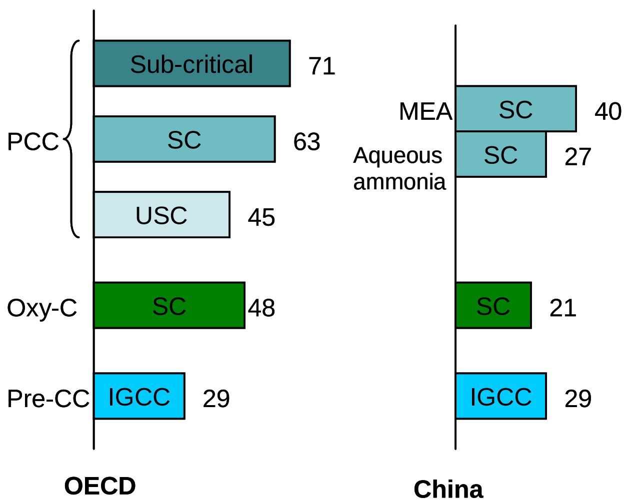
[ii] Polygeneration facility, coproducing 500 MW of syngas.

Costs of carbon capture

Cost is a key determinant in technology choices for power generation and CCS, but the dearth of commercial-scale operating experience in some CCS technologies means that cost estimates for CO_2 capture are uncertain and vary widely. Only more extensive, practical experience with real projects will reduce the inherent uncertainty of these cost estimates, and the cost figures cited here should only be treated as estimates. Technological advancements and adjustments in building costs may further reduce the costs of CO_2 capture over time.

With these caveats in mind, a recent evaluation of cost estimates reported from the Organisation for Economic Co-Operation and Development (OECD) countries in 2008 found that pre-combustion capture would be the most cost-effective approach based on current technology levels, if rolled out on a large scale.[72] Oxy-fuel combustion would come in second, and post-combustion capture would place third (see Figure 4.1). These costs are projections for when CCS systems are widely deployed, and thus take into account future advantages in areas such as economies of scale. As Figure 4.1 indicates, CO_2 capture costs, including CO_2 compression but not transportation and sequestration, range from $30 to $70 per ton of CO_2 avoided.[73]

Figure 4.1 Cost comparison of CO_2 capture technologies ($ per ton of CO_2 avoided)[i]



SC: Supercritical coal plant
USC: Ultra-supercritical coal plant
IGCC: Integrated Gasification Combined Cycle

Sources: OECD figures from Al-Juaied and Whitmore, 2009; China figures from NZEC, 2009 (converted from RMB at $1=6.82 RMB).
[i] Costs are relative to SC technology without carbon capture

A recent report by the UK-China Near Zero Emissions Coal Project (NZEC) estimates that unit costs for carbon capture in China will be only half of those in OECD countries, based on several case studies by different research groups.[74] Figure 4.1 includes a few of the estimates from this report. The NZEC study also found that retrofitting a supercritical coal-fired power plant with oxy-fuel combustion capture technology would cost less than both post-combustion capture and pre-combustion capture. Further, according to this study, IGCC with carbon capture and storage would provide no obvious economic advantages over post-combustion facilities. The NZEC report does not discuss the reasons for this IGCC finding, although it appears to be linked to assumptions that the capital costs for an IGCC plant would be 15 percent higher than for an oxy-fuel combustion plant and that IGCC would be only 1.2 percent more efficient than oxy-fuel power generation.

Another recent publication by Chinese researchers estimates that CO_2 capture for IGCC in China will cost $29 per ton.[75] The researchers reached this estimate by looking at existing industrial production processes for pure CO_2 in China. Similarly, a co-author of our report—Lifeng Zhao—has estimated pre-combustion carbon capture costs by looking at operational data from an existing Chinese coal-to-methanol plant that uses an advanced gasifier and separates CO_2 from syngas using the commercially available solvent Selexol. She estimates that CO_2 capture, including compression, would cost $18 per ton.[76] Because this study did not account for the energy penalty, (i.e., the extra energy required for the capture process), this figure is not the total cost of avoided CO_2, which should be somewhat higher.

Bearing in mind the large uncertainty in cost estimates for CCS, the expected cost of CO_2 capture in China still appears lower than in OECD countries, especially when using post-combustion technology. This difference can likely be attributed to cheaper fuel, labor, and materials, leading to lower capital, operations, and maintenance costs in China. For example, the capital needed to build a coal-fired power plant is about 30 percent lower for IGCC technology and 50 percent lower for subcritical and supercritical technologies in China than in industrialized countries.[77]

Existing high concentration CO_2 sources

Lowering the costs of the CO_2 capture technologies described above will be important for widespread CCS adoption, but initial demonstration projects could also reduce costs while building experience and targeting a sizeable portion of emissions by focusing instead on the "low-hanging fruit" in CO_2 capture. As described in the previous chapter, coal-to-methanol, ammonia, and coal-to-liquids production generate high-concentration CO_2 streams as byproducts. Because these chemical processes involve coal gasification, they already require the separation of CO_2 from hydrogen. Therefore, "capture" would simply require collecting these existing high-concentration CO_2 streams – instead of venting the CO_2 – and then dehydrating them (i.e., removing any water) before compressing the remaining CO_2 gas.

The incremental cost of CO_2 capture from these sources should be lower than for an IGCC power plant. Researchers at Princeton University and Tsinghua University evaluated 27 such CO_2 sources and their potential storage sinks in China and estimated that the costs of CCS for high-concentration CO_2 sources in saline aquifers – including transportation and storage – would be less than $21 per tonne of CO_2.[78]

While existing high-concentration CO_2 sources do not represent the full spectrum of emissions sources that CCS will likely need to address—most notably coal-fired power plants, which are the largest, most problematic sources of CO_2 emissions—they do present significant opportunities for initial implementation and demonstration of the technology at lower cost. In particular, early CCS demonstration projects in China could take advantage of high-concentration CO_2 sources generated by the country's fast-growing ammonia industry.

Status of CCS in China

As discussed in Chapter 2, China's efforts to reduce emissions from its coal-fired power plants have primarily centered on reducing energy demand through increased energy efficiency and installing new, more efficient generating technologies such as supercritical and ultra-supercritical boilers.

As explained in the following sections, China has recently begun intensifying CCS research and considering pilot CCS projects as a potential additional emissions control measure. China has also exhibited a growing capability in coal gasification technology, which, while not being used for CCS per se, opens up the possibility for CCS in the future.

Still, while China's research efforts in CO_2 capture technology are now wide-ranging, these studies exist mainly at the lab or bench scales. Thus, there is still significant potential for bi-directional cooperation and technology transfer between China and industrialized countries that have also been researching CCS and moving forward with demonstration activities.

CO_2 capture research

As China's interest in CCS grows, its universities and specialized research institutes are playing dynamic roles in fundamental research and applied technologies, especially in the area of CO_2 separation.

Tsinghua University, for example, hosts one part of a Joint National Key Laboratory of Chemical Engineering that is studying chemical solvents for CO_2 absorption including ammonia, amines, and sulfonate. With financial support from the energy company BP, Tsinghua's Department of Thermal Engineering set up a collaborative center in 2002 to focus on IGCC-related research. In early 2008, the university established a Low-Carbon Energy Lab that aims to integrate university-wide resources to conduct clean energy studies.[79]

The efforts at Tsinghua University are only some among many. Zhejiang University, Harbin Engineering University, Shanghai Jiaotong University, and Nanjing Agricultural University have also been active in the area of chemical absorption.[80] Chinese Mining University and Nanjing Chemical Institute have carried out significant research on physical adsorption for CO_2 capture.[81] Zhejiang University and a half dozen other Chinese universities are also studying membrane technology, particularly polypropylene hollow fiber membranes. Southeast University, Huazhong University of Science and Technology, Huabei Electrical Power University, and Zhejiang University have been studying oxy-fuel combustion.

In addition to universities, several specialized research institutes are taking the lead in certain areas. For example, Dalian Institute of Physical Chemistry and the Institute of Engineering Thermophysics, both of which belong to the Chinese Academy of Sciences, are national leaders in polymer and inorganic membrane research and chemical looping combustion, respectively. The Thermal Power Research Institute (TPRI) under the Huaneng Group—a state-owned power generator—is also a well-known Chinese leader in CO_2 capture technology, not only in the laboratory but also in its industrial pilots, as described below.

Post-combustion capture pilots

China's Huaneng Group is advancing post-combustion capture technologies through two pilot projects. As a result of its growing experience in post-combustion capture, Huaneng's TPRI intends to market its technology and engineering services outside of China.[82] The China Power Investment Corporation (CPIC) has also built one small capture facility in Chongqing, as described below.

- **Huaneng Gaobeidian Experimental Unit**. This is a 3000 tonne per year amine-based post-combustion capture project retrofit to the China Huaneng Group's Gaobeidian power plant near Beijing. The project first went into operation just prior to the 2008 Olympic Games. The effort has benefited from technological cooperation with Australia's Commonwealth Scientific and Industrial Research Organisation, under the auspices of high-level cooperative agreements.[83] TPRI has been the project's technical manager and successfully tested its chemical solvent for CO_2 capture in this unit. The institute has applied for patent protection in China.[84] The captured CO_2 is purified to above 99.5 percent and sold to the food industry.

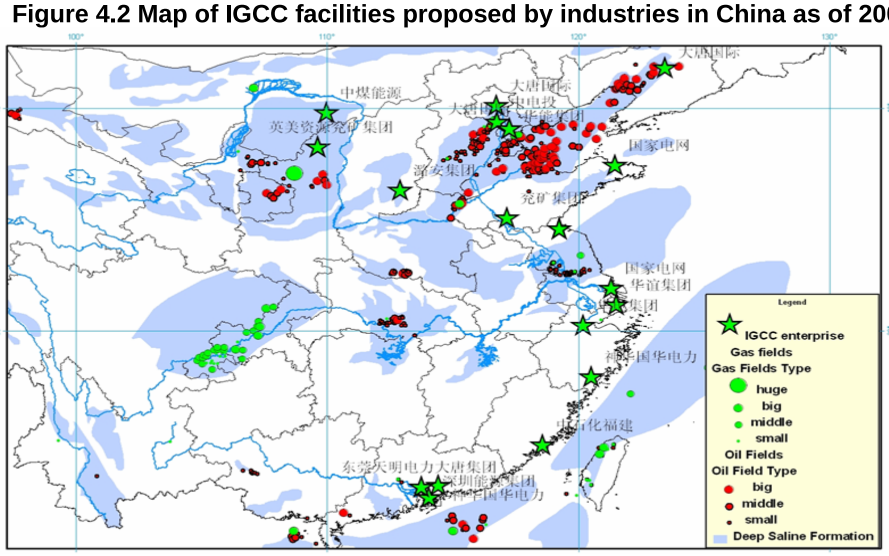
- **Huaneng Shanghai Pilot Unit**. To help promote the Shanghai World Exposition of 2010, the Huaneng Group and TPRI have constructed a larger post-combustion capture unit in Shanghai at Huaneng's Shidongkou Number Two Power Plant. The unit is designed to capture 100,000 tonnes of CO_2 per year using an amine-based solution. This facility became operational in 2010. The captured CO_2 from this project is also sold to industrial customers.[85]

- **CPIC Chongqing Pilot Unit**. In September 2008, CPIC began to construct a pilot post-combustion capture facility capable of capturing 10,000 tonnes of CO_2 per year at the company's Shuangkui Power Plant in Chongqing. The system relies completely on Chinese technology and equipment at a total investment cost of $1.8 million, and began operating on January 20, 2010.[86]

Coal gasification and pre-combustion capture pilots

Chinese coal and power companies are currently also considering several significant IGCC projects (see Figure 4.2). Most of these are only at their initial pre-feasibility study stages, however, and will require further approval from the central government before they can proceed to the design stage.[87]

Figure 4.2 Map of IGCC facilities proposed by industries in China as of 2009



Source: Co-author Xiaochun Li, 2009: Matching of IGCC and CCS, presentation at U.S.-China Workshop on Clean Energy and CCS hosted by Belfer Center for Science and International Affairs, Harvard Kennedy School, April.

Most of the proposed IGCC projects in China have not indicated a clear plan for carbon capture, with the exception of the Huaneng and CPIC projects discussed below.

- **Huaneng GreenGen Plant**: The first phase of this project, a 250 MW IGCC using Chinese gasification technology—TPRI's dry feed gasifiers—is under construction in Tianjin's Binhai New Area. As of August 2010, the construction of foundations and structures has largely been completed and equipment installation is scheduled to be finished by the end of 2010. The start up date for Phase I is the end of June 2011.[88] Relying on the syngas produced from this demonstration facility, Huaneng plans to first establish a 2 MW pilot system for testing coal-to-hydrogen, fuel cells, and carbon capture and sequestration.[89] A sequestration plan for the project is under development and may include enhanced oil recovery.[90] This project has received funding from China's national high-tech research and development (R&D) program—Program 863—as well as a grant from the Asian Development Bank. Chapter 6 provides more information on GreenGen.

- **CPIC's Langfang Plant**: This 2x488 MW IGCC project near Beijing has passed pre-feasibility study and Environmental Impact Assessment. It has also obtained permits on power and water usage, but has yet to be granted the final green light for construction by China's NDRC. The project plans to capture some of its CO_2. Chapter 6 provides more information on this project.

To develop its coal gasification facilities, China has imported key technologies and equipment from abroad, bringing its first foreign gasifier from Texaco (now merged into GE) in 1996. According to a recent study by Tsinghua University's BP Center, China now has nearly 100 large gasifers, most of which have been licensed from Shell or GE.[91] Five chemical manufacturing facilities in China brought gasifiers from Shell Global Solutions online in 2006, and an additional six facilities brought Shell gasifiers online in 2008. These activities represent more than half of all Shell gasification activity globally since the company initially developed its technology in the 1980s.[92] GE Energy and Siemens share similar experiences.[93]

In addition to purchasing technology, China has collaborated with foreign firms to manufacture gasifiers. In 2008, for example, GE reported that China fabricated 90 percent of the company's gasifiers.[94] The Hangzhou Boiler Works, located south of Shanghai, is currently constructing two gasifiers bound for the United States for Duke Energy's IGCC plant in Edwardsport, Indiana. China also manufactures some of Shell's gasifiers.[95]

Domestically, China has demonstrated growing capacity for coal gasification technology development and innovation. The Institute of Clean Coal Technology at the East China University of Science and Technology has developed an opposed multi-burner slurry feed gasifier technology. Five units using that technology had started up by the end of 2008, with at least 28 additional units under construction.[96] The industry-funded TPRI has also developed its own coal gasification technology, including a dry-feed gasifier that has been tested at pilot plant scale.[97]

Recently, East China University of Science and Technology's gasifier was evaluated for projects outside of China, including in North America. TPRI's gasifier was also selected for a 150 MW IGCC project in Pennsylvania.[98] It has been reported that the Mitsubishi Group will build a chemicals plant that will use Chinese gasifiers in Indonesia.[99]

While recent growth in China's coal gasification industry has boosted the country's overall gasification capacity and related technological abilities, most of this growth has focused on coal-to-chemicals and coal-to-liquids applications, which have serious climate implications. Because coal contains more carbon than oil does, replacing oil with coal without CCS will lead to twice as many CO_2 emissions.[100] Coal-to-liquid and coal-to-chemical also require abundant water resources, which are not always available in water-stressed China. China's NDRC called for restraint in developing coal-to-chemical projects in 2006 and mid-2008, and issued a moratorium on coal-to-liquid projects outside of two approved plans. In 2008, the NDRC specifically requested the suspension of a large indirect coal liquefaction project by Shenhua-Ningxia Coal Group and Shell that had ignored the 2008 moratorium and continued with its planning.[101]

Underground coal gasification

China is arguably the world leader in Underground Coal Gasification (UCG) technology, which involves using wells to gasify coal in situ in wet coal seams deep underground—then drawing out the syngas.[102] CO_2 can be captured from this syngas and injected back underground. Research is underway to establish whether this CO_2 can be pumped back into the same cavity for in-situ storage.

Several pilot projects have been proposed or are operating today in Australia, South Africa, and the United States, and it has been reported that the former Soviet Union used UGC for several commercial power plants.[103] A recent economic and technical analysis in the United States suggests that UGC may be an economical way to produce electricity from coal with CCS, due to comparatively low capital costs for production facilities.[104]

China began serious UGC research in the mid-1980s and has run several dozen trials to date, including in Xuzhou in Jiangsu Province, Tangshan in Hebei Province, and the central area of Shandong Province.[105] These projects use mine wells as the gasifiers. More advanced forms of UCG do not rely on well gasifiers. Rather, air or oxygen is directly injected into coal seams that are too deep to mine and syngas is extracted through production wells. ENN Group, a private Chinese company, constructed China's first such advanced UCG pilot in Wulanchabu in Inner Mongolia.[106] This project broke ground in April 2007 and started stably producing syngas that October.[107] Although the project encountered some technical problems in 2008, China's University of Mining and Technology in Beijing helped resolve those issues. In June 2009, ENN Group successfully began to use the low-heating value syngas to generate electricity (500 kW), and produce methanol.

While UCG linked with CCS may eventually become a promising option, right now it is difficult to ensure the integrity of such operations. The storage of CO_2 in shallow combustion cavities is not yet well understood, and the use of syngas from UCG for power generation or liquid fuel production at scale has yet to be demonstrated.[108]

Capturing high-concentration CO_2

Manufacturing of chemicals from coal is widespread and growing rapidly in China. China is the world's largest ammonia producer.[109] Close to half of the coal gasified in China in recent years has been used for ammonia production, and the total coal used for manufacturing chemicals may soon reach 180 million tons annually.[110] Given the very high concentration of CO_2 in the waste streams vented by these processes, and hence the low incremental costs for CO_2 capture (mainly a compression cost), sequestering CO_2 from ammonia production could be a stepping-stone for developing China's CCS capacity. Recognizing this, researchers at Tsinghua University have investigated large CO_2 point sources in the "Capital Circle" region of Beijing, Tianjin, and Hubei Province and identified 34 ammonia plants that, combined, release 13 million tons of nearly pure

CO_2 per year.[111] Depleted oil fields nearby these plants offer the potential for enhanced oil recovery.[112]

In Inner Mongolia, Shenhua's coal-to-liquid facility is now operational, and is eventually expected to produce coal-based transportation fuels along with more than 3 million tons per year of byproduct CO_2. Similar to the systems used for ammonia synthesis, Shenhua's project produces large quantities of hydrogen. Collection of the resulting byproduct CO_2 would be relatively inexpensive. Chapter 6 discusses in more detail how Shenhua is planning to collect several million tons of CO_2 per year as soon as suitable sequestration can be developed.[113]

Chapter 5: CO_2 Geologic Storage Capacity in China[c]

In the CCS process, captured CO_2 must be transported from its capture source to a suitable site where it can be injected underground for permanent disposal. This storage requires specific types of geologic formation. Initial studies suggest that China's geologic storage capacity for CO_2 likely far exceeds the necessary volume. This chapter briefly discusses the requirements for CO_2 transport and storage and China's geologic storage potential in more detail.

The capacity figures presented here are *theoretical* estimates based on basin-scale assessments that were carried out jointly by China's Institute of Rock and Soil Mechanics (IRSM) and the U.S. Department of Energy's Pacific Northwest National Lab (PNNL) (the same team that assembled data on China's large point sources of CO_2, as discussed in Chapter 3). The IRSM/PNNL work represents the most comprehensive study in the area of storage capacity in China to date.

However, much more extensive and detailed geologic information will be required to estimate China's effective and practical capacity for CO_2 storage. Such assessments will need to be performed at smaller scales with more geological data and taking into account storage efficiency and other factors. Nonetheless, the joint IRSM/PNNL team's high-level estimates are very useful in demonstrating China's unambiguous suitability for geologic sequestration at a large scale.

Overall, China's total theoretical CO_2 storage capacity in depleted oil and gas fields, deep saline formations, and unminable coal seams, as estimated by IRSM/PNNL researchers, could be about 3,120 billion tons—over 500 times China's total CO_2 emissions in 2004.[114] Deep saline formations offer the largest potential storage capacity in China, accounting for approximately 99 percent of the country's total geologic storage resources, as we further outline below. The IRSM/PNNL studies also show that numerous high-concentration CO_2 point sources are located near depleted oil and gas fields, making them potentially good candidates for CCS demonstration using enhanced oil recovery or enhanced gas recovery (EOR and EGR, respectively).

Although demonstration projects should be able to move forward, complications for a larger CCS strategy must still be overcome. Notably, China's heavily industrialized east and south-central regions have fewer on-shore CO_2 storage reservoirs than do other regions.[115] Follow-up assessments on the technical and economic feasibility of using nearby offshore reservoirs for CO_2 storage in these regions are needed.

Transport and storage of CO_2

After the capture stage, CO_2 must be compressed to a supercritical state—a temperature above 31.1°C and a pressure of 7.29 atmospheres. At that point, CO_2 becomes as dense as a liquid but continues to fill up containers as gas does—so that transportation is more economical over long distances than it would be for gaseous CO_2. Compared to capture and injection, transportation is a relatively simple task and can be done via pipeline, trucks, or ships. More than 5,800 kilometers (3,600 miles) of CO_2 pipelines operate today in the United States, with the oldest long-distance line having operated since 1972.[116] Design and operational protocols are well established to prevent leakage, corrosion, and blockage. CO_2 is commonly dehydrated and purified from

[c] Xiaochun Li and Ning Wei from China's Institute of Rock and Soil Mechanics are the main contributors to this chapter with most of their information drawn from their joint publications with the U.S. Department of Energy's Pacific Northwest National Laboratory.

contaminants to varying degrees before entering pipelines, depending on the specifications and the application.

Underground disposal of CO_2 requires a geologic formation that has a permeable layer, such as porous sandstone, that can absorb CO_2, which is also covered by an impermeable (cap rock) layer, such as shale, that will seal the injected CO_2 below. Two types of geologic formations have most widely been considered for possible CO_2 sequestration: depleted oil and gas reservoirs, and deep saline formations. A third possible formation for sequestration could be coal seams that are unlikely to be mined because they are situated too deeply, are too thin, or are too high in impurities like sulfur to be used economically.

Among potential geologic storage options, CO_2 injection in oil and gas reservoirs has been most widely practiced to date although storage in deep saline formations is also considered viable for the immediate term and beyond. Overall, global storage capacity in deep saline formations is believed to exceed the capacity in oil and gas fields by orders of magnitude.

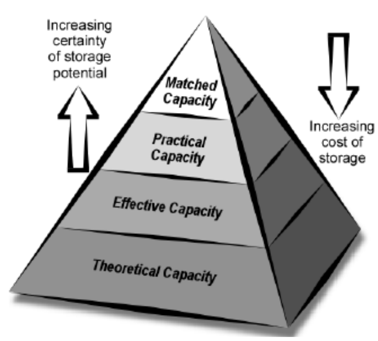
Deep saline formations share many of the same trapping mechanisms and operational engineering characteristics as oil and gas fields, but have not yet been mapped or characterized to the same degree as these areas—in part because EOR and EGS offer the advantage of generating additional oil and gas revenues. Deep saline formations are, however, currently utilized or planned in internationally well-known sequestration projects, the best known being the Sleipner project in the North Sea.

Injection and sequestration in coal seams is at an earlier development stage than for oil and gas fields, and is only now being tested at increasing scale. Several technical issues must be resolved before this method can be considered a viable, large-scale option.[117]

Geologic storage capacity for CO_2

Determining the available geologic storage capacity for CO_2 is a critical factor in developing CCS projects and strategies. The accuracy of capacity estimates depends on the scale of the assessment and the factors considered (see Figure 5.1).[118]

Figure 5.1 Techno-Economic Resource-Reserve Pyramid for CO2 Storage Capacity



Source: CSLF, 2007.

The Carbon Sequestration Leadership Forum (CSLF) recommends a techno-economic resource-reserve pyramid to describe the accuracy of storage capacity estimates. A larger, theoretical capacity estimate can be made based on high-level data. These estimates can then be refined to identify smaller subsets of Effective, Practical, and Matched Capacities by considering the following factors:

- Reservoir structure
- Sandstone porosity
- Brine concentration
- Cap rock tightness
- CO_2 injectivity
- Displacement pressure
- Permitting regulations
- Infrastructure constraints
- Economic viability.

The CSLF summarizes the scales of assessment as:[119]

- *Country-Scale Assessment*: high-level studies performed for a contiguous geographic area usually encompassing several sedimentary basins;

- *Basin-Scale Assessment*: more detailed studies focusing on a particular sedimentary basin;

- *Regional-Scale Assessment*: performed at an increasing level of detail for a large, geographically-contiguous portion of a sedimentary basin;

- *Local-Scale Assessment*: very detailed investigations of several candidate sites, usually performed at a pre-engineering level; and

- *Site-Scale Assessment*: performed for the specific storage unit, usually to model the behavior of the injected CO_2.

The joint IRSM/PNNL team used methods recommended by the CSLF to estimate the theoretical storage capacities described below.[120]

General characteristics of Chinese geology

China covers a land area of 9.6 million km^2, of which 4.58 million km^2 overlie sedimentary basins.[121] There are 373 Meso-Cenozoic basins (i.e., basins that are tens of millions to hundreds of millions of years old) that are expected to bear oil and/or natural gas, of which 210 have sizes over 1,000 km^2.[122] China's largest inland basin is the Tarim Basin, but this basin is located in the western part of the country, far from large CO_2 point sources.

While China's sedimentary basins are large in number, they are also among the most complicated worldwide and detailed localized studies and site characterization will be crucial to ensure successful CO_2 injection. Eastern China features rift basins, western China features compression type basins, and central China has combined forms. In general, China's basins are characterized by small size, numerous faults, and strong faulting activity, which have led to the formation of complex types of geologic traps.[123]

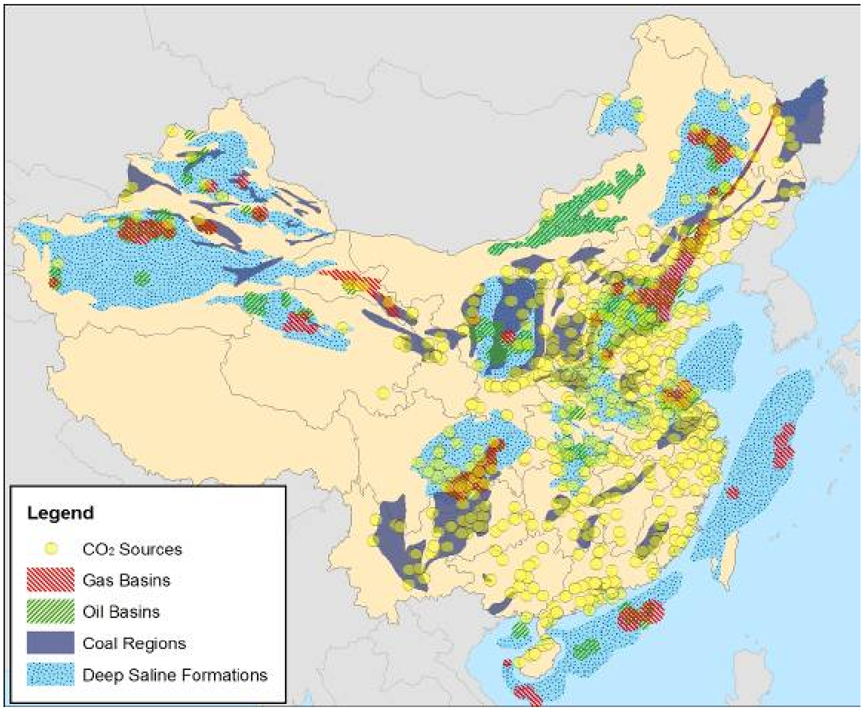
Figure 5.2 shows the major sedimentary basins and the distribution of the four major classes of deep geologic reservoirs in China. Table 5.1 shows the individual values for thickness, and porosity parameters assumed by the IRSM/PNNL team in estimating the CO_2 storage capacity of each class of deep geologic reservoir for the major basins.[124]

Table 5.1 Estimated theoretical capacities and key characteristics of China's onshore and offshore sedimentary basins

		Average Net Sand Thickness (m) / Porosity (%)	Capacity in Deep Saline Formations ($MtCO_2$)	Capacity in Oilfields by Proven OOIP($MtCO_2$)	Enhanced Oil Recovery Capacity (MBO)	Capacity in Gasfields by Proved OGIP($MtCO_2$)
	Onshore Basins					
1	Tarim	300 / 0.15	745,800	69	89	620
2	Ordos	300 / 0.15	256,500	360	700	1110
3	Bohai Bay	200 / 0.2	233,300	1,930	1,860	280
4	Songliao	200 / 0.15	227,800	1570	2510	590
5	Zhunggar	300 / 0.15	197,100	200	340	100
6	HeHuai	300 / 0.2	178,000			
7	Subei	300 / 0.2	89,900	100	130	8
8	Erlian	200 / 0.15	85,000	31	51	
9	Sichuan	300 / 0.05	77,600	20	32	1050
10	Turpan-Hami	300 / 0.15	54,300	120	160	36
11	JiangHan-Dongting	150 / 0.2	52,800	24	30	
12	Sanjiang	200 / 0.15	44,900			
13	Qinshui	300 / 0.15	29,000			
14	Qaidam	50 / 0.15	21,500	81	130	350
15	Hailaer	100 / 0.15	16,100			
16	Nanxiang	100 / 0.15	7,500	65	120	
17	Liaohe Depression			440	540	80
18	Jiuxi-Jiudong-Huahai			15	25	120
19	Yilanyitong			14	17	5
20	Yanqi			7	8	15
	Total Onshore		**2,317,100**	**4,895**	**6,531**	**4,323**
	Offshore Basins					
1	East China Sea	300	341,800			160
2	Southern Yellow Sea	300	133,800			
3	Bohai Wan	300	109,200	130	160	46
4	Zhujiangkou	200	68,700	41	89	12
5	Yinggehai	300	56,000			680
6	Northern Yellow Sea	300	31,500			
7	Beibu Gulf	300	23,800	18	34	
8	Western Taiwan	100	10,000			
9	Luzhou Island	100	1,900			
	Total Offshore		**776,700**	**189**	**283**	**898**
	TOTAL		***3,093,800***	***5,084***	***6,814***	***5,221***

Sources: Li, X. et al., 2009.

Figure 5.2 Large CO_2 sources relative to potential storage reservoirs



Source: Dahowski, R.T., X. Li et al., 2009a.

Deep saline formations

Deep formations containing brine appear to be the largest, most extensively distributed, and highest-capacity potential CO_2 storage formations. Four different CO_2 trapping mechanisms will work in deep saline formations. These are:

- Structural or stratigraphic trapping (enclosing CO_2 beneath the cap rock of a reservoir as a separate phase);
- Residual trapping (diffusing CO_2 in sandstones' pores and retention through capillary forces);
- Solubility trapping (dissolving CO_2 into the brine); and
- Mineral trapping (eventually mineralizing the CO_2 in rocks).

All of these mechanisms can provide potentially significant or very large storage capacities.[125]

The study by the IRSM/PNNL team considered only the solubility trapping mechanism by estimating the volume of brine contained in each sedimentary basin and how much CO_2 could dissolve in the brine.[126] Their assessment of 16 onshore and 9 offshore deep saline formations produced a total theoretical storage capacity of nearly 3,100 Gt of CO_2 (see Table 5.1).[127]

Depleted oil basins and enhanced oil recovery (EOR)

Depleted oil fields may provide convenient places to sequester CO_2 because these formations have closed structures and can trap pressurized CO_2. The injected CO_2 may further be used for EOR, thus reducing the net costs of CCS by providing offsetting revenue.

For depleted oilfields, detailed data on geologic characterization are usually already available. When estimating theoretical storage capacity of depleted oilfields, it is commonly assumed that

CO_2 can be held in the same volume as, and at a similar pressure to, the original-oil-in-place. Therefore, by using original-oil-in-place data, it is possible to estimate the maximum amount of CO_2 that an oil field could store.

The IRSM/PNNL researchers estimated theoretical CO_2 storage capacity at basin scale for oilfields using this method.[128] As Table 5.1 shows, the oilfields in the 16 largest onshore basins could ultimately store about 4,900 Mt of CO_2, assuming all of the oil will be replaced by CO_2. Adding several offshore basins, the total theoretical storage capacity of oilfields was estimated at around 5,000 Mt of CO_2. The incremental oil output through CO_2 EOR from those depleted oil basins may amount to 7 billion barrels, the equivalent of two and a half years of China's current total annual oil consumption.[129]

Because geologic and engineering factors limit the actual use of these theoretical capacities, Chinese researchers, supported by the NZEC, have also estimated the effective capacities—the storage capacity more likely to be available—of several specific oilfields. The reservoirs studied include the Daqing and Jilin oilfields in northeast China, Jiangsu oilfields in the eastern coastal area, Dagang oilfields in Tianjin, and Shengli oilfields in Shandong Province.[130] The NZEC and IRSM/PNNL studies were conducted at different scales so their numbers are not directly comparable.

Figure 5.2 shows the location of oil fields and sedimentary basins having potential for storing CO_2 in China.

Compared to deep saline formations, the storage capacity of depleted oilfields (gas fields as well) appears tiny—only 0.2 percent of the former, as indicated in Table 5.1. However, the possibility of enhanced oil recovery offers a financial incentive for early CCS projects, which could aid the transition to larger scale CCS.

Depleted natural gas basins and enhanced gas recovery (EGR)

Similar to depleted oil basins and EOR, depleted natural gas basins offer potential revenue opportunities in the form of increased gas production through emerging EGR techniques. The joint IRSM/PNNL team estimates that when all natural gas fields are depleted, they would be able to store about 5.1 billion tonnes of supercritical CO_2.[131] According to the study, the best depleted gas fields for CO_2 storage are primarily located in the Sichuan Basin, the North China plain (including Dagang Oil Area of Huanghua and Jizhong Depressions), the Songliao Basin and the southeastern part of the Zhunggar Basin.

Unminable coal seams

Coal has methane gas absorbed in its pores, which could be driven out by injecting CO_2 into coal seams. This process of enhanced coalbed methane recovery (ECBM) using CO_2 is being investigated as one way of sequestering CO_2, but it is not yet a commercial technology or proven technique. Nonetheless, ECBM may achieve some significance in the future. Since 2003 in China, there has been a $10 million pilot project for CO_2 ECBM, carried out jointly by the Canadian Alberta Research Council and the China United Coalbed Methane Company.[132] By 2006, 192 metric tonnes of liquid CO_2 was injected into a single coal seam in the south Qinshui Basin of Shanxi Province.[133]

The IRSM and PNNL researchers estimate that the theoretical CO_2 storage capacity of deep, unminable coal seams in China is approximately 12,000 Mt of CO_2 within 45 major coal basins, of which the top three are the Ordos basin in Inner Mongolia and the Turpan-Hami and Santang Lake basins in Xinjiang.[134]

CO_2 source-reservoir matching

From Figure 5.2, which overlays large CO_2 sources and the four main types of reservoirs, we can roughly see that: 1) major oil fields have some large CO_2 sources nearby; 2) the southeastern regions has few potential storage reservoirs unless offshore saline formations are considered; and 3) there should be easy source-reservoir matching in the southwestern and northern areas.

More rigorous matching through Geographic Information System (GIS) modeling by IRSM/PNNL has confirmed this visual interpretation that most large stationary CO_2 point sources in China are in relatively close proximity to at least one candidate for a storage reservoir.[135] The team has found that 54 percent of large CO_2 point sources have a candidate storage site in the immediate vicinity; 83 percent have at least one storage formation within 80 kilometers (50 miles); and 91 percent have potential storage places within 160 kilometers (100 miles).[136]

As a result of this relatively favorable source-reservoir matching, the IRSM and PNNL researchers estimate that the CO_2 emissions from 65 percent of the large point sources they identified can be transported and injected underground for less than $10 per ton (excluding capture costs).[137] However, there are over 250 large CO_2 point sources whose locations are disadvantageous with no easy access to sufficient CO_2 storage capacity in onshore basins.[138] These sources are predominantly located in the more industrialized areas of China's coastal and south central regions, where offshore basins may offer alternate storage options.[139] Future studies are needed to examine the costs associated with utilizing the offshore basins.

High-concentration CO_2 and EOR/EGR source-reservoir matching

From their database of China's large industrial CO_2 point sources, two co-authors of this report, Li and Wei, identified 185 high-concentration CO_2 sources, most of which are ammonia plants, and also analyzed the locations of these sources relative to potential storage reservoirs. As Table 5.2 shows, 85 out of the 185 sources (46 percent) are located within 80 km of an oil or gas field.

Table 5.2: Distance of CO_2 sources from nearest storage reservoir, by source and reservoir type

	All types	High-Concentration CO_2 sources only	All types	High-Concentration CO_2 sources only
Storage Reservoir Type	All on-shore types		Oil/gas field reservoir only[i]	
Number of sources	1,623	185	1,623	185
0 km	54%	45%	-	-
80 km	83%	75%	39%	46%
160 km	91%	92%	65%	62%

Source: Total number of large point sources and source-sink matching for all sources taken from Dahowski, R.T. et al., 2009 and Li, X. et al., 2009; GIS-based proximity analysis for high-concentration CO_2 sources was done by report authors Li and Wei.

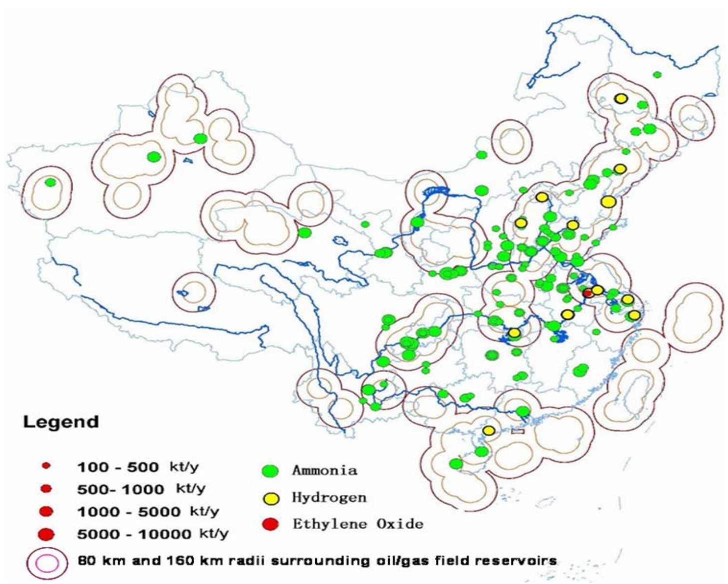
NOTE: Due to lack of reliable data on oil/gas field boundaries, oil/gas field reservoirs were treated as points rather than areas. As a result, these figures represent conservative estimates and the 0 km distance is not strictly applicable.

Figure 5.3 further shows the distribution of large high-concentration CO_2 point sources and oil/gas field reservoirs in China. East Sichuan, Chongqing, Hebei, Shanxi, Shandong, Jiangsu and Zhejiang provide the highest number of early opportunities for sequestering these high-concentration CO_2 sources through EOR/EGR. Other significant opportunities also lie in Heilongjiang, Jilin, Shaanxi, Hubei and Yunnan provinces.

Another team by China's Tsinghua University and Princeton University in the United States has done a source-sink matching for the largest 27 facilities that each emits over 1 million tonnes of high-concentration CO_2 per year.[140]

The researchers have found that while 23 out of the 27 plants are located less than 50 km from an onshore saline aquifer, only 2 are that close to an oilfield.[141] The team estimates that the transportation and injection costs for plants within 10 kilometers of a sink range between $9 and $12.6 per tonne of CO_2.[142] This suggests that it is necessary and practical to look beyond just EOR and EGR for early CCS projects.

Figure 5.3 Large high-concentration CO_2 sources relative to oil/gas field reservoirs



Source: Co-authors Li and Wei.

Chapter 6: Planned CCS Projects and Potential Opportunities

While China has not yet aggressively pursued CCS to reduce its CO_2 emissions, several CCS-related projects are underway in the country, and there are many other opportunities for early demonstration projects. This chapter describes seven such cases and potential opportunities for CCS demonstration that could pave the way for broader deployment of CCS technology in China.

Because no full-scale CCS projects have been carried out in China thus far, the first cluster of CCS demonstration projects will likely be smaller scale efforts that will allow China to gain experience in the technical, financial, regulatory, and social aspects of CCS. Most likely, these projects will meet all or most of the following criteria: they will capture lower volumes of CO_2; use existing high-concentration sources; select locations with close proximity between sources and sinks; and emphasize economic returns from EOR or EGR.

With such understanding, we describe three areas that have oilfields or gas fields and are close to relatively large sources of CO_2 emissions. Excluding the saline aquifers deep underneath the sites, the storage capacities of those oil and gas fields are not very large, but they may still serve as convenient near-term pilot opportunities. These projects are intended as discussion examples only and are not the result of a systematic screening or assessment. To move forward on these or other projects, additional analyses will be needed to define specific project criteria and acquire relevant information, such as local geologic data.

In addition to these sites, we profile four projects where CCS is already planned or might be possible: three IGCC plants in various stages of planning and with owners who have expressed their intent to capture CO_2 for sequestration, as well as the previously mentioned Shenhua coal-to-liquid project, due to its high-concentration waste CO_2 stream (a byproduct of hydrogen production). Chapter 4 previously discussed two post-combustion capture plants that are also relevant to this discussion, but not discussed in detail again here: the 3,000 tonne CO_2 per year facility at the Beijing Gaobeidian power plant and the 100,000 tonne CO_2 per year facility at Shanghai Shidukou power plant. Both of these projects are being developed by China's Huaneng Group.

Potential opportunities for CCS with EOR or EGR

The following sections describe three locations where EOR and EGR may be possible, based on combinations of specific geology and the presence of large CO_2 point sources.

Daqing and Jilin oilfields in the Songliao Basin[d]

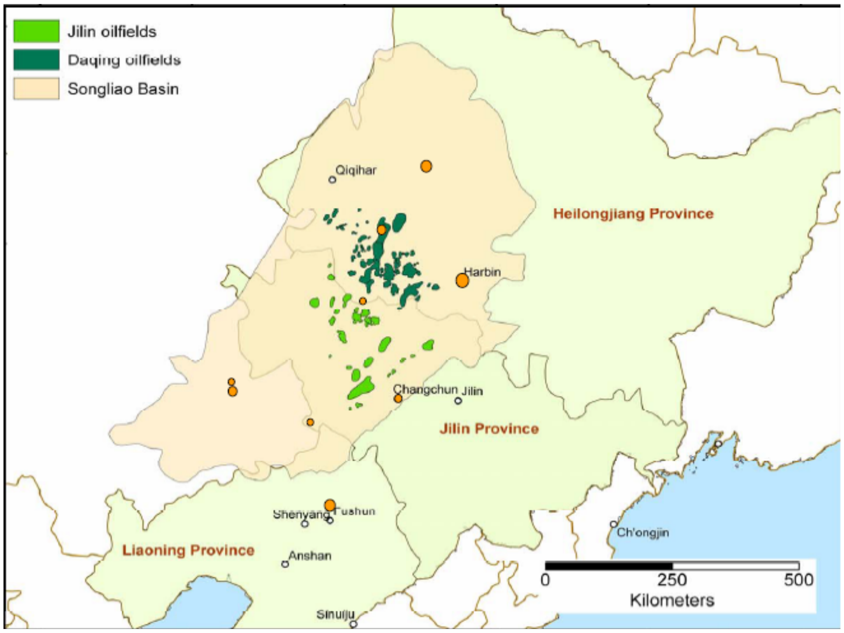
Geology

Supported by the UK-China Near Zero Emissions Coal (NZEC) project, Chinese and British experts[143] have assessed CO_2 storage capacities of several oilfields in the Songliao and Subei Basins, at sub-basin and reservoir scales. In the Songliao Basin, the team assessed seven oilfields in the Daqing oilfield complex and five oilfields in the Jilin oilfield complex (see Figure 6.1). In

[d] This section is drawn from NZEC, 2009 and Pearce, Jonathan, 2008.

the Subei Basin, they evaluated 108 oil reservoirs in the Jiangsu oilfield complex. In addition, they estimated the storage capacities in the deep saline aquifers in those basins.[144] Since this chapter is focused on potential near-term projects, we only describe their oilfield related findings here.

Figure 6.1 Daqing and Jilin Oilfields in the Songliao Basin



Source: NZEC, 2009.

The Songliao Basin is the second largest basin in China in terms of area (see Table 5.1). It extends across three provinces, but the largest portion is in Heilongjiang and Jilin provinces. The Songliao Basin has been the largest oil and gas producing region in China for over 40 years with a current annual oil production of around 350 million barrels, approximately 25 percent of China's total production in 2010. The Daqing and Jilin oilfields are the largest in this area.[145]

The NZEC researchers applied the CSLF methodology described in Chapter 5 and a Chinese methodology to estimate the Effective Capacity for CO_2 storage.[146] Among their studied oilfields, the team found that the seven oilfields in Daqing, Heilongjiang Province, appear to have relatively favorable conditions for both CO_2 storage and flooding for enhanced oil recovery. The total effective storage capacity of the seven Daqing oilfields is estimated at 593 Mt using the CSLF methodology.[147] The Chinese methodology, termed the CUP methodology, gave the total capacity number at 459 Mt.[148]

The Jilin and Jiangsu oilfields assessed in the NZEC study have shown much more limited storage capacities compared to those in Daqing. The five large oilfields in the Jilin oilfield complex have a combined effective storage capacity of 102 Mt of CO_2–based on the CSLF method—while the CUP method gave only 48 Mt. The team evaluated 108 reservoirs in Jiangsu oilfields and found 75 of them suitable for some EOR, but their combined capacity is only 16 Mt of CO_2 based on the CSLF methodology.[149]

CO_2 sources

Figure 6.1 indicates that large point sources of CO_2 are not concentrated in the regions near the Daqing and Jilin oilfields. Yet good source-reservoir matching is still possible for early demonstration projects. The NZEC team used GIS and a Decision Support System to map a single source to a single storage site with the least-cost pipeline route. Qian'an Oilfield has the largest estimated capacity in the Jilin Oilfield complex—40.46 Mt CO_2 using the CSLF methodology or 18.4 Mt CO_2 using CUP—and thus was selected for the matching study. Based on the study, the team recommended a 75 km pipeline route and estimated the cost of constructing the pipeline at 128 million RMB.[150]

Oilfields in Jianghan Basin and nearby high-concentration CO_2 sources[e]

Geology

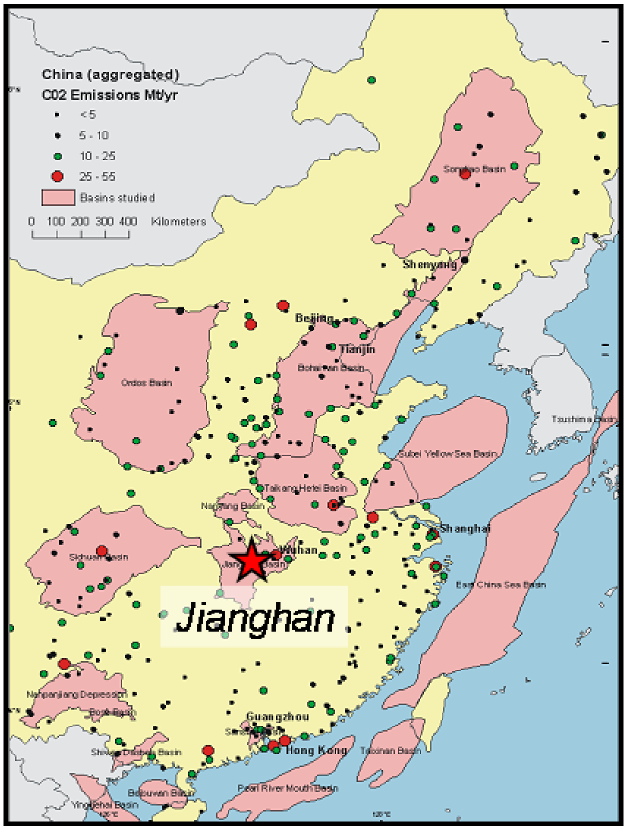
The Jianghan Basin is located in the mid-south of the Jianghan plain in Hubei province (see Figure 6.2). It is a Cretaceous-Early Tertiary Period salt lake fault basin, and has an area of 36,000 km^2. The basin is divided into 11 depressions and four uplifts, and its total thickness exceeds 10,000 m. The two major sets of source rock series are the Qianjiang and Xingou series, which are also the most important oil-bearing rock series. Other than the Tankou and Guanghuasi oilfields, all 25 discovered oilfields in this basin lie within these two series.[151]

On the whole, the formation seems solid, tight, and containing only a few internal faults. Overall, the trap is sufficient to provide enough scale for CO_2 storage—the sealing layer having relatively pure lithology and being stably distributed with good connectedness and high thickness.

Most cap rocks are made up of thick-layered Tertiary Period mudstone that has good sealing qualities. The effective porosity of the storage layer is larger than 15 percent, and the effective permeability is greater than 50×10^{-3} μm^2.[152]

[e] Two co-authors of this report, Li and Wei, are the main contributors to this section and the rest of the chapter unless referenced otherwise. The geologic information presented here was compiled by Li and Wei based on field visits and publically accessible corporate information, as well as the following: Li, G., and M. Lu, 2002: Atlas of Petroliferous Basins in China, 2nd Edition, Petroleum Industry Press, Beijing; Zhou, Y, Y Ronglong et al., 2004: Oil and Gas Resources in China, Beijing, China University of Geology; and Tong, Hengmao and Daiyong Cao, 2004: Analysis of the Complexity of Oil and Gas Distribution in Sedimentary Basins of China, *Petroleum Geology and Experiment*, 26(5), pp 415-421.

Figure 6.2 Location of Jianghan

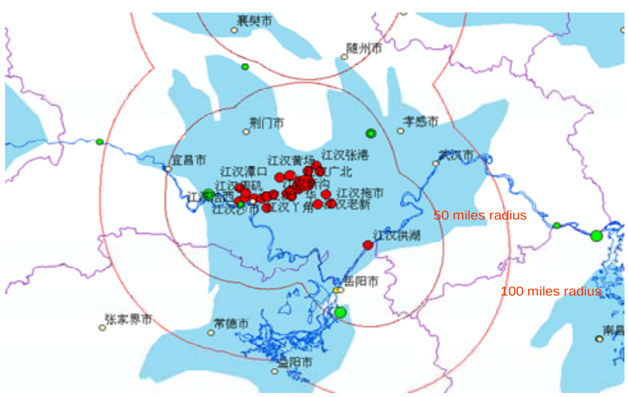


Map adapted from Friedmann, Julio, 2009b.

<u>CO_2 sources</u>

There are several cities surrounding the Jianghan oilfields, including Zhijiang, Tianmen, Qianjiang, and Wuhan (see Figure 6.2). Several ammonia plants, which manufacture fertilizer, are located 50 to 150 km from the oilfields and collectively emit over 4 million high-concentration tons of CO_2 per year (see Figure 6.3).

Figure 6.3 Source-reservoir matching for the Jianghan Basin



Green dot: ammonia plant (>100,000 tonnes/y); Red dot: oilfield

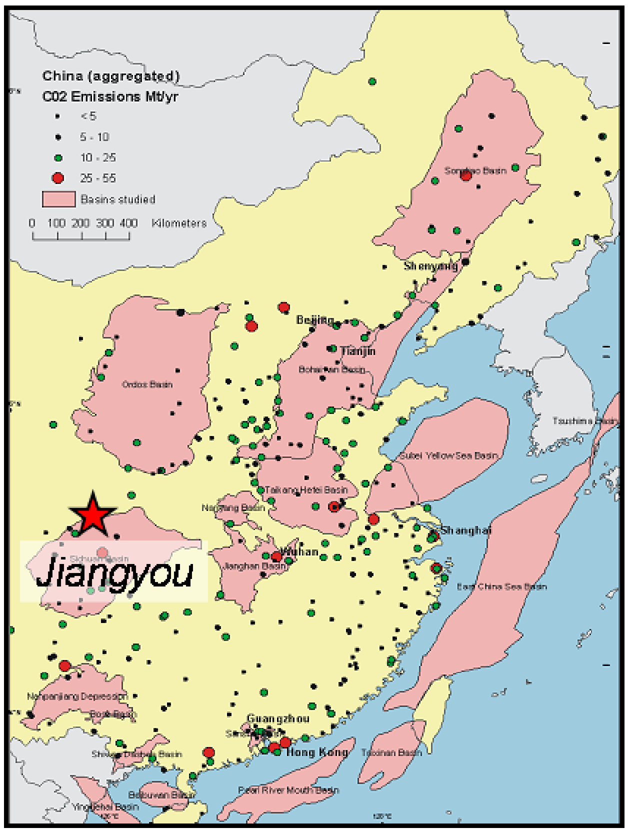
Source: Co-authors Li, X. and Wei, N.

Jiangyou gas fields for possible co-storage of low-quality CO_2

Geology

The Jiangyou gas fields are in Sichuan Basin, which covers an area of 180,000 km^2 and is an important gas-producing region in China (see Figure 6.4). The thickness of the sedimentary basin is 5,000 to 12,000 m, and the nearby Jiangyou gas field is well suited to carbon sequestration and offers potential EGR opportunities.

Figure 6.4 Location of Jiangyou



Map adapted from Friedmann, Julio, 2009b.

The Jiangyou gas field is an anticline-controlled, boundary-water type, sulfur-rich gas reservoir with a high initial production. Its gas-containing area is 13.4 km^2 with a depth of 3,140 to 3,510 m, and the field has a uniform pressure system with good connections. The pressure drop of the stratum is also small, without any apparent pressure drop funnel.[153]

The original gas-water interface lies 2,871 m below ground, and the proven reserves total 8.63 billion cubic meters of natural gas. The initial stratum pressure is 35.304 MPa and the stratum temperature is 86˚C. The primary water saturation rate is around 20 percent, and the natural gas present in the field is rich in H_2S (about 6.8 percent).[154]

One key advantage of the Jiangyou natural gas reservoir is that its cap rock is thick, with an effective thickness of 46.0 to 74.2 m. Moreover, the secondary pores, holes and slots in the storage formation are well distributed and developed with many pinhole layers—holes and micro fractures combine well—and permeability is relatively high. Analyses of the rock core show permeability ranges between $0.01\times10^{-3}\,\mu m^2$ to $35.04\times10^{-3}\,\mu m^2$. Porosity commonly ranges between 1 to 6 percent.[155]

<u>CO_2 sources</u>

Jiangyou is also the name of a small industrial city with a population of 830,000. It is situated in the northwestern part of Sichuan Basin, 24.5 km from a gas field that produces approximately 600 million cubic meters of natural gas annually. Crude natural gas from the field contains acid gas—CO_2 and hydrogen sulfide (H_2S)—which needs to be removed. Meanwhile, the city also has several large industrial point sources of low-concentration CO_2, including two power plants, two cement kilns, and an iron and steel factory. These large plants together emit around 11 million tons of CO_2 per year. The acid gas and the industrial low-concentration CO_2 may be mixed and used for EGR. Such a scheme can have a lower total cost than that of a typical CCS project because of the elimination of the carbon capture step at the industrial plants, the proximity of the sources to the Jiangyou gas field, and the revenues from the additional gas output. Transporting and sequestrating the mixed low-quality CO_2 can also provide opportunities for research. Preliminary discussions with the operators of the Jiangyou field indicated a clear interest in CCS demonstration.

Potential opportunity for CCS from a high-concentration CO_2 waste stream

High-concentration industrial CO_2 waste streams offer another important opportunity for early CCS projects due to the elimination or reduction of capture costs otherwise required for CCS. One opportunity for CCS from such sources is at the Shenhua Direct Coal Liquefaction (DCL) project mentioned earlier in this report.

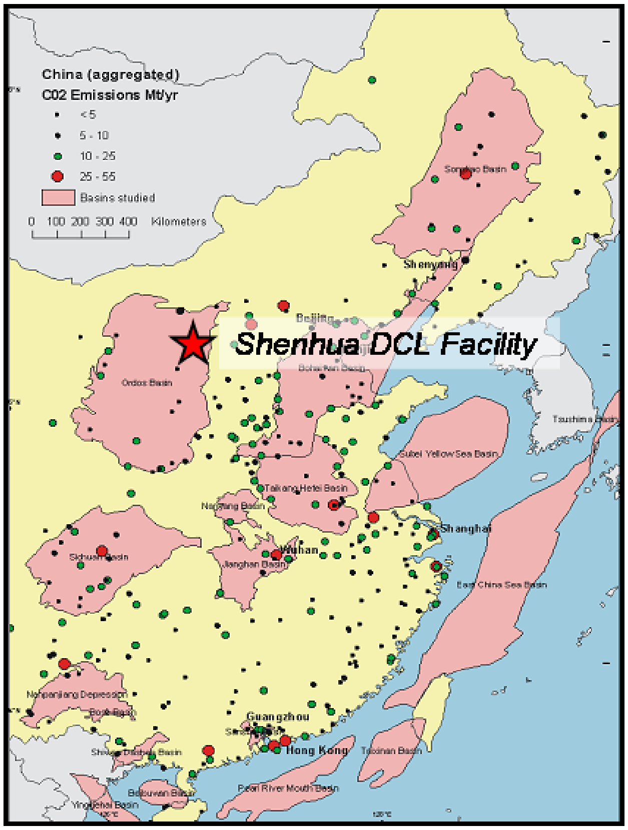
Shenhua Direct Coal Liquefaction project[f]

<u>Project background</u>

Shenhua DCL is a subsidiary of China's largest coal company, the Shenhua Group. The coal-to-liquid fuel plant is located at the Majiata coalmine in the Ordos Basin of Inner Mongolia (see Figure 6.5). The DCL project began its feasibility study in 2003, and built and successfully ran its first reactor train of the first phase in December 2008. This first reactor train can process 6,000 tons of dry coal per day and produce 1 million tons of diesel and gasoline annually (7 million barrels). About 2.9 million tons of CO_2 at high concentration will be released to the atmosphere, unless sequestered.

[f] Co-author Julio Friedmann made significant contributions to this section.

Figure 6.5 Location of Shenhua DCL facility



Map adapted from Friedmann, Julio, 2009b.

Shenhua has been collaborating with West Virginia University and the U.S. Department of Energy's Lawrence Livermore National Laboratory on looking into capturing the high-concentration CO_2 from the DCL facility and sequestering the gas in a nearby geologic formation. This collaboration is a part of Annex II of the U.S.-China Fossil Energy Protocol, which promotes cooperation between the two countries in key energy areas.[156]

In March 2009, work began on the carbon sequestration phase of the project. A pre-feasibility study for this site was completed drawing on published and proprietary data to estimate key site geology characteristics, such as local formation top depth, porosity and permeability, facies distribution, and rock and brine chemistry. This study cleared the way for a more extensive sequestration site assessment process, which is now in full swing.[157]

Status, challenges, and opportunities

The current sequestration site assessment phase involves efforts to gain a better understanding of the local subsurface geology surrounding the Shenhua DCL plant and identify an optimal storage site. 2D and 3D seismic reflection images of the subsurface structure are being taken, and test drilling is underway to collect core samples for analysis of porosity, permeability, rock and brine chemistry, and cap-rock strength. Eventually stratigraphic, depositional, and structural models of the local site will be built, with the goal to develop site-specific static geomodels that can be used to simulate the CO_2-rock-brine injection system.[158]

As part of this phase, storage options are also being considered. Though EOR and EGR were explored as an option due to the many mature oil and gas fields in the region, sequestration in a deep saline formation is now perceived as the more likely option due to the saline formation's closer location, which would reduce CO_2 transportation costs and allow the project to come online faster.[159]

However, the Shenhua DCL project faces many challenges due to the local geology. First, although there are many potential target reservoirs and seals in the Ordos Basin, overall permeability is low, which creates challenges in terms of injectivity but may also help improve the residual-phase trapping of CO_2 over time.

Second, the Ordos Basin faces overall under-pressure, posing the question of whether this is caused by leakage or depressurization pathways. Though this may reduce injection costs, it also adds uncertainty regarding the long-term effectiveness of storage, and requires further assessment to answer.

Lastly, the local area around the Shenhua DCL facility has very little subsurface geological data available. Though stratigraphic seals in the region are well-known and tested, there appear to be no deep wells close to the site and few places in the area with hard data available regarding rock porosity or permeability. [160] Thus the ongoing site assessment is a critical phase of the project.

In June 2010, China's main news agency Xinhua reported that Shenhua's CCS system, which is designed to capture and sequester 100,000 tons of CO_2 per year in the first phase, is expected to be operational by the end of 2010.[161] The project will need a total of 210 million RMB (30.8 million U.S. dollars) in investment and the operating costs of the facility are estimated at about \$50 per ton of CO_2.[162]

IGCC projects where CCS is planned

While IGCC is not necessarily linked to CCS, IGCC plants provide a good opportunity for CCS due to the relative ease of capturing their CO_2 as explained in Chapter 4. Below, we describe three IGCC projects in China where CCS is planned. The GreenGen project is in construction, but the other two are pending government approval.

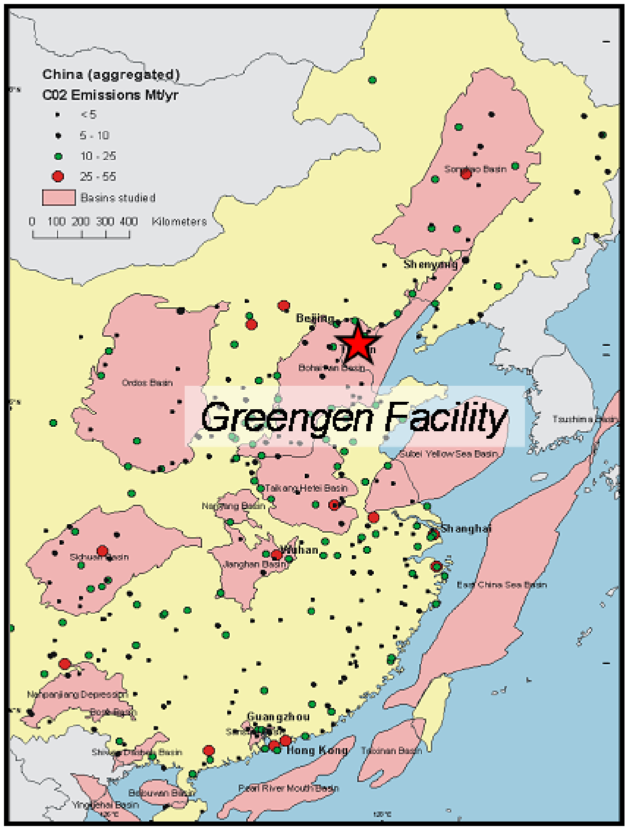
GreenGen IGCC project[g]

<u>Project background</u>

The GreenGen project is an IGCC project located in the Bohai Basin near Beijing and Tianjin (see Figure 6.6). This project grew out of China Huaneng Group's recognition of the relatively low efficiency of conventional coal-fired power generation in China as well as the environmental problems associated with these conventional plants. Greengen now aims to be the first IGCC CCS project in China, with the eventual goal of sequestering the vast majority of carbon emissions from the 400 MW IGCC plant.[163]

[g] S. Ming Sung and Mike Fowler made significant contributions to this section.

Figure 6.6 Location of Greengen



Map adapted from Friedmann, Julio, 2009b.

The China Huaneng group is the main shareholder in the GreenGen joint venture. Other participants include China Datang Group, China Huadian Corporation, China Guodian Corporation, China Power Investment Corporation, Shenhua Group, State Development & Investment Co., China Coal Group, and, more recently, Peabody Energy from the United States. The major players in GreenGen are all involved in the coal and electricity generation industry in China, and expect to gain valuable knowledge and experience from their participation in this pilot.[164] The Asian Development Bank recently offered a grant of over $1 million to support this project's CCS part, specifically for analysis and capacity building.[165]

The project plans to develop in three stages. Phase I involves operating a 250 MW IGCC plant. Phase II would add a low level of CO_2 capture (25,000 to 30,000 tons of CO_2 per year) for research and experimentation purposes. Geological sequestration experiments would also be conducted during this phase, with GreenGen currently exploring various saline and EOR sequestration options. The experience and data from Phase II will then be used to design the third phase of the project, which involves building a 400 MW IGCC plant to expand the facility's total capacity to 650 MW with a high level of CO_2 capture and sequestration. For comparison, efforts on Phase II of GreenGen are similar to those of earlier (planned if not yet implemented) IGCC projects in the United States, Europe, and Japan, while the goals set for Phase III would equal or exceed similar efforts in those countries.[166]

Status, challenges, and opportunities

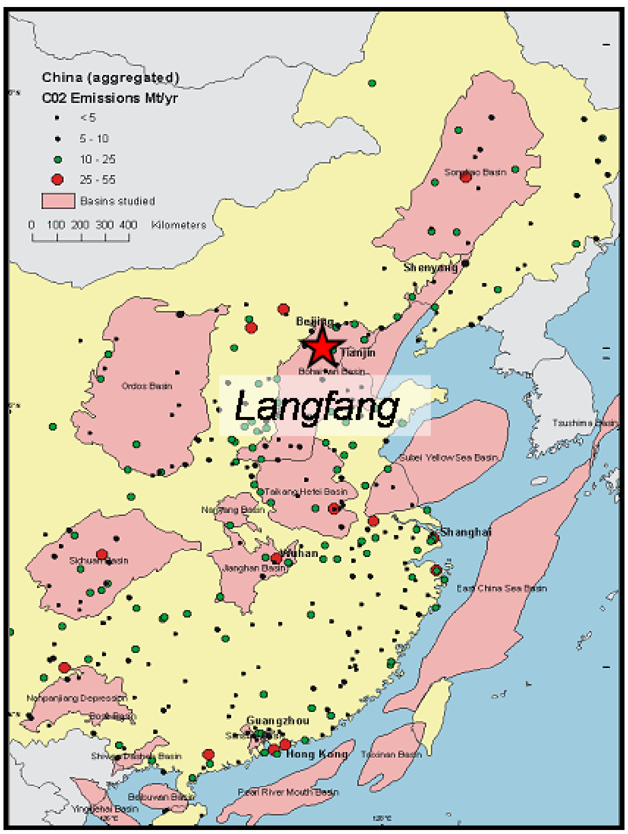
Phase I of the project is currently on track to start up between 2011 and 2012 with Phase II expected to commence between 2012 and 2013.Phase III is planned for 2017. The Bohai Basin in which Greengen is located has many potential CO_2 storage reservoirs and seal pairs as well as oil and gas fields nearby suitable for EOR/EGR although detailed assessment of specific sites is still needed.[167]

Langfang IGCC project[h]

Project background

The China Power Investment Corporation (CPIC) was one of the successors of the now-defunct State Power Corporation of China. CPIC is striving to increase clean energy in its generation portfolio and has been interested in IGCC technology for several years. After pre-feasibility studies, it has selected the city of Langfang as the location for its first IGCC facility. Located near Beijing and Tianjin, Langfang is within the Bohai economic circle and has strict environmental protection standards (see Figure 6.7).

Figure 6.7 Location of Langfang



Map adapted from Friedmann, Julio, 2009b.

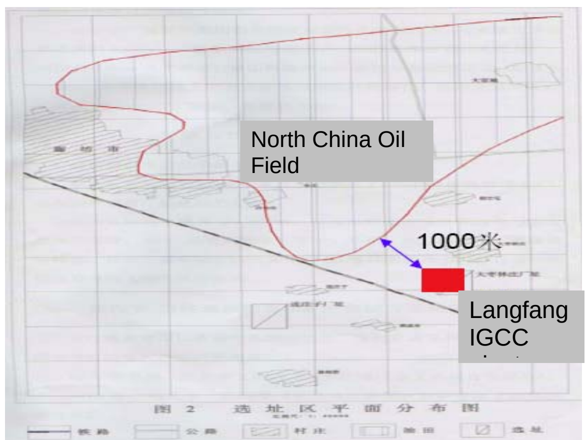
[h] Based on CPIC, 2009: Introduction of CPI Langfang IGCC Project, presentation at U.S.-China Workshop on Clean Energy and CCS hosted by Belfer Center for Science and International Affairs, Harvard Kennedy School, 17-18 April. Geological part is by co-authors Li and Wei.

As proposed, the plant will use Datong coal from Shanxi province, with an annual demand of 2 million tons. 7.15 million tons of water will come annually from a sewage treatment plant 2.3 km away. The project will aim to capture eight percent of the CO_2 in the syngas as a CCS demonstration project.[168]

Status, challenges, and opportunities

The geologic storage options for CCS at Langfang IGCC appear promising. The North China oilfields are located only 1 km away from the proposed facility, making EOR a prime possibility (see Figure 6.8).

Figure 6.8 Source-reservoir matching for the Langfang facility



Source: CPIC, 2009: Introduction of CPI Langfang IGCC project, China Power Investment Corporation, Beijing.

Bohai Bay Basin has an area of 310,000 km^2. The early Tertiary basement block has many uplifts and depressions. The mid-Tertiary sedimentation of the depressions has a thickness of 3,000 to 5,000 m, partly due to continental sedimentation partially influenced by marine transgression. The late-Tertiary stratum mudstone is 1,800 m thick and appears able to act as a very good cap rock.[169]

The Langfang IGCC plant will be close to the Jizhong depression, which has an area of 25,000 km^2. Some oilfields are less than 30 km away from Langfang city, including Langfang Hexiwu, Huabei Liuquan, Zhongchakou, Yongqing, and Fengheying.[170]

At the Biegezhuang oilfield, the oil-bearing formation has an average thickness of 2 to 4 m with the thickest section reaching 10 m. The single-well reservoir accumulative thickness is 40 to 60 m, with the largest reaching 103 m—the average effective thickness is 35.9 m. The distribution of the oil-bearing formation is stable: the connectivity rate of this first-class oil stratum is about 89 percent under the conditions of a well pattern with well distances of 300 m. In the vertical direction, the oil-bearing structure is concentrated in Oil Group I, and is controlled by tectonic movement in the horizontal direction. The oil-bearing formation in the higher tectonic zone has a thickness of 40 to 70 m, while the oil-bearing layer in the lower tectonic zone has a smaller thickness of 15 to 35 m. The reservoir rock composition is 60 percent quartz and 25 to 30 percent feldspar, and the median particle size is generally less than 0.1 mm. The separation and cylindrical grinding situation is good, and the cementing material is mud and calcium with both contact and pre-contact cementing types.[171]

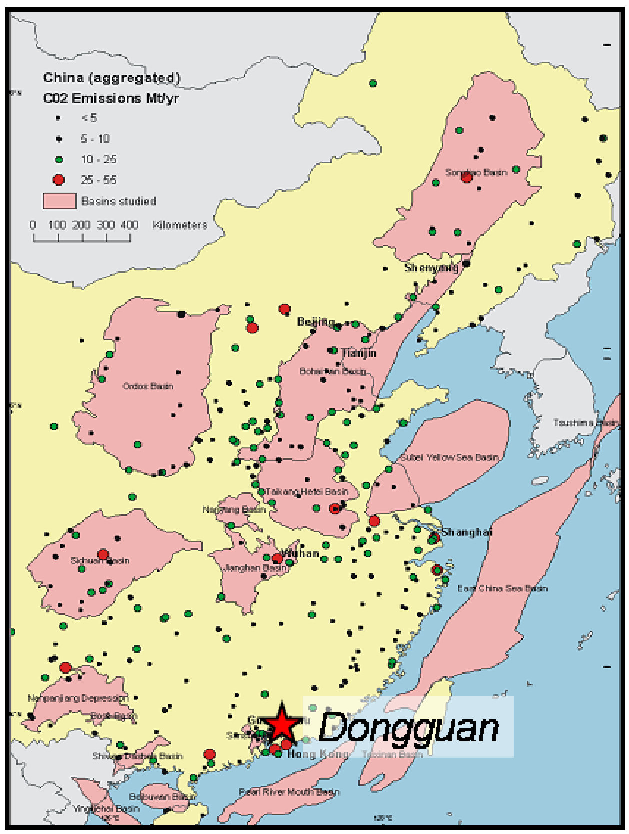
Specific plant location planning for the Langfang IGCC project started in October 2005. A preliminary feasibility assessment was completed in June 2006 with a second feasibility study completed in November of that year. The electricity delivery system design was approved in June 2007, environmental and water source assessments were approved in mid-2008, and since February 2009 the project has been awaiting final approval.[172]

Dongguan Taiyangzhou IGCC project[i]

Project background

The Dongguan Taiyangzhou Power Corporation is a subsidiary of Dongguan Power and Chemical Industry Holding Co., Ltd, and proposes to locate an IGCC plant in Dongguan city, Guangdong Province (see Figure 6.9).

Figure 6.9 Location of Dongguan



Map adapted from Friedmann, Julio, 2009b.

In order to meet the requirement to establish a supporting power supply within the load center of the Zhujiang Delta area and to coordinate and promote a clean electricity generation demonstration project in the *Outline of Zhujiang Delta Area Reform and Development Plan*, the

[i] Co-authors Lifeng Zhao, X. Li, and N. Wei made significant contributions to this section.

Guangdong Provincial Development and Reform Committee has submitted the Dongguan 800 MW IGCC project to the National Energy Bureau. The project has already received approval for early phase action, and is intended to help adjust and optimize the power mix structure and energy saving development in Guangdong province.[173]

The suggested location for this IGCC demonstration plant is the north side of the estuarine region of the south bystream of the East River at Hongmei town in South Taiyang Zhou, next to the coastal industrial zone planned by Dongguan city and adjacent to Humengang Harbor. With the Lisha Island Petrochemical Base under construction 1 km to the northwest and the development of Humengang harbor and the Dongguan coastal industrial zone, the Dongguan IGCC plant is set to become a critical electricity source for the region. The plant will consume 1.8 million tons of bituminous coal annually from Shanxi Datong for electricity generation.[174]

Status, challenges, and opportunities

The plant site lies about 100 km away from the Baoyue oil and gas field and the Zhushangang oilfield, both within the Sanshui Basin (see Figure 6.10). This makes EOR/EGR sequestration a viable option for the plant, thus significantly reducing costs. Sanshui Basin is located on the Beijiang River to the west of Guangzhou city, covering an area of 3,380 m^2 and lying more than 3,000 m deep.[175]

Figure 6.10 Source-reservoir matching for the Dongguan facility

Source: Li, X. and Wei, N.

The Sanshui Basin has very well-developed fractures, with primary fractures running north-to-northeast, northeast, and northwest, with a portion running east-to-west. The strong seal-off characteristics of the faults and fault-blocks have shaped various oil storage layers, and seem to also provide a variety of good sites for the sequestration of CO_2.

Under the Sanshui Basin lies a thick layer of Tertiary sandstone, divided into three primary sections. The total thickness is 58 to 88.5 m, while the thickness of a single layer can be 8 to 10 m. There seem to have good cap layer and storage layer for CO_2 sequestration.[176]

The Sanshui oil reservoirs lie at a depth of 650 to 1300 m. The proven petroleum reserve in the basin is about 100 million tons with a proved natural gas reserve of 100 billion cubic meters. Now that most of the oil and gas reserves have been depleted, these reservoirs are very suitable for EOR/EGR.

The Dongguan project has received financial support for IGCC R&D from the central government's High Technology Development program (Program 863) during the 10^{th} Five-Year Plan period (2005 to 2010). Most preparations have been completed and the project is awaiting government's final approval.[177]

Chapter 7: Developing a CCS Regulatory Framework in China[j]

To encourage further development and demonstration of CCS technology, China will need a regulatory framework that creates incentives while ensuring that CCS projects also protect human health and the environment. China's CCS regulatory framework will be unique and should be drawn to fit the country's existing legal and regulatory system. In the Chinese context, this framework will likely consist of a mix of laws, regulations, multi-year plans, and government guidelines that will together cover a wide range of relevant health and safety requirements, efficacy rules, and energy policy measures. To be successful, several different ministries and stakeholders will need to coalesce around a shared understanding for how China might enable CCS development. China is only now beginning to address these issues.

This chapter describes the parameters and possibilities for development of an environmental regulatory framework for CCS in China by first examining the various national-level regulatory frameworks that have emerged worldwide. Next, the chapter provides an overview of the Chinese regulations already in place that could influence CCS-specific regulations, key players in China's regulatory development process, and the key building blocks of Chinese regulatory frameworks. This chapter concludes with a discussion of the challenges faced in developing a successful CCS regulatory framework, and is followed in the next chapter by specific recommendations for policymakers, businesses, and the international community.

Purpose of CCS regulation

Enabling environmental policies must be adopted to ensure safe and secure CCS operations that are protective of human health and the environment. These policies, which are often implemented through regulations, have two primary purposes:[178]

- First, policies must address traditional concerns of the projects themselves: ensuring human health and safety in the project development phase, in its operations, and once the storage site has been sealed; ensuring safe drinking water and other underground natural and mineral resources; and protecting ecosystems – including natural ecosystems as well as those used by humans, such agricultural land.

- Second, in order to be credible, a project needs to ensure the effective storage of CO_2 beyond safety and health concerns. Regulators will need to consider how to account for CO_2 storage, including effective monitoring and verification to ensure that the CO_2 remains permanently stored. This is especially important if CCS is to gain public acceptance as a greenhouse gas mitigation technology. Projects that result in less than optimal performance in any country carry a significant danger of stalling CCS deployment worldwide. This underscores the importance of sound regulations not just in China, but in all developing and developed countries.

[j] The primary authors of this chapter are Deborah Seligsohn, Sarah Forbes, and Yue Liu of the World Resources Institute (WRI) and Zhang Dongjie of Tsinghua University. Some of the discussion in this chapter is also included in a separate publication from WRI published earlier this year. See WRI, 2010: CCS in China: Toward an Environmental, Health and Safety Regulatory Framework, World Resources Institute, Washington DC, available at: http://www.wri.org/publication/ccs-in-china.

Governments may also institute policies that foster the development of the CCS industry, to accelerate or broaden the deployment of CCS. It is important that such policies should be technology-neutral. While there are a growing number of excellent CCS technologies for each portion of the process, all need to be studied and evaluated as different approaches to CO_2 capture, transport, and storage may work better in some areas and in some applications than in others. As the technology develops, providing supporting policies that do not attempt to "pick winners" will be vital to the industry's healthy growth.

The process for instituting such requirements varies by country and region. Globally, there have been a few important efforts that have served to meet specific needs for applicable regulation of CCS efforts. These efforts have culminated in the drafting, and in some cases passing, of environmental regulations for CCS projects. The IEA has established an international CCS Regulators' network that meets periodically to share information regarding regulatory developments and has served an important role in global information sharing regarding how to regulate geologic storage projects. Below we summarize the most significant developments worldwide, as outlined by delegates to the network.

Development of CCS-specific regulations worldwide

Since 2005, significant efforts have focused on developing a robust set of rules for appropriately selecting and operating a CO_2 storage site, monitoring the CO_2 stored, carrying out maintenance and corrective action if needed, and eventually decommissioning the site, while ensuring human health and safety as well as protection of the environment. In 2008, environmental regulatory frameworks for CCS were released at the state and federal levels in the United Statesand Australia, while a Directive for CCS, which included environmental regulations, was passed at the European Union level.[179]

Although these frameworks draw on distinct existing laws and regulations for each jurisdiction, they are largely consistent in the ways they ensure that CCS operations are conducted safely with secure, effective CO_2 storage. A common global understanding of how to safely implement and regulate the technology seems within reach.

In 2005, Australia became the first country to adopt guidance for CCS-specific regulations.[180] The Government then passed national legislation for offshore storage, which amended the existing Offshore Petroleum Act of 2006 via the 2008 Offshore Petroleum Amendment (Greenhouse Gas Storage) Act of 2008. This provides an enabling framework for CCS, including regulations for site selection, closure, and liability.[181] Australia's regulations for on-shore geologic storage are being addressed at the state level, and Victoria became the first state to adopt a framework for onshore regulation in 2008, based on existing regulations for the petroleum and geothermal industries. The regulations came into effect in 2010.[182]

On December 17, 2008, the European Union adopted an enabling policy framework for CCS, as one part of a comprehensive legislative package on climate and energy. The Directive on Geologic Storage of CO_2 (COM(2008) 18 final) addresses environmental risks of CCS in a regulatory framework and provides a framework for member states to use in drafting country-specific regulations.[183] In addition to establishing the new Directive for Geologic Storage, several existing Directives were modified to accommodate CCS, including the following:

- Environmental Impact Assessment Directive (85/337/EC);
- Integrated Pollution Prevention and Control Directive (96/61/EC);
- Large Combustion Plant Directive (2001/80/EC);

- Waste Framework Directive (2006/12/EC);
- Water Framework Directive (2000/60/EC); and
- Environmental Liability Directive (2004/35/EC).

In the United States, the Environmental Protection Agency (EPA) released a draft rule for geologic sequestration under the Underground Injection Control Program in July 2008, which is currently scheduled to become effective in early 2011.[184] This regulation differs from what other countries have done because it deals exclusively with regulating underground injection for the purpose of protecting underground sources of drinking water. As such, it constitutes only the first step of what is likely to be a much more extensive regulatory infrastructure in line with the United States developing legal framework for regulating greenhouse gas emissions. An additional rulemaking is under way by EPA to establish greenhouse gas reporting requirements for sites that inject CO_2 underground. This is also scheduled to take effect in late 2010 or early 2011. In the United States, as in Australia, individual states, such as Washington, have also established their own regulations for geologic storage, or are in the process of doing so.[185]

Recent legislative proposals in the United States have also contained provisions that would move the country's regulatory process for CCS forward considerably. The American Clean Energy and Security Act of 2009 (ACESA), passed in 2009 by the U.S. House of Representatives contained several CCS provisions that would have provided for:

- A comprehensive regulatory framework for geologic storage that safeguards human health and the environment (and not simply groundwater);
- Emissions reporting for geologic storage;
- EPA reporting to Congress on performance of geologic storage sites and evaluation of the regulatory framework;
- A task force to scope the design of the legal frameworks;
- A study on CO_2 pipelines;
- R&D support and incentives for early deployment; and
- Performance standards for coal-fired power plants sufficiently strict that they cannot be achieved by efficiency improvements alone.

Additionally, the ACESA bill contained significant incentives, on the order of 200 billion USD, for the deployment of power sector and industrial CCS. While the U.S. Senate did not pass the ACESA, legislation proposed in that body has contained similar provisions on CCS regulation.

As countries develop their regulatory infrastructure, there is a need for knowledge sharing and the documentation of CCS best practices. In the United States, for example, where it is anticipated that communities and environmental groups could have strong opinions about siting, pipelines, and disposal practices, the World Resources Institute (WRI) facilitated a stakeholder process with over 80 participants from industry, business, academia, governments, and environmental groups to establish CCS guidelines.

There have also been several important efforts towards establishing accepted protocols for how to responsibly deploy CCS technology from a technical and scientific perspective, which have influenced the development of country and region-specific regulations, including the WRI Guidelines for Carbon Dioxide Capture, Transport and Storage. These guidelines are now being used as a starting point for a Tsinghua University-WRI effort to develop CCS Guidelines for China. This process brings together China's industry leaders, together with the country's NDRC and other stakeholders, to discuss key criteria for China's CCS policies, such as:

- Should a permit for a CCS operation be granted along with the approval for the industrial facility, or should it be a separate approval?
- Should the focus for China's CCS demonstration be on CCS via pre-combustion or post combustion?
- How should international collaboration be established?
- What will role of China's government entities and industry enterprises be in the development of CCS technology?;
- What is the technical and scientific status of the technology and how can the technical risks be overcome?

Although the WRI-Tsinghua University project was initially designed to focus on protecting safety for people and the environment and ensuring efficacy of storage, the feedback received from government representatives suggests that China's National Energy Administration (NEA) and NDRC would also like to have options presented that address policies for enabling CCS deployment. Such policies might include measures such as tax incentives, special pricing, direct subsidies, favorable loans, and others.

Performance standards and state policies

Governments worldwide are beginning to consider formal plans that require future or existing coal plants to adopt CCS technologies. For example, the European Commission has stated its belief that, by 2020, all new coal-fired power plants should be built with CCS, and that existing plants should then progressively follow the same approach.[186]

The United Kingdom government released its response to the consultation on the Framework for the Development of Clean Coal in November 2009. In the response, the government outlines its plans to establish a requirement for any new coal power station to demonstrate the full CCS chain (capture, transport, and sequestration) at commercial scale. The longer-term intention is to see CCS ready for wider deployment by 2020, and for any new coal plant constructed from then on to deploy CCS fully from day one.[187]

Along similar lines, the states of California, Washington, and Montana in the United States now have laws in place that any new long-term financial investment in "baseload" generation resources has to meet a greenhouse gas performance standard which is set at just above the level of a combined cycle natural gas plant.[188] The Canadian government is also currently considering proposals to set emissions performance standards for new coal-fired power plants, as well as plants at the end of their economic life (greater than 45 years in age).[189]

In the United States, performance standards for new coal-fired power plants were embedded in ACESA and subsequent U.S. Senate proposals during the 111th Congress. The exact proposed standards, triggers, and timelines varied between bills, but in general the standards would have applied to plants permitted after January 1, 2009/2010, that rely on coal and/or petroleum coke for 30 percent or more of their fuel, and would have required plants permitted from 2009/2010 to 2020 to achieve a 50 percent reduction in annual emissions between 2020 and 2025[190] or earlier (depending on the level of commercial deployment of CCS technology), and plants permitted from 2020 onward to achieve a 65 percent reduction in annual emissions from the unit.[191]

Key criteria for geologic storage regulatory regimes

A comparison of the regulatory approaches followed in the European Union, the United States, and Australia suggests six important themes or criteria, which are identified in WRI's CCS guidelines, for any country to consider in framing geologic regulations. These criteria are based on the knowledge that geology, even within a specific location, can be heterogeneous and that uncertainties in operating in the subsurface can be managed through integrated monitoring and risk analysis.

Site selection should be based on site-specific geologic data

Site selection that assures the successful safe storage of CO_2 underground is the single most important step in developing a CCS project. Essential geologic characteristics of an appropriate site include the presence of a cap rock that is laterally extensive, relatively thick, and without penetrations or faults that are predicted to serve as conduits for CO_2 to escape outside the injection reservoir, in addition to the presence of an injection formation that can store the anticipated volume of CO_2 at the desired rate.

Monitoring plans should be adapted as needed and be designed for the geology at a specific site

A monitoring area must reflect the site-specific geologic conditions and be based on modeling and CO_2 injection simulation that employs site-specific data. This area may also change through the course of a CCS effort and should be periodically re-evaluated. Further, it is impossible to establish a standard suite of default monitoring technologies. The development of a site-specific monitoring plan that is based on the unique local geologic conditions and informed by site-specific data collected during characterization is critical to the success of storage at any one site. Different technologies will be used at different sites and should be selected based on the site-specific geologic conditions.

A simulation of the injection should be conducted, and data should be collected routinely and reported to the regulator

Operational monitoring requires important data information. For example, an operator should report the composition of the injected fluid, the volume injected, the flow rate, and reservoir pressure. A model and simulation of CO_2 injection should be required, and that model must be integrated with data collected during operational monitoring as well as site characterization (or exploration). This integrated planning is important to the overall success of CCS operations because by updating the model periodically with monitoring data the model can, over time, better resemble geologic conditions in the field and better predict CO_2 behavior in the subsurface.

A comprehensive risk assessment should be conducted based on site-specific data

The operator must identify potential leakage pathways and evaluate them in the context of modeling that is based on site-specific data. A site-specific risk analysis that is informed by data collected during characterization and operations is essential to ensure successful site selection and operation. Similarly, having plans in place to manage any unexpected movement of CO_2 is critical to responsible CCS operations.

The area to be evaluated and monitored should extend beyond the CO_2 plume

Potential impacts of a project extend beyond the boundary of the injected CO_2, to include any area of elevated pressure in the surrounding formation fluid. This expanded project footprint should be the area of consideration for modeling, monitoring, and risk assessments.

The regulatory framework should be reviewed with time and adapted as new information becomes available

Emerging regulatory approaches are driven by site-specific data collection and plans that reflect the geology of a specific site. This approach should ultimately lead to a regulatory review of the site-specific plans rather than requiring a metric that is less specifically fit to the relevant local geology. Incorporating the inherent heterogeneity among (and sometimes within) geologic reservoirs into the confines of a regulatory framework can be a challenge, and there will be some degree of uncertainty in geologic storage projects that is expected but manageable—much like oil and gas operators manage uncertainty in existing subsurface operations. A regulatory framework for CCS should allow flexibility to adapt as data collected informs the operators understanding of the subsurface. The approach proposed in the ACESA would have included a formal required review of the environmental regulatory framework once every three years.

The Chinese regulatory system and CCS

Existing regulations

The Chinese government has not yet begun to work specifically on CCS regulations; however, this does not mean that CCS projects are unregulated. Various government ministries and agencies administer over a dozen different laws and regulations regarding air pollution, pipeline construction and operation, hazardous waste storage and monitoring, groundwater protection, subsurface property rights, mining, and environmental impact assessments that affect CCS projects.[192]

Thus, although the legal aspects of CCS is a relatively new topic in China (as it is for the rest of the world), existing laws and regulations do exist that govern specific aspects of current CCS projects and can provide working models for a CCS-specific regulatory framework in the future.

Importantly, China's projects also must go through a project approval process, which involves, in the case of subsurface projects, at least the NDRC and the Ministry of Land and Natural Resources (MLR), as well as an Environmental Impact Assessment review under the Ministry of Environmental Protection (MEP). This provides the Chinese government an additional opportunity to specify safety and performance standards for specific projects even in the absence of CCS-specific regulation.

Key players in China's CCS regulatory development process

Chinese regulatory development generally takes two to three years. Moving forward, the development of a CCS regulatory framework in China will likely occur in parallel with research, pilot deployment, and, potentially, commercial deployment of CCS technology. As noted in previous chapters, coal and power companies in China are seeking to experiment with different carbon sequestration options, and companies and research organizations are already developing CCS pilots in China.[193]

CCS regulatory framework development will necessarily involve several different Chinese governmental institutions, ministries, and stakeholders. The Chinese Communist Party, the legislature and, most importantly, the executive branch and its various agencies will play important roles in directing this process, and provincial governments and key companies can also play influential roles in shaping regulatory requirements and the details of the CCS project approval process.

While the Party has significant power in policy-making, it does not have a formal role in the establishment of laws or regulations. Political issues, such as what future carbon targets might be, or whether CCS is worthy of government investment, might well be a focus of Party discussion, as has been the issue of climate change itself.[194] But the government bureaucracy generally handles the type of highly technical regulatory process associated with CCS.

China's legislature, the National People's Congress, meets in full session only once a year, and its Standing Committee meets only four times annually. The laws that are passed at these sessions are much shorter than in most Western countries and essentially provide the broad structure, but little detail, for most activities.

The Executive Branch, which is headed by the President, then below him the Premier, who chairs the State Council, and a cascading set of offices is likely to have the greatest role in developing requirements. Traditionally, the President oversees more of the political and military aspects of government while the Premier leads economic policy. Each Vice Premier (of which there are four) or State Councilor (of which there are five) then oversees several ministries, and these are generally grouped together in a fairly logical fashion:

- Economics, finance and trade
- Education and science
- Energy and environment.[195]

Cross-cutting issues where different ministries answer to different Vice Premiers are often not resolved at the working level, but are sent to the State Council to resolve instead.[196]

The State Council has its own staff and think tank—the Development Research Center—to assist its members in making policy decisions. Its decisions include the development of the Five-Year Plan; the major programmatic planning document for all Chinese departments; the establishment of major government programs and goals, including the Energy Saving and Pollution Abatement Policy and the National Climate Change Action Program; and the establishment of specific regulations.[197] The State Council also establishes Working Groups or Leading Groups, comprising different ministry representatives, to facilitate coordination on key government objectives. A National Climate Change Leading Group was established along with the Energy Conservation Group and an Emissions Reduction Leading group.[198]

As a result of this proliferation of various government agencies, for any given CCS decision, several government agencies may be involved, as shown in Table 7.1.

Table 7.1: Governmental agency involvement and roles in CCS decisions

Ministry	Role	Overlaps
National Energy Administration (NEA)	• Sets energy policy • Approves energy projects • Officially not a full Ministry – complex relationship with NDRC	• Significant overlap with NDRC Departments on both policy and project approvals • Projects also subject to MLR and MWR constraints • Major energy companies have significant autonomy • Many decisions also made at provincial level
National Development and Reform Commission (NDRC)	• Overall economic planning ministry • Departments of Climate, Energy, Industry and Environmental will also play a role in CCS decision-making • Has both macro policy and project approval functions	• Project approval overlaps particularly with NEA and MLR • Funding overlaps with MOF • Climate policy driven by both domestic concerns and international negotiations strategy (on CCS desire not to give too much away in international negotiations)
Ministry of Land and Natural Resources (MLR)	• Governs land use and maritime uses within China's Exclusive Economic Zone (EEZ) • Sets land use laws, including underground mineral rights • Project approvals for siting	• Land planning functions interact with NDRC's industrial planning • Project approvals interact with NDRC's project approval • Land and water resource protection interact with MEP and MWR
Ministry of Environmental Protection (MEP)	• Regulates pollution, including air pollutants, groundwater protection, and landfill and hazardous waste regulations • Requires and evaluates Environmental Impact Assessments (EIA)	• EIA process can conflict with NDRC and MLR project approvals • Water quality protection interfaces with MLR allotments
Ministry of Water Resources (MWR)	• Ground and surface water protection • Water allocation	• Interactions with MEP and MLR approval processes • Water allocation will be necessary for capture
Ministry of Industry and Information Technology (MIIT)	• Regulates industry • Oversight role in industrial project and demonstration approvals	• Energy industry mainly differentiated with NEA, but there are some overlaps
Ministry of Finance (MOF)	• Controls government budget • Decision-making for any government-funded projects	• Interacts with NDRC in particular on design of government-funded projects – for energy can also involve NEA

Source: E.g., see Downs, E., 2008: China's "New" Energy Administration: China's National Energy Administration, Brookings Institution, Washington DC, available at http://www.brookings.edu/~/media/Files/rc/articles/2008/11_china_energy_downs/11_china_energy_downs.pdf; China NPC, 2002; China NPC, 1995; China NPC, 2000a; China NPC, 2000b; China MEP, 1991.

Provinces and key companies are likely to play a role in setting regulatory requirements. The large State-owned enterprises in the energy sector were once independent ministries.[199] While this is no longer the case, they still retain significant autonomy. The State-owned enterprises are also essential stakeholders who convey their interests directly to the ministries and the State Council. Provinces in China do not have independent law-making authority to pass laws, and their authority to make local regulations is limited by national law.[200] But provinces do have considerable power in project approval, property and water rights allocations, legal and regulatory enforcement and budgetary allocations.[201]

Components of a CCS regulatory framework: laws, regulations, plans, and guidelines

In the Chinese context, a CCS regulatory framework will likely consist of a unique mix of laws, regulations, multi-year plans, and government guidelines. Chinese regulations are not as closely tied to legislation as regulations are in most Western nations. The State Council and the ministries issue regulations or guidelines that may or may not be tied to a specific law.[202] For air quality, the link is fairly clear. There is an air pollution control law, and while various regulations may not all be tied directly to a specific article, the law provides the framework for the system of air pollution standards, fines and enforcement. [203] In other areas, particularly in the governing of industrial concerns, regulation can take place without a specific law, such as the regulations covering gas pipelines.

Moreover, the National People's Congress (NPC) passes the highest-level budget and policy decisions in China—the Five-Year Plan and the annual budget—not as laws, but as separately labeled items. Sometimes, as in the case of China's Renewable Energy Law, incentive or policy-type programs are passed as legislation.[204] At other times, they are simply an element of the Plan or disseminated in guidelines. Local governments look first to Plans and policies for guidance as to priorities, rather than to legislation.[205] Thus, the key determinant for the current emphasis on both energy efficiency and criteria air pollution abatement is a top-level national policy announced in 2007, rather than the earlier laws and regulations, especially on air pollution.[206]

As noted above, CCS regulation could potentially involve two separate aspects of policy—enforcement governing environmental health and safety and environmental efficacy (both whether CCS might damage humans or the ecosystem and whether the CCS ensures the CO_2 stays out of the atmosphere) and energy policy. In China, enforcement of environmental health and safety will likely be covered by regulations, though these regulations may or may not be tied to specific laws. On the other hand, efficacy rules for CCS could be set out as regulations or as parts of a plan, and might well come under both, such as with accounting rules set out in guidelines and overall CO_2 limits set by regulations but annual or five-year targets set by a plan. Similarly, energy policy items, such as incentive systems to promote CCS development, may be established either by law (as with the renewable energy and energy efficiency laws in China), by government regulations (as has recently been the case with new programs to promote new technology vehicles and solar installation), or by plans and guideline documents (such as tax programs or directives detailing which industries are responsible for what aspects of CCS).

Challenges presented by existing Chinese legal framework

As noted above, China is by no means starting with a blank slate for CCS. Several existing laws could be relevant, and requirements must be fit to a basic framework in the legal tradition that sets out how to address technical, environmental, and energy policy issues. Nevertheless, China's environmental regulatory development is only 30 years old.[207] The body of laws and regulations has more gaps than would be the case in Europe or the United States. The environmental agency gained enforcement powers only in the early 1990s, and became a Ministry only in 2008.[208] China's relatively limited experience in dealing with these issues must be considered in developing CCS requirements. An initial challenge will be how to design laws or regulations within the existing framework, ensuring that the regulations supplement and enhance existing areas, while recognizing that the underlying structure may not be sufficient to govern these new activities. In other words, even if the Chinese government chooses to use a similar set of guiding principles to those being adopted in other countries, the actual regulations may look quite a bit different, and may have greater detail on issues ranging from environmental health and safety to property use to make up gaps. Chinese requirements will thus need to be developed to uniquely match China's existing legal structure.

A second issue in drafting will be how to address divided authority for many CCS activities. The divided authority consists both of areas of law governed by multiple ministries, such as the underground mineral rights governed by Ministry of Land Resources (MLR) and the groundwater protection responsibility of the MEP.[209] Authorities and regulatory structures also differ by industry. As noted above, many of China's major State-owned industries originally had ministry status. Traditionally, industrial functions were carried out by government bureaus, which have been gradually corporatized since 1979. The major energy companies derive from ministries specifically devoted to each major fuel source or use—power, oil, and coal. The metals companies come from ministries that covered major industrial production.[210] Even after the industrial ministries began to be corporatized, the new State-owned enterprises continued to have self-regulating responsibilities for several years. There has been a steady evolution over the past 30 years to clarify ownership and to establish independent regulatory and policy-making agencies. But this complex historic legacy means that regulations and policies are often industry-specific.[211] As a result, the existing regulations that may apply to CCS will vary depending on whether CCS is used in the power, coal, oil and gas, or other industrial sectors. In designing regulations, policymakers will need to build on this diverse background in a way that harmonizes the underlying regulations and adds additional content in those areas that are needed, but also fosters unified standards that enable the relevant industries to grow with a coherent goal.

The existing regulatory framework also presents an overarching conceptual challenge. There are two key aspects to the success of emerging international CCS regulations: first, that they be written in a technology-neutral way that focuses on ends rather than means; and second, that they incorporate new data and be updated in an iterative way as experience builds.

The iterative nature of CCS regulation is not dissimilar to approaches used in the oil and gas sector, but it is quite different from those used in the power and coal industries, and from which their regulators are accustomed to using. Since much of the early focus on CCS has been on the power sector, where regulations are based on engineering specifications rather than continuous decision-making based on monitoring and modeling data, the concept is somewhat unfamiliar. While China has demonstrated experience from regulating its oil and gas sector for decades, this process has involved a fairly small set of actors and limited growth. The CCS sector involves many industries and their regulators are generally not used to an adaptive approach, generally relying on very deterministic regulatory models. As outlined in Chapter 4, China's CCS industry is already showing signs of becoming an innovation leader. As a result, China has the potential to institute a regulatory system that ensures maximum flexibility while also ensuring health, safety, and efficacy. What remains to be determined, however, is whether such a framework can be in place before the first large demonstration projects begin operation in China. If this cannot be achieved, then interim arrangements will likely be needed to ensure the continued good track record and public acceptance of CCS projects worldwide.

Chapter 8: Summary and Recommendations

As discussed at the beginning of this report, if China and the world are to avoid the worst consequences of climate change, then China's rapid growth in total carbon dioxide emissions—though approaching only the world's average level on a per capita basis—must be curtailed and begin to decrease within the next two decades. This process must happen in parallel with deep emissions reductions by industrialized countries, starting now, in order to save the world from dangerous climate change.

Based on what the world currently knows and is capable of achieving, CCS will likely be a necessary strategy, in concert with other measures, to realize critically needed emissions abatement in China and other large fossil fuel consuming countries. Because CCS involves large-scale systems engineering and geologic expertise, international collaboration will be indispensable for accelerating CCS development and deployment in the countries that need the technology. For China, which still faces daunting development needs and has relatively limited technological, financial and regulatory capacities in some areas, international collaboration and assistance are all the more critical.

The previous chapters further underscored that near-term demonstration projects on CCS are a vital step toward widespread deployment of the technology. Demonstration projects can start on a smaller scale than will eventually be required over the long term. Further, to reduce project costs, CO_2 can be injected into depleted oilfields that have smaller storage capacities but will help develop CCS know-how, from design to construction and from monitoring to regulating. Full-size demonstration projects that use deep saline reservoirs are also an important next step with the main goal to drive down the costs of CCS and nurture a CCS industry.

Ultimately, CCS has to become practical for the numerous existing coal-fired power plants and certain industrial facilities as well. Getting over the initial cost hurdles will be achieved significantly faster with adequate funding for early demonstration projects, favorable climate policies, and successful international and public-private partnerships. In this process, businesses and the broader international community have significant roles to play. Chinese policymakers will also be key to the creation of a CCS industry in China.

With this big picture in mind, we propose the following recommendations with the aim of accelerating safe and effective CCS development in China. These measures will benefit not only China but also the entire world. Several recommendations revolve around cooperation between Chinese and foreign governments and businesses. We believe that collaboration is key to overcoming the specific circumstances surrounding CCS development in China. Although we describe the collaboration needs in general terms, the exact nature and most suitable platform will need to be worked out on a case-by-case basis by businesses and governments. Some collaborative projects could be formed as a natural continuation of existing initiatives and platforms, although we see new ones as being necessary to cover the breadth of work recommended.

For the international community, governments, and businesses

Cooperation on financing early CCS opportunities

International support and China-foreign partnerships are crucial to help transform the considerable existing potential for CCS in China into actual projects. As noted in Chapter 6, there are numerous existing high-concentration CO_2 point sources situated closely to depleted oil and gas fields, as well as on-going and planned coal gasification projects, all of which appear promising for CCS demonstration. To date, however, these sources only represent *potential* CCS demonstration projects, and there are few concrete plans to capture and sequester CO_2.

While the first few demonstration projects will be intrinsically more expensive and risky from the point of view of individual private developers, the parties involved in these projects will also benefit technically, politically, and economically in a carbon-constrained world. Currently there is little incentive for CCS in China and there are some doubts about its technological feasibility within political and business circles. To overcome these barriers, international co-funding and technical collaboration is critical to help initiate demonstration projects that utilize different capture technologies in a variety of geologic formations.

Direct involvement in CCS demonstration projects in China

Forging international partnerships on specific CCS projects in China could help accelerate learning, develop best practices, and share knowledge and expertise across countries and companies. The most promising near-term CCS candidates are likely to combine favorable geology with proximity to large, inexpensive sources of CO_2, particularly pairing EOR/EGR with ammonia plants, as outlined in Chapter 6.

International involvement in Chinese CCS projects would be of most value in three key technical areas of geologic sequestration: subsurface geologic engineering, long-term monitoring and verification, and long-distance CO_2 transportation infrastructure, where industrialized countries have valuable experiences to share. Relevant expertise could be provided from research institutions and/or experienced companies, and would be facilitated through government support.

With its extensive CO_2 EOR infrastructure and subsurface geologic engineering expertise, the United States is highly qualified to play a key role in collaborative CCS demonstration projects in China through its scientific community and corporations. Forming public-private partnerships to study the suitability and capacity of potential reservoirs for CO_2 storage, their response to injection, and the long-term fate of injected CO_2 would be extremely valuable. All project participants could gain valuable information on the operating costs of CCS facilities in different geologic conditions, allowing more accurate assessments of CCS economics.[212]

The United States is also a leader in CO_2 transportation technology, and has more than 5,800 km of CO_2 pipelines already in place.[213] In contrast, China currently operates only one CO_2 pipeline of 6.5 km in length.[214] Therefore, China could benefit from cooperation with U.S. laboratories and pipeline operators in developing and building a CO_2 transportation infrastructure.

Finally, the international community and businesses could also share knowledge and technology for monitoring and verification as well as risk management of CCS projects—through mutually beneficial ways with intellectual property rights (IP) properly protected—to avoid CO_2 releases and groundwater contamination. Long-term monitoring to ensure environmental efficacy and public safety is vital, and must be part of any CCS projects in China from the outset.

Mutually beneficial transfer of technology and joint R&D and demonstration

Collaboration in R&D and demonstration rather than competition could be a better way of addressing technology transfer and IP in many cases, and could lead to innovation and breakthroughs needed to lower the costs of CCS. China has been conducting CCS research and development and has achieved notable progress in recent years in coal gasification and CO_2 capture technologies. As mentioned in Chapter 4, several Chinese companies and academic institutions have developed proprietary coal gasification technologies and patents, and are also active in advancing CO_2 capture technologies. As China rapidly improves its technical capabilities in CCS, technology transfer may eventually become a two-way street. Since IP will always be an important issue in technology transfer, it is critical to design partnerships that make IP an incentive rather than a barrier.

Assistance with development of regulations and policies on CCS

China and its government officials could benefit greatly from partnerships with industrialized country officials and experts that have extensive experience in establishing and enforcing regulatory frameworks for environmental protection, and are also the front-runners in developing the regulations and policies needed for CCS projects. As noted in Chapter 7, the Chinese government is still in the early phase of formulating a CCS regulatory framework. Australia, the European Union, and the United States have experience in addressing many of the regulatory issues and questions China now faces. The United States has launched the *Building Regulatory Capacity in China—Guidelines for Safe and Effective Carbon Capture and Storage* project, while the European Union has launched the *Support to Regulatory Activities for Carbon Capture and Storage* project.[215] This is also an area where international NGOs can make substantial contributions, as evidenced by the ongoing WRI-Tsinghua University Guidelines project.[216]

It is unclear what the exact timing of the establishment of a regulatory framework for CCS in China will be. However, it is possible and perhaps likely, that the first CCS demonstration projects will be constructed and begin operation before a specific regulatory framework can be established. It is critical that these projects are held to high standards and operating practices. A strong team by China to develop and oversee these projects, combined with input and assistance from experts in industrialized countries, could help ensure the safety and efficacy of these early projects, and maintain the excellent track record of CCS to date.

Industrialized countries also have greater experience in devising and implementing mechanisms to promote low-carbon energy, such as cap-and-trade systems, carbon taxes and fee-bates, and emissions performance standards, which could help inform Chinese policymakers' choices and decisions.[217]

For Chinese policymakers

There are four key areas to which we recommend Chinese policymakers pay particular attention: CCS-related R&D, establishing a regulatory framework, monitoring and verification capabilities, and incentives for low-carbon energy systems.

Strengthening R&D and demonstration in CCS

All areas of CCS would greatly benefit from additional support in the form of government grants and leadership by national laboratories. In particular, however, the Chinese government should give priority to four key areas:

1. Demonstration of "full-scale" CCS, initially taking advantage of lower-cost, existing high-concentration CO_2 point sources and EOR/EGR, but also in other geologic settings, and a variety of capture technologies where possible;

2. Study and characterization of key offshore basins for carbon sequestration because of the scant availability of suitable onshore reservoirs near the heavily industrialized eastern and southern areas;

3. Study of subsurface geology, which is particularly complex and heterogeneous in China, as described in Chapter 5, in the context of storing CO_2, and better characterization of CO_2 storage capacity. Cooperation from state-owned oil and gas companies in sharing information and technical expertise is very important to facilitate knowledge and data acquisition at the level of detail required for CCS projects; and

4. Developing or improving capture technologies to reduce energy use and costs. This is an area that is particularly suited to the Chinese scientific and industrial base, and could lead to significant technology export potential outside China's borders.

Timely development of a regulatory framework for CCS

As mentioned above, it is critically important to ensure that the first CCS demonstration projects are conducted with adequate site characterization, risk assessment, environmental impact assessment, permitting, and ongoing operational requirements. The risk of the alternative is that sub-standard projects could call CCS as a whole into question and slow down its deployment.

It appears unlikely that a comprehensive CCS framework will be in place in China before the first CCS demonstration projects are in place. Those projects are likely to inform the development of this framework in a process of learning by doing. Industrialized countries can and should share with China their best practices and standards and collaborate on these early projects. Thus, international funding to support early demonstration projects is highly recommended.

In the meantime, Chinese policymakers should consider addressing some specific problems, including how to design CCS laws or regulations within the existing legal framework, how to address divided authority for many CCS activities, how to harmonize existing regulations that may differ between industries, and how to keep the regulations technology-neutral, adaptive, and evenly applied in a manner that will allow China's nascent CCS industry to successfully experiment with a multitude of different approaches and technologies. The WRI-Tsinghua University Guidelines project represents an early effort to address these issues.[218]

Building strong monitoring and verification capacities

Releases of CO_2 from the geologic containment system are possible, even though such incidents are avoidable and can be managed through properly selecting, designing, and managing sequestration sites and projects. It is nonetheless important to develop a comprehensive monitoring regime, which could be based on a variety of measurements and tools. It is equally important to develop sufficient human capacity and expertise to fully implement these monitoring and verification tasks. The ability to perform internationally acceptable verification of CO_2 sequestration will become increasingly significant in the context of global carbon trading, and China should prioritize investment in the training of personnel and the development of monitoring and verification expertise.

Incentivizing safe low-carbon energy systems

Incentives should be established for all safe low-carbon options that are in need of assistance. The objective is not to promote CCS alone but to cut carbon emissions. As discussed in Chapters 1 and 2, while CCS is not the sole or preferred mitigation option for coal-dependent countries, it very likely will be needed as part of the interim climate solution. China should consider adopting measures to limit the construction of coal-fired power plants and other industrial facilities without CCS, while allowing all cleaner technologies, such as energy efficiency, renewable energy sources, and CCS, to thrive.

Different low-carbon energy options have different merits and drawbacks, as well as different deployment timelines and economic and capacity limits. No single option can stabilize global CO_2 emissions alone, and at this point, all solutions are needed.[219] In a cap-and-trade system, the carbon market will decide the exact mix of technologies that will provide the needed reductions. In its mature phase, CCS will compete with other options and eventually occupy its own market. If direct regulations and a carbon tax are used instead of cap-and-trade, the cost of carbon and mandates on coal-fired power plants and other applications without CCS will be set by the government, and must need to be tiered and adjusted over time in order to allow various low-carbon options to make their due contributions.

Initial power plant CCS projects will be expensive, but R&D and demonstration efforts and growing economies of scale are expected to reduce these costs by two-thirds or more over time.[220] Economic incentives and regulations could help support these development efforts and quickly achieve the economies of scale needed to bring costs down dramatically. In the absence of a clear market and regulatory signal that drives emission reductions and also assists CCS to overcome its initial cost hurdles, deployment is destined to be minimal or limited at best.

Carbon taxes and/or emissions control subsidies may be used together, with the emissions fee revenues going to fund rebates for CCS-equipped facilities—a combination often called a *feebate* system. The levels of carbon tax and rebates may be increased over time to guide the speed and breadth of CCS deployment and make it easier for power plants and industrial carbon emitters to adapt. For these policies to be effective, the net difference between the carbon tax and the rebate must eventually reach levels high enough to offset the costs that CCS would incur.

An emissions cap on carbon by itself is not sufficient to drive the more profound technology changes we need to harmonize economic growth and climate protection. Complementary policies and measures to speed the deployment of "big change" technologies in critical areas—such as CCS—are also needed. Direct regulations and performance standards can require power plants and other industrial CO_2 emitters either to meet increasingly stringent CO_2 emission standards or adopt specific alternative technologies over a given timeframe. Of these two options, the former approach would likely result in lower costs as it would allow operators greater flexibility to choose ways suitable for specific plants to comply. This approach also has the benefit of being an extension of China's current power plant pollution control policy.

Market-based cap-and-trade systems have proven cost-effective in reducing pollution. Such a system for CO_2 would allow companies to choose the options that best suit them, such as energy efficiency, renewable energy, and CCS when the CO_2 trading price is above the cost of CCS. Such a scheme by itself is unlikely to result in prices that drive power sector CCS development in its early days, as cheaper options will be utilized first. Additional assistance will be needed to overcome the initial cost hurdles of CCS while carbon prices climb. In China, however, in contrast to many industrialized countries, lower cost CCS options abound. If CCS is therefore recognized in the context of a global carbon emissions trading system, Chinese companies may be able to implement projects and boost revenues by earning and selling carbon allowances or offsets.

Conclusion

Despite China's commendable efforts to reduce coal's role in the country's energy supply, coal will remain a significant part of the energy mix for several decades. As a result, China is likely to need CCS as one of many important tools for CO_2 emissions mitigation. Pioneer studies on China's numerous large CO_2 point sources, geologic storage capacity, and the spatial distribution of storage sites strongly suggest that the country is well suited for meaningful CCS deployment starting immediately. However, despite the broad suitability, much work remains to be done in the areas of geologic characterization, technology improvement and exchange, and building practical experience.

At present, to reduce the impacts of China's coal use, the priority should be to capitalize on the many "low-hanging fruit" opportunities, and pursue demonstration projects to advance CCS technology, build experience, lower costs, and develop a comprehensive regulatory framework. Industrial processes that produce high-concentration CO_2 streams in the vicinity of storage locations are prime opportunities for early projects. Longer term, a wider array of technologies and CO_2 sources will need to be tapped in order to achieve deeper emissions reductions. International support and collaboration in project financing, IP-protected technology transfer, engineering and scientific expertise transfer, and joint R&D are needed.

The future of CCS in China depends on the extent of international partnerships and the incentives that Chinese as well as international policymakers will adopt for reducing carbon emissions and developing a robust CCS industry. International cooperation in CCS is important for China and the rest of the world not only in terms of climate safety, but also in terms of shared benefits in technology advancement and economic competitiveness.

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