

## Advancing Carbon Capture and Sequestration in China: A Global Learning Laboratory

By Craig Hart and Hengwei Liu

*China's dependency on coal fuels the country's phenomenal economic growth but at a major cost to the country's air and water quality, ultimately threatening human health and the country's continued economic growth. The Chinese government's efforts to put China onto a cleaner, low carbon development path have been substantial; however China's pollution and greenhouse gas emissions continue to grow. In an attempt to develop its own advanced coal generation technologies to improve the country's air quality and energy efficiency, the Chinese government is investing heavily in gasification and other technologies that can be employed in carbon capture and sequestration (CCS) applications. This investment has turned China into a global laboratory for CCS pilot projects, attracting foreign governments, multilateral institutions, nongovernmental organizations, and business partners. China's leadership in developing CCS technology could ultimately help lower its costs and promote its commercialization globally, representing a major step forward to solving the global climate dilemma.*

China has the most coal-dependent economy on earth, which has fueled the country's phenomenal economic growth. But this coal-fueled growth has come at a major cost to air and water quality, and China is now the leading emitter of carbon dioxide (CO<sub>2</sub>). Although China's leadership has adopted aggressive policies to promote energy efficiency and renewables, as well as ambitious greenhouse gas (GHG) reduction targets, the country's pollution and GHG emissions continue to grow, albeit at a slower rate. In order to substantially curb China's CO<sub>2</sub> emissions, the Chinese government must implement carbon capture and sequestration (CCS) technology on a massive scale over the next few decades.

Geologic CCS involves the capture, transport and injection of CO<sub>2</sub> into subsurface geologic formations (principally saline formations); depleted oil and gas reservoirs; and deep uneconomically mineable coal seams. The CO<sub>2</sub> would be captured at a power

plant or any industrial facility that emits it in high concentrations. CCS can potentially make a significant contribution to lowering GHG emissions by permanently storing CO<sub>2</sub> underground.

CCS technology is advancing through pilot projects in Europe, the United States, Africa, Australia, Japan and China. China's efforts to develop CCS technology put it among the leading nations in the industry.

Before surveying the various efforts to develop CCS in China, we first discuss the coal challenge that drives China's leadership to invest in alternative energy, energy efficiency, and low carbon technology. Next we discuss China's domestic efforts to develop policies, technology and projects that have fomented the development of the country's emerging supply chain to support CCS. We then describe how China has become a laboratory for CCS pilot projects, attracting foreign governments, multilateral institutions, nongovernmental

organizations (NGOs), and business partners. We close with a discussion of key steps that China's decision-makers could take to support the adoption and diffusion of CCS in China.

## CHINA'S ENERGY AND CO<sub>2</sub> CHALLENGE

China's phenomenal economic growth since it began its reform and opening-up policy in 1978 has produced an average annual growth rate of approximately 10 percent over three decades, far in excess of the world annual average of three percent. From 1978 to 2008 China increased its gross domestic product (GDP) by 83 times (NBS, 2009), and lifted 235 million of its citizens out of poverty (*People's Daily Online*, 2008).

Much of China's dramatic growth benefits the rest of the world. China produces only six percent of the world's GDP, though its

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industry consumes a much larger percentage of global energy resources in order to supply commodities to the world. As of 2009, China was the world's largest energy consumer, accounting for almost 20 percent of global primary energy consumption, 47 percent of global coal consumption and 10 percent of global oil consumption, almost half of which is imported from other countries (BP, 2010; NDRC, 2009). China deploys its resources to supply 48 percent of global cement production, 49 percent of global flat glass production, 35 percent of global steel production, and 28 percent of global aluminum production (Rosen & Houser, 2007). Industry accounts for over 70 percent of China's final energy consumption, while the residential, commercial

and transportation sectors only account for ten, two, and seven percent, respectively (Rosen & Houser, 2007).

China's energy consumption and CO<sub>2</sub> emissions have more than doubled between 1990 and 2006, and will double again by 2030 if unabated (IEA, 2009). Although its emissions are only a quarter of U.S. emissions on a per capita basis, over the last few years China surpassed the United States as the world's largest emitter of CO<sub>2</sub> and its emissions continue to rise rapidly. Without major advances in decarbonizing its economy, China will account for about 23 percent of global energy consumption and 29 percent of global CO<sub>2</sub> emissions by 2030 (IEA, 2009).

### International Climate Talks as Catalyst for Greater Action

China does not have a quantified emission reductions obligation under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). However, pursuant to the Bali Action Plan adopted at COP 13, China and other developing countries agreed to undertake "nationally appropriate mitigation actions" (NAMAs) under a post-2012 agreement to address climate change.<sup>1</sup> The Bali Action Plan calls for deep and urgent cuts in GHG concentrations based on Intergovernmental Panel on Climate Change findings that concentration levels should be kept below 450 parts per million (ppm) CO<sub>2</sub>-equivalent to avoid dangerous climate change. To achieve this goal, developed countries must reduce emissions by 25 to 40 percent of 1990 levels by 2020, and 85 to 95 percent of 1990 levels by 2050.

The Copenhagen Accord adopted in December 2009 reaffirmed the objective of the UNFCCC to stabilize GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with

the climate system, and recognized that the global temperature should remain below 2°C. To achieve these goals, large, rapidly growing developing countries must also emit less than their business-as-usual projections. China, in particular, will need to make dramatic reductions in its emissions.

Driven by concerns over domestic energy security, air pollution problems from coal, and the need to address climate change, China has announced its own goal to reduce its carbon intensity by 40 to 45 percent of 2005 levels by 2020. This is in addition to its target to improve energy efficiency by 20 percent of 2005 levels by 2010, and its targets for renewable energy (see Table 1) and fuel switching. The Chinese government is implementing an impressive array of policies to achieve these targets, including:

- providing capital and other incentives for renewable energy and energy efficiency;
- forcing industry to upgrade or close highly polluting, inefficient power and industrial facilities; and,
- entering into voluntary agreements with industry to reduce emissions and increase efficiency.

The government's steadily growing investment in cleaner energy further supports these aggressive low-carbon policies. In 2009, China ranked as the number one clean technology investor, investing \$34.6 billion, almost double U.S. investment that year (Pew Charitable Trusts, 2010). Even with these policies, however, China's ambitious carbon intensity and energy efficiency targets will be difficult to achieve.<sup>2</sup>

**TABLE 1. CHINA'S TARGETS FOR KEY RENEWABLE ENERGY TECHNOLOGIES**

Technology	Type	2010 Target	2020 Target
Hydropower	Large scale	190 GW	300 GW
Bioenergy	Generation	5.5 GW	30 GW
	Biofuel pellets	1 million tons	50 million tons
	Biogas	19 billion m <sup>3</sup>	44 billion m <sup>3</sup>
	Bioethanol	2 million tons	10 million tons
	Biodiesel	200,000 tons	2 million tons
Wind	Generation	5 GW	30 GW
Solar	On-grid solar PV	150 MW	1.5 GW
	Off-grid solar PV	150 MW	0.3 GW
	Solar thermal	150 million m <sup>2</sup>	300 million m <sup>2</sup>

Source: NDRC, 2007b.

### **CCS as Key to Reducing China's Emissions**

Notwithstanding the Chinese leadership's efforts to put the country onto a low carbon development path, China's ability to successfully reduce its GHG emissions will ultimately depend on reducing emissions from coal.

China is both the world's largest producer and consumer of coal, accounting for more than 48 percent of global coal production in 2008 (Asian Development Bank, 2009). Coal accounts for over 70 percent of China's total energy consumption, and will remain its main energy source in the coming decades (BP,

2010). Over 80 percent of China's electricity is generated by coal-fired power plants (CEC, 2009; Rosen & Houser, 2007).

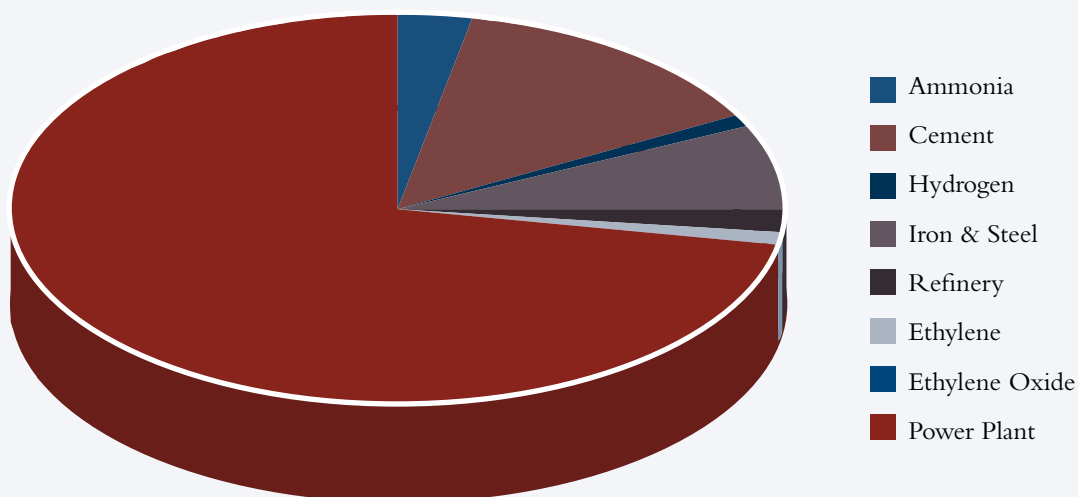
The likelihood of China decreasing its dependence on coal is low due to rapid urbanization and rising energy use by China's growing and increasingly wealthy middle class. Even if China meets its targets for energy efficiency improvements, renewable energy and fuel switching, the country would rely upon coal for more than 50 percent of its power generating capacity through 2030 (Liu & Gallagher, 2009).

After energy efficiency and fuel switching, CCS will be China's primary option for reducing emissions in the power, chemical and other industrial sectors that depend on fossil fuels. The main driver of China's increasing CO<sub>2</sub> emissions is rapid growth in the power sector. China's installed capacity increased from 57 gigawatts (GW) in 1978 to 793 GW in 2008 (Tian, 2008; IEA Clean Coal Centre,

2010) (See Figure 1 for overview of main CO<sub>2</sub> point sources). An estimated 1,062 GW of new capacity will be installed in China by 2030, resulting in a total installed capacity of 1,936 GW—equivalent to the current installed capacity of the United States and European Union combined (IEA, 2009). Assuming China continues to rely on coal for power generation, CCS must be widely deployed in order to keep global greenhouse concentrations below 450 ppm CO<sub>2</sub>-equivalent (Liu & Gallagher, 2009).

Beyond the power sector, CCS presents China with opportunities to reduce emissions from industrial sources of CO<sub>2</sub>, particularly chemicals, petrochemicals, steel and cement. Opportunities for application of CCS in the chemical industry are especially promising, as chemical production produces high volumes of relatively pure CO<sub>2</sub> streams that could significantly reduce China's CO<sub>2</sub> emissions at modest cost if captured.

FIGURE 1. CONTRIBUTIONS OF LARGE POINT SOURCES OF CO<sub>2</sub> IN CHINA



Source : Dahowski et al., 2009.

## Box 1. INTEGRATED GASIFICATION COMBINED CYCLE (IGCC) (PRE-COMBUSTION)

IGCC technology converts solid fuels (such as coal, oil, biomass and waste) into synthetic gas (syngas) for the purposes of generating electricity and/or feedstock for the production of chemicals and fuels. In a gaseous state, carbon dioxide (CO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), nitrous oxides (NO<sub>x</sub>), mercury and particulates can be more easily and cost-effectively removed. Once these substances are removed, the syngas can be used to power a gas turbine for the generation of electricity. In a combined cycle plant, waste heat from the gas turbine is then run through a steam turbine to generate additional electricity.

The process of transforming solid coal into syngas takes place in a gasifier in two distinct processes: gasification and an optional shift-reaction to increase the energy content of the product. Coal fuel is fed to the gasifier through one of a number of methods including fixed-bed, fluidized-bed, and entrained-flow. Coal or other feedstock is subjected to high temperatures (between 1,400° and 2,800° F) and pressure, and mixed with carefully controlled amounts of steam and air or oxygen, which is supplied by an oxygen plant. The gasification process breaks apart the chemical bonds of the coal and results in a syngas consisting of a mixture of carbon monoxide (CO), CO<sub>2</sub>, hydrogen (H<sub>2</sub>) and other trace substances. If the syngas is shifted in a water-gas reaction (syngas reacts with water vapor to produce hydrogen and carbon dioxide in an exothermic reaction: CO+H<sub>2</sub>O → CO<sub>2</sub>+H<sub>2</sub>), the reaction produces H<sub>2</sub>, which enriches the gas or liquid fuel, and CO<sub>2</sub> that becomes highly concentrated in high pressure gas. The highly concentrated CO<sub>2</sub> can be separated from the syngas prior to being supplied to the gas turbine, at lower variable cost than compared to post-combustion removal from flue gases in conventional pulverized coal plants, where CO<sub>2</sub> is at lower pressure and diluted with other exhaust gases. IGCC also enables the economically efficient removal of sulfur, nitrogen oxide, mercury, and particulates from the syngas using such methods as activated carbon filtration and sorbents, resulting in much less pollution than conventional coal-fired power plants.

IGCC plants currently in operation can achieve efficiencies of 40 to 45 percent on a lower heating value basis (Liu et al., 2008; Higman, 2009). If waste heat is used in industrial processes or to heat buildings, efficiencies potentially could be increased to as high as 85 percent (American Council for an Energy-Efficient Economy, 2010).

There are over twenty IGCC plants for power production that burn coal, petcoke and/or oil operating in Europe, the United States and Asia. However, the power industry still has limited operational experience with IGCC plants. Some of these plants have taken years to reach their maximum availability, which is still lower than conventional pulverized coal units. There is general consensus that another five to ten plants are necessary to provide the learning and testing required to optimize the operation of IGCC technology.

## Box 1. CONTINUED

### SELECTED COAL-FIRED IGCC POWER GENERATION PLANTS IN OPERATION TODAY

Power station	Buggenum	Wabash River	Tampa Polk	Puertollano	Vresova
Country	Netherlands	USA	USA	Spain	Czech Republic
Time of operation	1994	1995	1996	1997	1996
Net capacity MW	253	265	250	300	400
Gasifier	Shell	Destec	Texaco	Prenflo	Lurgi
Gas Turbine	V94.2	GE-7FA	GE-7FA	V94.3	GE-9E
Efficiency % (LHV)	43.3	40	37.8	45	Not available
Availability	86.1%	>80%	77%	66.1%	90%+

Source: Liu et al., 2008; Higman, 2009

## Box 2. GASIFICATION TECHNOLOGY IN CHINA

Gasification technology has been used for many years in China in the chemicals industry. GE Energy (formerly Texaco technology) has issued 38 licenses, Shell has licensed 19 plants, and Siemens is building 5 coal gasification plants for chemical production in China (IEA Clean Coal Centre, 2010; Cai, 2010). Experience gained through the construction and operation of imported gasifiers has helped China develop its own large capacity gasifiers for chemicals and power generation. Chinese gasifiers include the "Opposed Multi-burner Coal-water Slurry Gasifier" developed by East China University of Science and Technology (ECUST) based on a GE/Texaco gasifier; the "Two-staged Dry Feed Pressurized Coal Gasifier" developed by the Xi'an Thermal Power Research Institute (TPRI) based on a Shell design; and the "Two-staged Water-coal Slurry Gasifier" developed by Tsinghua University based on a GE/Texaco gasifier (Liu et al., 2008).

## Box 3. POST-COMBUSTION, OXY-FUEL AND CHEMICAL LOOPING TECHNOLOGIES

### Post-Combustion

Post-combustion separation and recovery of CO<sub>2</sub> involves the treatment of flue gas, usually through a chemical solvent absorption method (such as monoethanolamine). Reuse of the chemical agent requires low-pressure steam to break the bonds between the absorbent and the CO<sub>2</sub>, and the compression of the recovered CO<sub>2</sub> into a supercritical liquid state (about 100 atmospheres) to facilitate transport and sequestration. Removal of sulfur dioxide, nitrogen dioxide and particulates occur in separate processes, such as limestone absorbent for desulfurization and bag-type particulate removal. The largest post-combustion capture demonstration plant is in China and other smaller projects are taking place in North America and Europe:

- 845 MW China Huaneng Power Plant in Beijing;
- 180 MW AES Warrior Run coal-fired power plant in Cumberland, Maryland;
- 300 MW SaskPower Oxyfuel lignite-fired power plant in Canada; and,
- 280 MW power and 350 MW heat Statoil natural gas combined heat and power plant at Mongstad, Norway.

### Oxy-Fuel Combustion

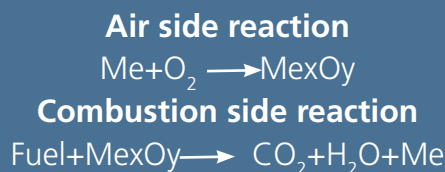
Oxy-fuel combustion technology utilizes oxygen instead of ambient air for combustion of fossil fuel. Oxy-fuel processes involve the removal of nitrogen from ambient air, producing a near pure stream of oxygen that is used as an oxidant for fossil fuel combustion. The resulting flue gas contains high concentrations of CO<sub>2</sub> (generally exceeding 80 percent by volume), water vapor and small volume particulates, NO<sub>x</sub>, SO<sub>x</sub> and trace elements. These elements can be removed from the flue gas, resulting in a CO<sub>2</sub> stream available for other applications or sequestration. Oxy-fuel combustion also reduces NO<sub>x</sub> emissions, due to the reduced nitrogen content in the combustion chamber. The oxy-fuel process is advantageous for power generation and industrial processes such as glass and metal production that require high temperatures. The higher efficiencies associated with combustion at higher temperatures and higher concentrations of CO<sub>2</sub> in the flue gas offer the potential to reduce the overall cost of CCS as compared to other capture technologies. No pilots using this technology have yet been completed in China.

### Chemical Looping

Chemical looping combustion for CO<sub>2</sub> capture is technology currently being developed at pilot scale that releases energy based on chemical reaction through the indirect contact of fuel and air without flame combustion. In its basic form, metal oxide (Me<sub>x</sub>O<sub>y</sub>) and metal (Me) are circulated in a loop in two continuous reactions. In the air side reaction, oxygen is separated from air and then combined with metal to form metal oxide. In the combustion side reaction, metal oxide is then combined with fuel (typically coal) to produce CO<sub>2</sub>, H<sub>2</sub>O in steam form, and regenerated metal (Me). The fuel obtains oxygen for combustion from the metal oxide without direct contact with air, eliminating the potential introduction of N<sub>2</sub>. The reaction takes place at low-temperature, which reduces the corresponding production of NO<sub>x</sub>. The resulting combustion product is high-concentration CO<sub>2</sub> and steam, from which CO<sub>2</sub> can be separated

## Box 3. CONTINUED

and recovered through steam condensation. The steam is used to drive a steam turbine in power applications. Chemical looping is less capital intensive compared to IGCC because the oxidation process eliminates the need for an air separation unit and the capture process can be highly efficient because it produces a relatively pure stream of CO<sub>2</sub> and steam, from which CO<sub>2</sub> can be separated simply by condensing the steam without the energy penalty associated with IGCC.



**TABLE 2. ENVIRONMENTAL PERFORMANCE OF IGCC AND SELECTED COAL-FUELED TECHNOLOGIES**

Parameter	Pulverized Coal with Advanced Pollution Controls*	Atmospheric Fluidized-Bed Combustion with Selective Non-Catalytic Reduction (SNCR) for NO <sub>x</sub> Reduction	Pressurized Fluidized-Bed Combustion (Without SNCR)	IGCC Plant
SO <sub>2</sub> (lb/MWh)	2.0	3.9	1.8	0.7
NO <sub>x</sub> (lb/MWh)	<1.6	1.0	1.7 – 2.6	0.08
PM10 (lb/MWh)	<0.3	0.12	0.13 – 0.26	<0.14
CO <sub>2</sub> (lb/kWh)	2.0	1.92	1.76	1.76
Chloride as HCl (lb/MWh)	0.01	0.71	0.65	0.007
Fluoride as HF (lb/MWh)	0.003	0.05	0.05	0.004
Cyanide as HCN (lb/MWh)	0.0003	0.005	0.005	0.00005
Ammonia (lb/MWh)	0	0.001	0.001	0.004
Water Use (gallons/MWh)	1,750	1,700	1555	750 – 1,100
Total Solids (lb/MWh)	367 (Ash and Gypsum)	494 (Ash and Spent Sorbent)	450 (Ash and Spent Sorbent)	175 (Slag and Sulfur)

Source: Ratafia-Brown et al., 2002. CO<sub>2</sub> emissions are based on coal with 67% total carbon content.

\*Pulverized coal with selective catalytic reduction, electrostatic precipitator, and flue gas desulfurization.



## CCS POLICY AT A CROSSROADS

Until recently, China had not elaborated a domestic policy to promote the development and deployment of CCS. In 2005, CCS technology was first integrated into *China's National Medium- and Long-term Science and Technology Development Plan*, which guides science and technology development during the 2006 to 2020 period. In 2007, China's National Climate Change Program set a goal to strengthen the development and dissemination of advanced technologies, including CCS (NDRC, 2007a). That same year, *China's Scientific and Technological Actions on Climate Change* prioritized research, development and demonstration (RD&D) of CO<sub>2</sub> capture, utilization and sequestration technologies.

Notwithstanding these policies, China's leadership has not yet mandated implementation of CCS as a part of its policy for reducing CO<sub>2</sub> emissions (MOST et al., 2007). China's Ministry of Science and Technology (MOST) has advanced CCS-related RD&D through its administration of China's technology development programs. As CCS technology enters the deployment stage, the National Development and Reform Commission (NDRC), which is responsible for economic planning and climate change policy, exercises jurisdiction over CCS projects through its implementation of China's low carbon and energy efficiency targets, setting electricity tariffs and approving new power plants and industrial facilities. To date, GreenGen is the only IGCC power project that has received NDRC approval. According to a former NDRC official, China's policymakers are unlikely to require CCS, or approve it for broad deployment, until technological advances resolve the loss of energy efficiency resulting from the additional energy requirements of carbon capture, reduce the high capital costs of CCS, and address concerns regarding the safety of CCS when deployed at large scale (Tian, 2010). China's embracing CCS technology to reduce its carbon emissions will ultimately depend upon further technology development.

Yet, the extent of CCS activity taking place in China puts China's CCS policy at a crossroads. The government, through the National Energy Administration, NDRC and other agencies, is working with stakeholders such as the World Bank and the Asian Development Bank on CCS projects and capacity building for the power sector. All five large state-owned utilities (Huaneng, Datang, Huadian, Guodian and China Investment Power Corporation) are actively pursuing carbon capture projects that incorporate sequestration components. Shenhua Group and PetroChina expect to complete China's first CCS facility by 2010. In addition to the 863 Program RD&D projects described in this article, MOST, NDRC and industry stakeholders have announced plans for fourteen additional IGCC plants for power, liquid fuel and/or chemical production that are in the early definition and design stages (Cai, 2010). While broad implementation of CCS domestically would require advances in technology, the number of projects being implemented and planned in China strongly suggests that China's policymakers are expanding China's leadership role in developing CCS technologies, and that these CCS activities will ultimately cause policy to evolve.

## CHINA'S CCS TECHNOLOGY DEVELOPMENT EFFORTS

China's CCS activities currently focus on technology development and domestic capacity building, as well as knowledge sharing through demonstration projects and international cooperation. China's RD&D programs focus on developing capture technology for power and industrial gas applications, utilizing CO<sub>2</sub> for revenue generating activities such as recovering hydrocarbons, and assessing and testing China's geological sequestration capacity. China is developing various capture technologies with emphasis on pre-combustion IGCC technology. Enhanced oil recovery (EOR) and enhanced coal bed methane recovery are also

being considered to support CCS because these applications provide additional revenue to offset its cost. Increasing attention is being placed on geologic assessment while the development of policy and regulation are in the early stages. China has yet to start the development of a CO<sub>2</sub> transportation network, such as dedicated pipelines, which would be required for full-scale deployment of CCS. Our review focuses on RD&D projects sponsored by MOST and other selected projects that are at the implementation stage.

### DRIVING DOWN CAPTURE COSTS

China's RD&D programs are appropriately designed to increase the efficiency and to reduce the overall cost of CCS, primarily by focusing on capture technology, which accounts for approximately 90 percent of the cost of CCS (Al-Juaied & Whitmore, 2009). There are four types of carbon capture technologies currently being developed for application in CCS and other industrial processes in China and other countries: (1) integrated gasification combined cycle (IGCC) (pre-combustion); (2) post-combustion capture; (3) oxy-fuel combustion; and (4) chemical looping.

IGCC is the focus of several pilot projects in China. (See Box 1). Gasification technology has been used in China's chemical industries for many years. (See Box 2). It potentially offers the best economic and environmental performance

of any other existing pollution control technologies, particularly in terms of lower SO<sub>2</sub> and NO<sub>x</sub> emissions, water use efficiency, and solid waste production. (See Table 2). Post-combustion capture and chemical looping technologies are also being developed in China. (See Box 3).

### China's Pilot Projects for Capture Technologies

The Chinese government's 863 Program advances a wide range of strategic technologies with the goal of making China technologically independent. MOST, which administers the 863 Program, has mandated and partially funded the development and construction of two IGCC coal-to-liquids plants, three IGCC demonstration power plants, and one gas turbine demonstration project for use with IGCC. MOST is providing up to 350 million Yuan in seed funding for these projects. None of the plants will sequester carbon dioxide upon completion; sequestration would require further modifications to these plants and development of transportation and sequestration infrastructure. However, these projects are an important step in developing the capture component of CCS in China.

TABLE 3. 863 PROGRAM COAL-TO-LIQUIDS DEMONSTRATION PLANTS

Company	CTL Capacity	Location
Yankuang Group	100,000 tons/year	Yulin, Shaanxi Province
Lu'an Group	160,000 tons/year	Lu'an, Shanxi Province

### 863 Program Coal-To-Liquids Demonstration Plants

The 863 Program supports two coal-to-liquids demonstration projects that use IGCC technology (See Table 3). These projects may be adapted to produce power by diverting a portion of the syngas through a turbine to

generate electricity. Coal-to-liquids and other industrial applications provide easier to operate, lower cost plants to demonstrate CO<sub>2</sub> separation using IGCC technology, relative to power generation and polygeneration (See discussion of polygeneration below).

TABLE 4. 863 PROGRAM IGCC DEMONSTRATION PLANTS

Power Generation	Company	Gasifier	Location
250 MW GreenGen	China Huaneng Group	TPRI Two-Stage Dry-feed Pressured Coal Gasifier	Tianjin, China
230 MW Greenfield	China Huadian Corp.	ECUST Opposed Multi-nozzle Water-coal Slurry gasifier	Hangzhou, Zhejiang
800 MW Greenfield	Dong Guan Power & Chemical	To be	50 million tons

#### Program 863 IGCC Demonstration Plants Huaneng GreenGen Demonstration Project

China Huaneng Group, the largest power generation company in China, initiated the GreenGen project in 2004 to research, develop and demonstrate a near-zero emission coal-based power plant. The project's first phase is to develop a 250 MW, 2,000 tons of coal per day IGCC plant using domestic gasification technology and GE 9E-class gas turbines. Xi'an Thermal Power Research Institute (TPRI), which is part of the China Huaneng Group, developed the dry-feed gasifier used in the plant and provides systems integration and technical expertise. During the first phase, GreenGen will also research and test key technologies for the next stages, including hydrogen production through coal gasification, fuel cells, and CO<sub>2</sub> capture and sequestration. GreenGen's first phase may also include a 30,000-ton CO<sub>2</sub> test injection into a nearby oil field. The second phase (2012–2014) will optimize the gasification technology. Further research and development will be conducted on CCS technologies, including EOR with PetroChina. The third phase (2014–2016) will be the construction

of a 2×400 MW IGCC for power generation with CCS. The plant will release nearly zero emissions, capturing 1 million tons of CO<sub>2</sub> per year and injecting it for EOR.

GreenGen is 52 percent controlled by the state-owned Huaneng Group. GreenGen's other owners, each holding a 6 percent share, are China's other large power producers (Datang Group, Huadian Corp, Guodian Corp and China Power Investment Corporation), top coal mining companies (Shenhua Group, China Coal Group), China's State Development and Investment Corporation (SDIC), and U.S.-based Peabody Energy Corporation. GreenGen is projected to cost about 7 billion Yuan. The 863 program provided startup funding and the Asian Development Bank provided construction loans and grants (described below).

#### Huadian Banshan 230MW Greenfield Project

Huadian Power International Corporation is developing a 230 MW IGCC plant at the Huadian Banshan power facility located in Hangzhou city, Zhejiang province. The plant is tentatively set to start operation in 2010. The facility employs a single water-coal-slurry gasifier

with a capacity to burn about 2,000 tons of coal per day. The total cost of the project is expected to be 2 billion Yuan. The project research team includes the National Power Plant Combustion Engineering Technology Research Center, the Institute of Engineering Thermophysics of the Chinese Academy of Sciences, East China University of Science and Technology, Zhejiang Electric Power Design Institute and Hangzhou Huadian Banshan Power Generation.

***Dong Guan Power & Chemical Company  
800 MW Sun State Project and 120  
MW Tian Ming Retrofit Project***

Dong Guan Power & Chemical Company (DGPC), a majority privately-owned power company located in Dong Guan city, Guangdong province, received an 863 award to develop and construct an 800 MW IGCC facility, known as the Sun State Island IGCC Power Station (“Sun State”), in Dong Guan. DGPC plans to commence construction in 2011. Sun State will use four GE 9E gas turbines, each of which will produce 200 megawatts of electricity, and has not yet selected the gasifier supplier. It is expected to cost approximately 6.1 billion Yuan.

In late 2009, DGPC started retrofitting its existing Tian Ming power plant to a 120 MW IGCC facility. Although not part of the 863 program grant, the Tian Ming facility will provide DGPC with valuable experience in developing the much larger Sun State IGCC project. In addition to generating electricity, the Tian Ming plant will be equipped to divert a portion of the syngas for use as feedstock for chemical production (methanol and ammonia). The project is the only stand-alone IGCC retrofit of a power plant anywhere in the world to our knowledge. The Tian Ming project will employ a combination of domestic Chinese technologies and a gasifier developed by the U.S. firm Kellogg, Brown & Root to be built primarily in China. The plant will use its existing GE gas turbines, locally made steam turbines and locally made heat recovery systems.

Chinese firms will provide engineering design services and control systems.

***Shenyang Gas Turbine/ IGCC  
Demonstration Project***

The Shenyang IGCC project, located in Shenyang, Liaoning province will have 1,000 MW capacity consisting of 2×200MW IGCC units and 2×300MW conventional units. This demonstration project is listed in the 863 Program as “Fabrication of R0110 Gas Turbine Based on Mid-/Low-Heat Value Fuels and Its Application in Engineering of IGCC Power Station.” One of the objectives of the project is to test the China-made heavy-duty R0110 gas turbine with medium- and low-caloric fuels in an IGCC power station. The managing committee of Shenyang High Tech Industrial Development Zone and China Power Investment Corporation oversees this project.

***863 Program Polygeneration Projects***

A polygeneration IGCC plant produces electricity and diverts a portion of the synthetic gas from electricity generation as a feedstock to produce chemical elements and compounds for liquid fuels and other chemical products. Common chemical products include ammonia (fertilizer), methanol (fuel) and hydrogen. By producing high value chemicals, polygeneration could potentially improve the economic performance of IGCC power plants, and allow greater operational flexibility to optimize a project for market conditions.<sup>3</sup> However, cycling an IGCC plant for changing power demand and chemicals production involves significant engineering and operating challenges, which must be mastered in order to achieve potential gains from polygeneration.

China has developed two IGCC polygeneration plants in collaboration with the Chinese Academy of Sciences and industry stakeholders, and a number of other polygeneration plants are under development. The Yankuang IGCC plant in Shandong province produces 60 MW of power and up to

240,000 tons of methanol and 200,000 tons of acetic acid per year using coal. The facility uses a gasifier developed by the East China University of Science and Technology based in part on a GE/Texaco gasifier design. The plant began operation in April 2006, and started generating power in May 2008. According to the company, this plant operates at approximately 36 percent thermal efficiency as a power generator.

The second IGCC polygeneration project in Quanzhou City, Fujian province commenced operation in 2009. It was developed by the Fujian Refining & Chemical Company with Fujian province, ExxonMobil, Sinopec, and Saudi Aramco as joint partners. The project produces 280 MW of power and several chemical products.

#### ***Huaneng Post-Combustion CO<sub>2</sub> Capture Demonstration Projects***

China completed its first Post-Combustion Capture (PCC) demonstration project in July 2008, in collaboration with the Australian Commonwealth Scientific and Research Organization (CSIRO) and China's TPRI, under the Asia Pacific Partnership for Climate and Development. TPRI built and operates the PCC pilot plant at the Huaneng Beijing Thermal Power Plant, using domestically made amine capture equipment based on technology licensed by CSIRO. The facility is recovering more than 85 percent of CO<sub>2</sub> from flue gas that is run through the capture process; however, most of the flue gas is vented. The plant captures only one percent of total CO<sub>2</sub>—or about 3,000 tons of CO<sub>2</sub> annually, which will be used in the soft drinks industry. We understand that this system captures CO<sub>2</sub> at \$40/t (Friedmann, 2009), which would be significantly less expensive than other commercial capture systems for power plant applications.

Based on the Huaneng-CSIRO project, a second PCC project is being built at the Huaneng Shidongkou No. 2 Power Plant in Shanghai. The project is expected to achieve annual capture of 100,000 tons of CO<sub>2</sub>—about

three percent of the total CO<sub>2</sub> emitted from the plant. Like the Beijing project, the CO<sub>2</sub> will be used for industrial purposes.

#### ***CPIC Post-Combustion CO<sub>2</sub> Capture Project***

In early 2010, China Investment Power Corporation completed a post-combustion capture facility at its coal-fired Hechuan Shuanghuai Power Plant in Chongqing, capable of processing 50 million cubic meters of flue gas (less than 1 percent of total flue gas). The system was designed and built with domestic equipment by Yuanda Environmental Protection Engineering Company Ltd, a CPIC subsidiary at a reported cost of 12.4 million Yuan. The facility can produce up to 10,000 tons of CO<sub>2</sub> per year at a cost of 394 Yuan per ton. With prevailing prices for CO<sub>2</sub> of 620 Yuan per ton, the facility is expected to generate a profit, with a payback period of 5 to 6 years (Cockerill, 2010).

#### ***Shenhua Coal-to-Liquids Project***

Shenhua Group, the world's largest coal company, developed and operates a \$1.46 billion direct coal liquefaction plant with a hydrogen facility in Ordos, Inner Mongolia employing Chinese-developed technology. The liquefaction plant was completed in late 2008, started limited operations in December 2008, and became fully operational in 2010. China National Petroleum Corporation, the country's largest oil producer, designed the capture part of the plant, which will be completed by 2010 at an estimated cost of 210 million Yuan (*China Daily*, 2010). The project plans to inject into the Ordos Basin 100,000 tons of CO<sub>2</sub> per year, and 2.9 million tons per year from the hydrogen facility by 2012 (Friedmann, 2009), making it the first sequestration facility in China. The project has been supported by collaboration between the NDRC and U.S. Department of Energy (DOE), with technical support from West Virginia University, the National Energy Technology Laboratory and Lawrence Livermore National Laboratory (described below).

***Oxy-fuel Combustion and Chemical Looping***

Several Chinese research institutes are developing oxy-fuel combustion and chemical-looping technology. Zhejiang University, in collaboration with the French company Air Liquide and Tsinghua University, is developing oxy-fuel combustion processes. The Chinese Academy of Sciences' Institute of Engineering Thermophysics and Southeast University, Nanjing are researching chemical looping technology.

## CHINA'S CARBON UTILIZATION INITIATIVES

Chinese and foreign companies and government institutions are researching enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced coalbed methane recovery because these applications are significant revenue-producing economic activities that at the same time can sequester CO<sub>2</sub>. EOR and EGR in particular, could be important during the early stages of development of CCS in oil and gas fields as preparation for deployment in saline formations (See Box 4).

### **National Basic Research Program of China (973 Program): Geologic Carbon Storage with Enhanced Oil Recovery (2006–2011)**

China's 973 Program conducts basic research on the geological, physical and chemical aspects of geologic carbon sequestration and EOR, non-linear flow mechanics problems of EOR and carbon capture and anti-corrosion problems. Funding for the research program is 35 million Yuan. The program's objectives are to enhance oil recovery ratios through the use of CO<sub>2</sub>, increase profitability of oil operations and mitigate CO<sub>2</sub> emissions.

**PetroChina**

PetroChina conducted CO<sub>2</sub> injections in its oil fields before discontinuing the practice due to

a shortage of CO<sub>2</sub> resources. PetroChina has also conducted CO<sub>2</sub> injections for EOR in cooperation with MOST and several research universities. Experimentation with EOR has been conducted in the Jiangsu fields, the Jilin fields, the Changun fields, the Zhongyuan fields, the Ordos Basin (Inner Mongolia), and the northern Tarim Basin (Xinjiang province) (Liu et al., 2008; Friedmann, 2009). PetroChina has also experimented with CO<sub>2</sub> injection for enhanced coal bed methane recovery (Friedmann, 2009).

**China-Japan EOR Project**

China and Japan will commence a project to capture 1 to 3 million tons of CO<sub>2</sub> annually from the Harbin Thermal Power Plant in Heilongjiang province, and possibly other plants, transport it 100 km by pipeline, and inject it into China's Daqing oil field for both EOR and permanent sequestration. The oil field currently produces over 40 million tons of oil annually; the project is expected to increase production by 1.5 to 2 million tons and to demonstrate the field's ability to permanently sequester over 150 million tons of CO<sub>2</sub> in the future. Japan's Research Institute of Innovative Technology for the Earth, Toyota Motor Company, JGC Corporation, and China National Petroleum Corporation also participate in the project (Gasnova, 2008a and 2008b).

**China Coal Bed Methane Technology/CO<sub>2</sub> sequestration project**

China's Ministry of Commerce, China United Coal Bed Methane Corp. and the Canadian government completed a project to transfer Canadian technologies to assess coal beds for the recovery of methane and sequestration of CO<sub>2</sub>. The project involved site identification, small- and large-scale tests, evaluation and training, and contributes to improved environmental management and safer working coal-mining practices in China (Alberta Research Council, 2007).

## Box 4. ENHANCED OIL RECOVERY AS A DRIVER FOR CCS

In enhanced oil recovery (EOR), CO<sub>2</sub> is injected into an oil reservoir in order to increase well pressure and reduce the viscosity of oil, thereby increasing the flow of oil and production. CO<sub>2</sub> floods can increase a field's production by 7 to 15 percent of original oil in place and extend the life of a field by 15-30 years (Moritis, 2001). One ton of CO<sub>2</sub> can lift anywhere from 1.5 to 6.5 barrels of oil, with an average of about 2.5 barrels (Martin & Taber, 1992). Results vary by field characteristics: porosity, permeability, miscibility, gravity of the oil, operating depth, original and current reservoir pressure, location of oil in reservoir, operating temperature of reservoir, and geologic structure (e.g., dolomite, sandstone, carbonaceous).

Results also depend on operating decisions whether CO<sub>2</sub> injection is conducted solely to enhance oil production or also to achieve CO<sub>2</sub> sequestration. A portion of the CO<sub>2</sub> is separated and recovered from the lifted oil and re-injected into the reservoir; the remaining portion of the CO<sub>2</sub> is trapped in the reservoir. Through repeated cycles, a significant portion of the CO<sub>2</sub> can be permanently sequestered, depending on operating decisions. A similar process is followed for recovery of natural gas in fields.

By some estimates, first generation CCS plants will add 8-12 ¢/kWh to the cost of electricity produced compared to conventional plants, or approximately \$120-180/ton of CO<sub>2</sub> avoided. Based on a hypothetical plant assuming 2008 capital costs, EOR revenues can offset the additional cost of CCS with an oil price of approximately \$75 per barrel (Al-Juaied & Whitmore, 2009).

### GLOBAL PARTNERSHIPS EXPLORE CHINA'S GEOLOGIC STORAGE POTENTIAL

Although China has not yet completed a comprehensive geologic survey for CCS, Chinese and foreign oil companies, research institutions and government laboratories have conducted geologic assessments that provide a starting point for assessing China's sequestration resources.

China's Ministry of Science and Technology, together with the Australian government's Geoscience Australia, launched the China Australia Geological Storage of CO<sub>2</sub> (CAGS) project to develop China's capacity to assess potential CO<sub>2</sub> sequestration sites. CAGS is funded by the Australian government under the

Asia Pacific Partnership for Clean Development and Climate. The Administrative Centre for China's Agenda 21, China's Academy of Sciences, China Geological Survey, and China University of Petroleum also participate in CAGS.

Researchers from the Chinese Academy of Sciences, Institute of Rock and Soil Mechanics and the Environmental Studies Department of China University of Geosciences together with the Battelle-Pacific Northwest National Laboratory are estimating China's sequestration capacity based on publicly available data originally produced by Geoscience Australia. Results show that China has over 3,000 gigatonnes of CO<sub>2</sub> sequestration capacity, with deep saline formations accounting for 99 percent of the total capacity. Even if only 10 percent of total theoretical capacity is available

for sequestration, China has enough capacity to store over 100 years' of its CO<sub>2</sub> emissions from large point sources. Importantly, over 90 percent of the country's large CO<sub>2</sub> point sources (defined as emitting at least 100,000 tons of CO<sub>2</sub> per year) are within 100 miles of onshore sequestration reservoirs and, for a majority of the sites, costs of transport, storage and monitoring are estimated between \$2 to \$9/tCO<sub>2</sub> (Dahowski et al., 2009).

In 2009, Stanford University's Global Climate and Energy Project awarded nearly \$2 million to initiate an international collaboration with Peking University, China University of Geosciences at Wuhan and the University of Southern California to address fundamental issues associated with large-scale sequestration. The three-year program integrates geological modeling, reservoir simulation and laboratory experiments to develop methods for sequestration of CO<sub>2</sub> in saline aquifers in China.

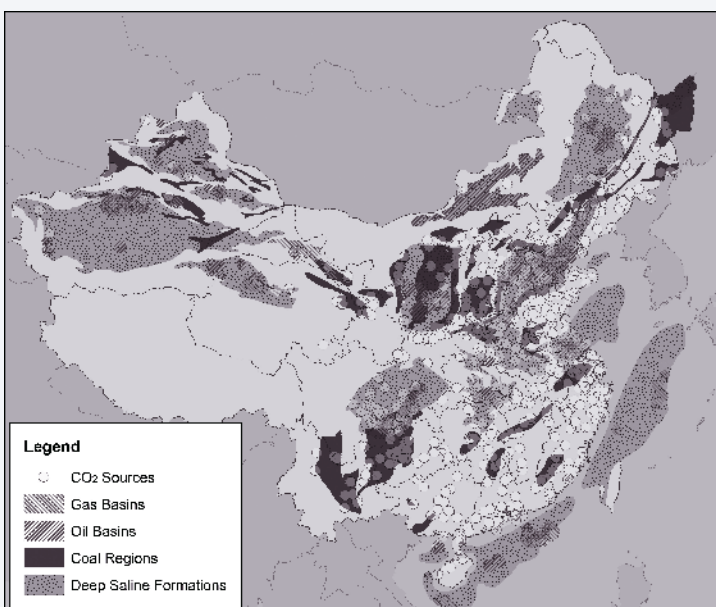
Researchers from West Virginia University and Lawrence Livermore National Laboratory

are modeling the Ordovician in the Ordos Basin, located in the western part of China's northern table, as part of an effort to assess its potential sequestration capacity to support the Shenhua Group coal liquefaction project (described above). The modeling is based on a hypothetical 10,000 ton per year CO<sub>2</sub> injection into a reservoir approximately 3,500 meters below the surface and estimates water chemistry, permeability, plume size and saturation.

## INTERNATIONAL KNOWLEDGE SHARING

Chinese government, business, and research institutions are engaged in a number of international efforts to foster cooperation on the development of CCS. Outlined below are some of the more significant partnerships that are specifically dedicated to supporting CCS development in China. China also participates in other collaborative efforts that are designed to promote CCS globally (See Table 5).

### MAP 1. POTENTIAL SEQUESTRATION SITES IN CHINA



Dahowski, R., Xiaochun Li, Casie Davidson, Ning Wei, and James J. Dooley. (2009). Regional Opportunities for Carbon Dioxide Capture and Storage in China: A Comprehensive CO<sub>2</sub> Storage Cost Curve and Analysis of the Potential for Large Scale Carbon Dioxide Capture and Storage in the People's Republic of China. Pacific Northwest National Laboratory.



**Cooperation Action within CCS China-EU (COACH)** is a Sino-EU research project aimed at creating ongoing cooperation between China and Europe. COACH was launched in 2006 with funding from the EU's 6th Framework Program for Research. Focused on developing new energy technology options for China that employ CCS, including use of CO<sub>2</sub> in enhanced oil recovery and enhanced coal bed methane recovery, COACH's key objectives include preparing the implementation of large-scale clean coal energy facilities by 2020 and coordinating activities performed under the EU-China Memorandum of Understanding on Near Zero Emissions Coal.

**UK-China Near Zero Emissions Coal (NZEC)** is a joint venture initiative between the United Kingdom's Department of Environment, Food and Rural Affairs and Department of Trade & Industry, and China's MOST, to explore options for near-zero emissions coal in China, build capacity for CCS and construct and operate a CCS demonstration plant. COACH and NZEC are part of the EU-China Partnership on Climate Change. Chinese partners include the Administrative Centre for China's Agenda 21, Tsinghua University, Zhejiang University and GreenGen.

**UK-China CAPPCCO Project.** Chinese Advanced Power Plant Carbon Capture Options (CAPPCCO) is sponsored by the United Kingdom's Department for Business, Enterprise & Regulatory Reform, MOST and China's Environmental Transformation Fund. CAPPCCO seeks to develop and define options for integrating capture technologies with advanced Chinese pulverized coal power plants to allow rapid CO<sub>2</sub> emission reductions, assess performance of advanced non-CO<sub>2</sub> pollutant control technologies on Chinese coals, and identify and engage key stakeholders to facilitate information transfer. CAPPCCO also plans to finance capture ready and capture retrofit plants. Participants include Imperial College London, University of Cambridge,

Doosan Babcock, Alstom, Harbin Institute of Technology, National Power Plant Combustion Engineering Technology Center, Harbin Boiler Company, Yuanbaoshan Power Plant, Datang International Power Generation Company and Xi'an Jiaotong University.

**The U.S.-China Joint Clean Energy Research Center** launched in July 2009 by the U.S. and Chinese governments will conduct CCS research.

**The IEA Clean Coal Technology Centre** conducts ongoing research and exchange on CCS in China. **The IEA Working Party on Fossil Fuels** is launching a CCS financing initiative with a focus on China.

**Harvard-MOST IGCC Initiative.** In 2002, Harvard University's Kennedy School of Government, together with MOST, established a series of dialogues between Chinese and U.S. academic and government officials on cooperation in the areas of clean coal technologies, IGCC and CCS. The initiative has sponsored research by Chinese academics and government officials in the United States on clean coal technology and policy, and has been instrumental in supporting U.S. government policy development on clean coal in China. The initiative is now operated with Tufts University's Fletcher School of Law and Diplomacy.

**Natural Resources Defense Council** is preparing a study identifying facilities that produce pure CO<sub>2</sub> streams in China, primarily in the chemicals and natural gas industries that could be captured at low cost and sequestered. The study is intended to help potential project developers jump-start CCS in China (Qian et al., 2009).

**Asia Society and Center for American Progress** are jointly developing a roadmap for U.S.-China cooperation on CCS research, development and demonstration projects. This roadmap is an effort to help facilitate government-to-government cooperation.

**Business-to-Business Collaboration.** International business-to-business collaboration

is essential to technology transfer and development, and the ultimate adoption and diffusion of CCS technology. Business-to-business collaboration is well developed in China's coal-fired power sector in general (IEA Clean Coal Centre, 2010), and is increasing in CCS-related applications, for example, Kellogg, Brown & Root's involvement in the DGPC Tian Ming project and Peabody Energy's participation in GreenGen, both described above. In addition, China's largest power producer, Huaneng, and the third largest power producer in the United States, Duke Energy, signed a memorandum of understanding in August 2009 to develop technology for coal-based CCS. The Chinese energy company ENN Group and Duke Energy established a collaborative relationship in September 2009 to share information and develop coal-based carbon capture technology using algae and other clean energy technologies.

## INTERNATIONAL CCS FINANCING

The **European Union** and the **United Kingdom** have funded CCS research and project development in China through their COACH, NZEC and CAPPCCO projects (described above). In 2009, the European Commission announced it will fund a scoping study examining the feasibility of up to three CCS plants in China. The Commission plans to expand these funds in order to provide financing of between 300 to 500 million for the development of a commercial-scale CCS project in China (Carbon Capture Journal, 2009; Marin, 2010).

The **Asian Development Bank** (ADB) provided a loan of \$135 million to the GreenGen project to be used towards construction costs, and an accompanying grant of \$5 million from its Climate Change Fund to finance long-term maintenance contracts for the coal gasifier and gas turbines, and civil works associated with the air separation unit

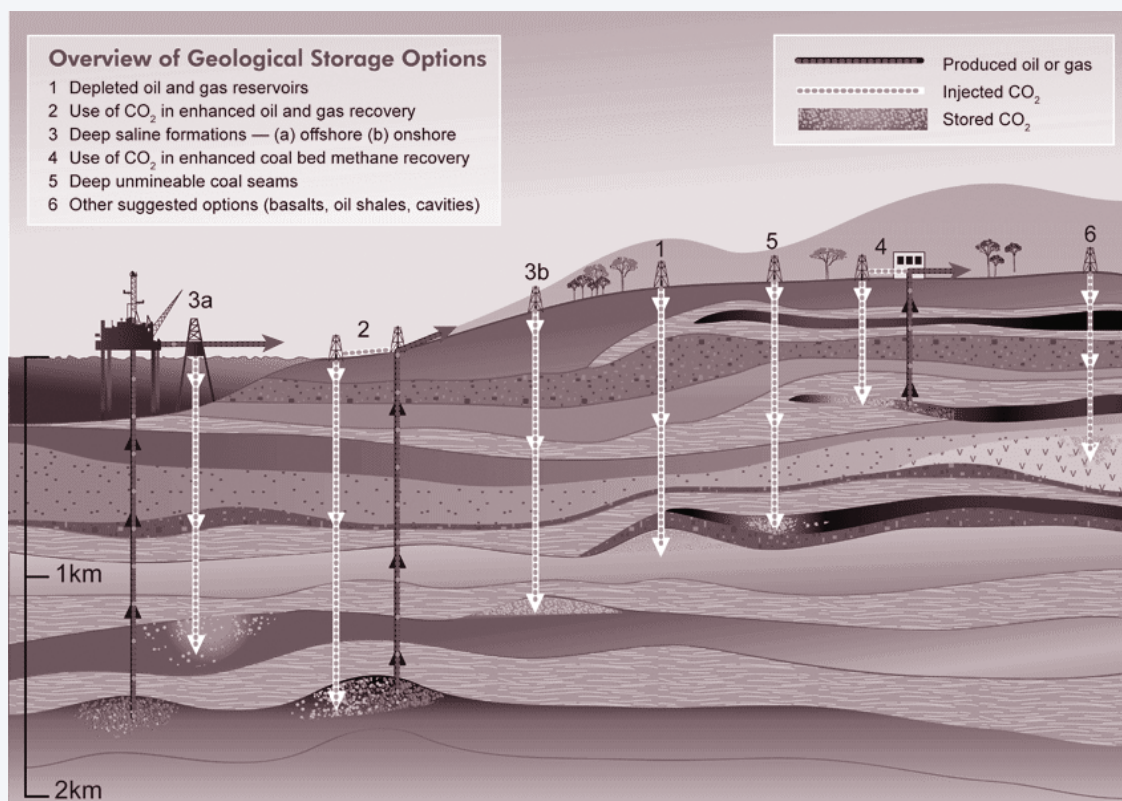


Photo Credit: The Cooperative Research Centre for Greenhouse Gas Technologies

**TABLE 5. CHINA'S PARTICIPATION IN INTERNATIONAL COLLABORATIVE INITIATIVES**

<b>Carbon Sequestration Leadership Forum</b>	Ministerial-level international climate change initiative focused on the development and diffusion of improved cost-effective technologies for CCS through collaborative efforts.
<b>FutureGen Alliance</b>	Public-private partnership to build a coal-fueled, near-zero emissions power plant in the United States with support from U.S. Department of Energy. Members include nine power producers and electric utilities. China Huaneng is a member of the alliance.
<b>Asia-Pacific Partnership (APP)</b>	Voluntary partnership among seven major Asia-Pacific countries—Australia, Canada, China, India, Japan, Korea and the United States—to address increased energy needs and the associated issues of air pollution, energy security and climate change. APP supports development and deployment of cleaner, more efficient technologies.
<b>GeoCapacity</b>	Provides sequestration capacity data required for broad adoption of CCS in Europe and a framework for international cooperation and technology transfer for countries undertaking similar efforts. MOST joined GeoCapacity as a full project partner, and coordinates the participation of Tsinghua University and the Chinese Academy of Sciences in GeoCapacity research projects.
<b>CO<sub>2</sub> Capture Using Amine Processes: International Cooperation and Exchange (CAPRICE)</b>	CAPRICE is an international research project on amine and membrane capture technology among governmental, private sector and research organizations from ten countries. Tsinghua University participates on behalf of China.

and chemical island plant. ADB also provided \$1.25 million from its Climate Change Fund to support the NDRC, the Chinese Academy of Sciences and GreenGen to develop a CCS technology roadmap for China, which will include technological, legal/regulatory, financial and institutional capacity aspects. At the request of the Carbon Sequestration Leadership Forum,<sup>5</sup> ADB's Climate Change Fund also provided a \$350,000 technical assistance grant to support a study of barriers to implementing CCS demonstration projects in developing countries.

**The World Bank** launched its CCS Trust Fund in December 2009 to help spur CCS in developing countries, with initial funding of \$8 million contributed from Norway and the Global CCS Institute. In China, the CCS Trust Fund will strengthen the institutional capacity of China Power Investment Corporation, one

of the five large state-owned power companies in China, for the development and piloting of CCS technology, and to strengthen the technical capacity of the National Energy Administration and the NDRC for the assessment of IGCC, CCS and carbon capture and utilization proposals. The World Bank is working with China Power Investment Corporation, which is currently planning four IGCC projects, and intends to pilot CCS and carbon capture and utilization. The World Bank is funding Tsinghua University, through a grant to the NDRC, to develop a methodology to credit emissions reductions from polygeneration IGCC facilities under the Clean Development Mechanism. The methodology would credit emissions reductions resulting from power generation and production of feedstock for chemicals and liquid fuels (but not reductions from storage of CO<sub>2</sub>).

**The Global CCS Institute**, launched

in 2009 and supported financially by the Australian government, is funding a wide range of CCS activities in China, including the ADB's CCS program that is developing a CCS roadmap for China, the World Bank's CCS fund, and studies conducted by private sector and nongovernmental organizations on CCS in China. These efforts are part of its broader capacity building efforts, which span technical, regulatory, financial, public engagement, and knowledge sharing aspects of CCS. Ultimately, the Global CCS Institute is seeking to help finance demonstration-scale projects globally, including in China.

### BUILDING UP CCS REGULATIONS AND POLICY

The development of CCS technology has moved faster than supporting policy, which could explain some of the gaps in China's CCS supply chain. To help fill these gaps, the World Resources Institute, together with Tsinghua University and Chinese experts, is developing guidelines for deployment of CCS technology in China based on the guidelines WRI developed in the United States. The guidelines will include provisions for capture, transport and sequestration. The project is partly funded by the U.S. Department of State under the Asia Pacific Partnership.

The EU's Support to Regulatory Activities for Carbon Capture and Storage (STRACO<sub>2</sub>) Project, which supports the development and implementation of a comprehensive regulatory framework in the EU for CCS, includes a program to build EU-China cooperation on CCS under the EU and China Partnership on Climate Change. The program focuses on capacity building for China's policymakers and the identification of future joint activities in the CCS area. STRACO<sub>2</sub>'s China CCS program is coordinated with the Administrative Centre for China's Agenda 21.

### PRIORITIES FOR DEVELOPMENT OF CCS IN CHINA

China's efforts in CCS are nascent, yet impressive. In order to advance CCS, we identify five priority areas that require action by policymakers to develop, adopt and diffuse CCS technology in China.

***Making the Policy Case.*** China's CCS strategy must serve its development priorities, including technological and energy independence. CCS programs that emphasize the development of export markets for Chinese-developed technologies, enable the country to exploit domestic coal reserves, and produce environmental co-benefits beyond climate change, such as cleaner air and water, exemplify the factors necessary to attract support within Chinese policy circles. Ultimately, to gain support among policymakers, China's RD&D efforts must reduce the capital cost of CCS using domestic technology and increase its efficiency to reduce the energy penalty associated with CCS in power applications, or exploit the lower costs of capture in carbon-intensive industrial gas applications.

***Driving Down Capture Costs.*** The first CCS plants in developed countries are expected to be expensive, adding 8-12 ¢/kWh to the cost of electricity compared to conventional plants, or approximately \$120-180/tCO<sub>2</sub> avoided, based on 2008 capital costs. By some estimates, the capital costs for initial plants will be 70 percent higher than those of conventional plants, due to increase in costs associated primarily with the capture portion of the plant and decrease in net power output (Al-Juaied & Whitmore, 2009). To place this in perspective, for a 630 MW power plant built in North America, CCS would increase capital costs by approximately \$1.5 billion over that of a conventional plant.

The capture component is projected to account for over 90 percent of the cost of CCS. China's current efforts in CCS are appropriately focused on capture technologies, with projected

capital and operating costs substantially lower than those in the United States and Europe. China's projected costs for constructing IGCC plants are approximately one-third to one-half that of projects in the United States and Europe based on projects we have surveyed. This lower cost structure offers an opportunity for industrial collaboration. The development of domestic CCS technologies at low cost is also critical to adoption of CCS by China's policymakers and industry. One of China's potential contributions to combating climate change can be to scale up its industrial production of capture technologies so that they become affordable globally.

**Demonstration Projects.** Demonstration projects are an essential way to prove technology, identify and assess risks, test geologic conditions, and foster collaboration and learning. China's demonstration projects also promote the development of a supply chain that is necessary to build a domestic CCS industry. While they have appropriately focused on capture technology as a priority for reducing the cost of CCS technology and increasing its efficiency, China must broaden these projects to include geologic assessment, sequestration and eventually the construction of pipelines for CO<sub>2</sub> transportation if China is to adopt and broadly diffuse CCS technology. Programs such as the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) and the U.S. Department of Energy's Regional Carbon Sequestration Partnerships program could provide technical assistance and other resources for China's efforts to expand its demonstration projects to include assessment and sequestration.

**Regulatory Framework.** The adoption of CCS in China will require a regulatory framework appropriate to China's institutional and legal system. A regulatory system that could support widespread diffusion of CCS would at a minimum include guidelines governing the following areas:

- Performance requirements for CO<sub>2</sub> capture;

- Safety, operation and access standards for CO<sub>2</sub> transportation pipelines;
- CCS site selection, permitting, operation and closure;
- Long-term monitoring, remediation and financial responsibility for CCS sites;
- Health, safety and environmental liability; and,
- Liability for CO<sub>2</sub> leakage, including for CO<sub>2</sub> reduction credits or obligations.

**Financing and Technology Collaboration.** The future development of CCS in China provides an important opportunity for international collaboration to address climate change. We believe that high-profile international financial resources and cooperation can play an important role in China increasing its investments in domestic CCS programs. This is particularly important for demonstration projects that lack full financial resources from China's central government, or are not fully compensated through electricity tariffs.

CCS also presents an opportunity to promote collaboration in the joint development of technology and intellectual property. As CCS is a rapidly evolving field with significant potential for innovation and growth in the near future, joint technology collaboration could benefit both Chinese and foreign companies. Governments and international institutions must place a higher priority on financing technology collaboration and transfer in order to promote the adoption of CCS in China and other advanced developing countries.

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<sup>1</sup> Actions by developing countries under the Bali Action Plan are conditional upon their receiving adequate financial, technical and capacity building support—all while developing their economies in order to achieve poverty reduction.

<sup>2</sup> Xie Zhenhua, former head of China's state environmental protection agency and now the country's chief climate change negotiator, said that there is still a large gap in meeting the 2010 energy efficiency targets. Additionally, Zhang Lijun, China's Vice Minister in China's Ministry of Environmental Protection, noted in early June 2010 that China's sulfur dioxide emissions had risen by 1.2 percent year-on-year in the first quarter of 2010 -- the first jump since 2007. He stated that this trend has sounded the alarm for China's emissions reduction work and indicates "that the prospects of emissions cuts are not very optimistic" (AFP, 2010).

<sup>3</sup> One study concluded that polygeneration could potentially reduce capital expenditure by 11 percent for methanol and single-generation power systems (Liu et al., 2008).

<sup>4</sup> The Ordovician is a geologic period that lasted between 490 and 443 million years ago.

<sup>5</sup> The Carbon Sequestration Leadership Forum is a ministerial-level international climate change initiative that facilitates the development and deployment of technologies for CCS. For more information see: [www.cslforum.org](http://www.cslforum.org).

<sup>6</sup> Authors' calculations are based on figures from Al-Juaied & Whitmore (2009).

# 金木水火土

## FEATURE BOX

### **It's Hard to Build a Skyscraper from the Sky Down: Paving the Way for Subnational Cooperation on Climate Action Planning in the United States and China**

By Thomas Peterson, Anne Devero, and Zach Friedman

While the results of the December 2009 global climate talks were widely viewed as a failure, the Copenhagen Accord and related developments clarified the importance and effectiveness of subnational policy advancement as a reliable method for building and enacting national commitments and, in turn, the international agreements. In short, a bottom-up approach to climate policymaking is clearly needed as a precursor to higher-level commitments. As former President Clinton has remarked more than once regarding the Kyoto Protocol negotiations “it’s hard to build a skyscraper from the sky down.”

In the United States, the majority of leadership and innovation on climate policy in the last decade has occurred at the sub-national level, and going forward, state and local implementation efforts will be central to achieving real-world greenhouse gas (GHG) emissions reductions. In November 2008, within days after his historic election, then President-Elect Barack Obama gave much-publicized remarks at an international conference of sub-federal leadership convened by climate leader Governor Arnold Schwarzenegger that established a new U.S. policy of engagement and pursuit of national GHG targets that are consistent with and based largely upon the work and commitments of U.S. states.

If China and the United States—the world’s two largest emitters of GHGs—deliberately and cooperatively advance sub-national climate actions, the spillover effects to national

commitments in both nations, as well as actions by other key nations, are likely to be significant.

Since 2000, 34 U.S. states have undertaken or completed comprehensive climate action plans, including 24 plans facilitated by the Center for Climate Strategies (CCS)—a nonpartisan, nonprofit organization established in 2004 to help governments and their stakeholders tackle climate change issues by fostering consensus-based actions through collaboration and advanced technical assistance. Recent actions implemented by U.S. states are estimated to remove 535 million metric tons carbon dioxide equivalent by 2020. Scale-up analysis by CCS shows that full implementation of existing state action plans by all U.S. states would reduce GHG emissions to 27 percent below 1990 levels by 2020, with a net gain of 2.5 million jobs and \$248 billion in gross domestic product, while cutting household energy prices.

Historically, many national laws and policies in the United States originate at the state level and are followed by federal actions that create national frameworks, programs and governance (e.g., Clean Air Act, Clean Water Act, Civil Rights Act, Consumer Protection). The United States is not alone in this phenomenon; many countries, including China, base many national policies on local-level policy actions.

The role of the state and provincial actors was apparent at the UNFCCC COP-15 meeting in Copenhagen. The presence of governors, mayors and state agency officials



from around the world constituted the second largest delegation at COP-15. The numerous side-events and behind-the-scenes negotiations gave testimony to the increasing agenda to reduce GHG emissions at the sub-national level. Along with many other organizations, CCS and its strategic partner in China, the Global Environmental Institute (GEI), jointly presented side-events focused on the need to build a strong China-U.S. partnership on mitigating climate change at the subnational level. At the next UNFCCC COP-16 in Mexico, CCS and GEI plan to engage a wider range of global actors to promote the need for more ambitious climate mitigation initiatives at the sub-national level.

#### **CHINA'S CARBON INTENSITY AND ECONOMIC GROWTH TARGETS**

China is in the process of developing its 12th Five-Year Plan that starts in 2011. China's 11th Five-Year Plan had overall energy efficiency targets of 20% by 2010 for its provinces that were directed at the most energy intensive power and industrial sectors. The Chinese government is implementing a phased approach to fulfill its 40-45 percent carbon intensity reduction target by 2020. For the first time, the 12th Five-Year Plan will have carbon intensity targets incorporated at the provincial level. In terms of absolute GHG emissions reductions, when compared against baselines, carbon intensity targets can be translated to GHG reductions and will require significant new actions by China.

Carbon intensity targets can be more complicated than energy efficiency targets and require better data collection, economic analysis, stakeholder engagement, and comprehensive planning. Chinese central and provincial level officials responsible for reaching these targets will need assistance from experts who have experience facilitating these processes and

performing analyses in order to achieve the twin goals of economic growth and emissions reductions.

China's central and provincial governments need a way to reduce GHG emissions while continuing to grow the economy. Beyond domestic and international pressure to reduce

***F**ull implementation of existing state action plans by all U.S. states would reduce GHG emissions to 27 percent below 1990 levels by 2020, with a net gain of 2.5 million jobs...*

greenhouse gas emissions, China faces the immediate need to bring its large rural population out of poverty and continue with the three decades of economic development that has occurred since China's reform and opening up policies. Within the framework of its Five-Year Plans and cadre evaluation and promotion system, China puts a premium on economic growth, attracting investment, and industrialization. Provincial officials have great leeway to structure and reform both their province's economy as well as energy production and use. Yet, local governments in China are often unaware of how to balance development of the economy with environmental protection and emissions reductions. Thus, there is a need for a climate action planning process at the provincial and/or city level that will construct consensus on the most cost effective climate policy options that will promote economic expansion of the new energy economy, realize energy savings, promote environmental sustainability and reduce GHG emissions.

By working with U.S. states and stakeholders through comprehensive planning processes, CCS has demonstrated how the joint attainment of economic growth and GHG emissions reductions can be met through

specific sector-based policies and measures. The tools and techniques used to achieve these results in the United States can be helpful to China's provinces in meeting their future GHG emissions reduction and economic growth goals. The transfer of these innovative processes to China will require an intensive exchange to acculturate the program to China's needs and local context, and will require support from CCS and key U.S. states.

### CENTER FOR CLIMATE STRATEGIES WORK IN CHINA

In October 2009, CCS was invited by GEI to give several presentations in China on the CCS Climate Action Planning process used by over 24 U.S. states. GEI, a highly regarded environmental civil society organization in China, has strong programs at both the national and provincial levels. Through its work, GEI has developed a good working relationship with influential government institutions, particularly the National Development and Reform Commission (NDRC), China's top economic



Jin Jiamen, founder of Global Environmental Institute, speaks about U.S.-China subnational climate action planning cooperation at a July 2010 meeting at the China Environment Forum.  
Photo Credit: David Hawxhurst

and climate policy planning body. GEI has excellent convening power and a strong history of guiding international organizations in China. GEI believes that CCS brings a unique set of tools to the challenge of advancing sound climate change policy. Prime among these are:

- An extensive track record of successful consensus building and policy development in all regions of the United States involving over 1,500 stakeholders and technical working group members from a variety of representative interests and organizations.
- World-class CCS microeconomic and macroeconomic modeling capabilities to analyze cost-effectiveness, macroeconomic impact, and economic co-benefits, including advanced use of the Regional Economic Models, Inc. Policy Insight Plus (REMI PI+) model.
- A well recognized, multi-disciplinary network of issue experts from key sectors such as electricity and energy supply; residential, industrial, and commercial; transportation and land use; agriculture, forestry and waste management; and climate adaptation.
- Substantial expertise in the development of GHG emissions inventory and forecasting techniques at the sub-national level.
- A comprehensive and tested database of over 1,000 climate policy options in all economic sectors, levels of government, and policy instruments, as well as a modeling system that allows scaling of sub-national to national level action, and the ability to extrapolate results from one geographic region to others.

### A THREE-PART PLATFORM FOR CLIMATE ACTION PLANNING IN CHINA

CCS and GEI envision a three-part platform for sub-national climate action planning in

China. This three-part platform is designed within the framework of the CCS Climate Action Planning Process properly adapted to the Chinese context. The planning period for this multi-year program will be designed to coincide with China's Five-Year Planning cycle.

**1. Policy and Technical Exchange Platform.** This platform will be created for conducting ongoing match-ups between policy and technical experts in U.S. states and Chinese provinces. CCS will be conducted the first such match-up between Guangdong Province and the city of Chengdu in Sichuan Province and New York, Pennsylvania, and Maryland in July 2010. It is envisioned that this will be the first of many such match-ups.

**2. Capacity Building Platform for the Climate Action Planning Process.** It is envisioned that a five-year capacity building program will be developed in at least the following areas:

- a. Designing the climate action planning process for cities/provinces
- b. Managing/facilitating the climate action planning process
- c. Defining the GHG emissions baseline (in both current and forecast years) at the city/provincial level
- d. Microeconomic and macroeconomic analysis of policy options and co-benefits
- e. Institutional capacity required for implementation

**3. Pilot Projects and Best Practice Sharing Platform.** GEI and CCS plan to jointly conduct pilots to demonstrate the viability with the relevant government agencies and institutions of using the CCS Climate Actions Planning Process at the province/city level in China. During the first two years and annually thereafter, GEI and CCS will conduct workshops to promote provincial/city level official-to-official information sharing. This will

facilitate more accurate information about what other provinces and states are doing on climate and better inform capacity building programs.

*For more information on CCS activities please see: <http://www.climatestrategies.us>.*

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## Greening Their Grids: U.S.-Chinese Cooperation on Electricity from Renewables

By Derek Vollmer

As the world's top two energy consumers and carbon emitters, the United States and China will play a decisive role in a clean energy future. Experts agree that renewable energy is a key area in which the United States ought to "significantly enhance" its cooperation with China, pointing out that the two countries will have no alternative but to become far more active partners in developing low-carbon economies (CFR, 2007; Asia Society & Pew, 2009). Both countries are motivated by a set of related goals, namely job creation, energy security, and pollution reduction, making renewables development a strategy with wide-ranging implications. Given the size of their electricity markets, any substantial progress made between the two countries will mean important progress on the technological learning curve, and immediate benefits for the global community. As major technology exporters, they are poised to jointly lead the way in fostering a worldwide transition to renewable energy-based economies.

The U.S. and Chinese Academies of Sciences and Engineering have a history of close collaboration spanning more than a decade and have jointly conducted several bilateral studies on energy and the environment. These reports reach a diverse audience, including national policymakers, academic researchers, environmental managers, industries, and local decision-makers, and have influenced policy such as China's recent decision to pursue a regional air quality management strategy and regulate ozone and fine particulate matter

(PM<sub>2.5</sub>). The Academies' current bilateral study, which will be released in the fall of 2010, focuses on opportunities for deeper collaboration on electricity from renewable resources,<sup>1</sup> and is being delivered on the heels of the Copenhagen discussions and in time to influence China's next Five Year Plan. Expert committees from both countries have been working collaboratively since December 2008, conducting meetings and site visits in both countries in order to better understand the complex, on-the-ground challenges of increasing the scale of renewable energy development. Their bilateral report provides recommendations to the governments of both countries and to the clean energy community writ large, on priorities for enhancing U.S.-Chinese cooperation in this field.

### CURRENT STATUS OF RENEWABLES DEVELOPMENT

Given their large land mass and coastal populations, the United States and China share similar resource profiles and associated challenges of transmitting renewable power to load centers. Conventional hydropower is currently the predominant source of electricity from renewables, and though both countries are focusing on increasing the share of other renewable resources, China expects to continue developing hydropower as a source of baseload power. Massive solar and wind resources exist in remote regions of each country, but large-scale transmission has not yet been built, and

there is considerable debate as to how much of these resources can and will be exploited cost-efficiently. Biomass, particularly in the form of wood, agriculture, and municipal waste, offers another substantial resource, though in many cases it may be preferentially used to develop liquid fuels (e.g., ethanol). Other resources, such as geothermal and hydrokinetic, are being exploited to provide some baseload generation as well as other energy services (heat and cooling). Both countries also possess resources at smaller scales, which are better distributed among population centers and generally more accessible by existing transmission and distribution systems. The challenge in scaling up these distributed resources is generally a function of (1) their costs compared to conventional generation and (2) their ability to be tied to the grid.

Existing technologies are sufficient in both countries to support accelerated deployment. Real progress will need to be measured in terms of kilowatt hours (kWh) generated, not merely gigawatts (GW) of installed capacity. The challenges in achieving more renewable power generation will have to do with integrating them into the current grids, and balancing intermittent generation within a service area. China in particular has taken impressive strides to improve its manufacturing capability and capacity in wind turbines and solar photovoltaics (PV), though the latter are almost exclusively being sold as exports. The United States has recently become the world's top market for wind turbines, and a leading supplier of second-generation, thin-film PV materials. Much of the growth in renewables in both countries will be in wind installations, as well as some larger-scale solar generation. Due to its emphasis on PV manufacturing, China favors PV for central station plants, whereas the United States relies more on solar thermal technologies for central stations, and PV for distributed applications (including large installations on commercial roofs). Storage will be important as each country moves beyond 20 percent of its generation

coming from intermittent sources—up to that point, however, utilities should be able to incorporate and utilize new generation sources coming online.

While the two countries exhibit similarities in terms of their resource base and technology focus, their policy approaches have been markedly different. This reflects different governing styles and policy priorities, but it also provides an opportunity for mutual learning. Both countries are seeking to support and build their clean energy industry, despite abundant supplies of domestic coal, and comparatively low prices for conventional electricity generation. In the United States, inconsistent policies have hampered a transition to renewables. Current rates of development and deployment are the result of state-led portfolio standards as much as federal policy. Federal production and tax credits have had a substantial impact on the industry, but it has been cyclical, rising and falling as the short-term credits expire before being reauthorized. China's national government, on the other hand, has given more clear and consistent signals to support the nascent industry. Its Renewable Energy Law, adopted in 2005, is the most aggressive national law among developing countries, calling for 20 percent of electricity to come from renewable resources by 2020. This law offers financial incentives, including a national fund to foster renewable energy development, discounted lending, and tax preferences for renewable energy projects. Other mandates require a certain percentage of domestically-manufactured components for installed units (e.g., a wind turbine). These policies have undoubtedly contributed to China's surge in installed wind capacity, though the low prices offered for wind concessions have arguably distorted the industry and may challenge its long-term growth.

## CHALLENGES IN ACHIEVING SCALE

As noted above, meaningful progress in the United States and China will have to be measured

in terms of renewable power generated (and utilized), which will signal that demand is being increasingly met by clean, sustainable sources. Excluding conventional hydropower, renewables' share of generation in both countries is still

*...there is a tremendous opportunity for the United States to learn from China as the latter rapidly builds new transmission capacity and incorporates it into a nationalized grid.*

quite small (less than 3 percent from non-hydro sources), as is the scale of most renewable power projects, in comparison to fossil-fuel power stations. In China, despite grand announcements of large-scale renewable power plants, most installed capacity has been in small-scale or off-grid generation. Deploying more small-scale projects would be easy, but both countries must now direct their focus on increasing the scale of these efforts. This does not preclude significantly more distributed generation (e.g., rooftop PV systems), but it does signify the need to expand the scope of such projects, moving from individual homeowner initiatives to citywide programs capturing abundant local resources, including solar, waste, and other renewables.

As both countries make this transition to clean energy economies, deployment issues will come to the fore. Ancillary requirements in workforce development (skilled manufacturers, installation technicians, and equipment operators) must be addressed if these technologies are to be widely deployed. Operating experience will also become a valuable tool—utility and grid operators in both countries have much to gain from sharing their experiences in integrating and managing larger shares of renewable power generation. Renewables will be competing with more-established industries, and so this growing industry must share best practices in

forecasting, and balancing intermittent resources, among other things. In this regard, there is a tremendous opportunity for the United States to learn from China as the latter rapidly builds new transmission capacity and incorporates it into a nationalized grid. Current U.S. projects to incorporate components of the “smart grid” will need to be evaluated, scaled-up, and widely deployed to further enable more renewables coming on line.

Consistent and supportive policies should help both countries' industries, but over the long-term renewable power will need to focus on becoming cost-competitive. Clearly, a price signal for carbon should help favor renewables over most conventional alternatives. However, access to capital could be a limiting factor—renewable power technologies are capital-intensive. Innovative financing mechanisms for these projects, which have lower operating costs over their lifetime, could help overcome this challenge.

Large-scale use of renewable power should yield many positive environmental benefits, but there are legitimate concerns about potential negative consequences. Land-use is often cited as a drawback of central-station renewable power plants. However, numerous studies and experience have shown that these obstacles can be overcome through a combination of land optimization (e.g., wind turbines on animal grazing land, or PV on building facades) and resource optimization (e.g., concentrator lenses for PV cells, or waste biomass utilization rather than dedicated crops). Production processes are also an area of concern, particularly for silicon PV manufacturing. As China continues to position itself as a world-leading manufacturer of PV products, it will need to work closely with environmental regulators and learn from industrial best practices to manage any emissions of silane, silicon tetrachloride, hydrofluoric acid and other acids used in cleaning wafers.



Photo Credit: Joanna Lewis

Failure to do so could undermine the industry, particularly in the global marketplace, since nearly all of China's PV materials are sold as exports.

## FUTURE DIRECTIONS

The United States and China are entering an interesting period, where they will need to be both collaborators on critical global challenges as well as primary competitors in the marketplace. This signals a change from typical modes of cooperation—broad memoranda of understanding and technology transfer projects—to much more sophisticated collaboration, involving sustained intergovernmental dialogue matched by closer cooperation among industry and NGOs. Both countries recognize that it is in their mutual interest to support one another's efforts to be leaders in developing and deploying clean energy, and they are poised to guide the way in scaling up electricity from renewable resources.

In addition to short-term goals, such as sharing best practices in deploying and operating

specific renewable power technologies, there is a need for enhanced U.S.–Chinese cooperation on key enabling technologies that could form part of a sustainable energy structure, which will have important medium and long-term impacts. Chief among these is the implementation of smart grid technologies, which address intermittency issues and manage increased shares of distributed or on-site renewable power generation. Energy storage techniques could also benefit renewables as they reach a much larger share of generation capacity. The United States has experience with several techniques, such as pumped hydro and compressed air storage, which may be applied to the grid to maximize production from renewable resources. Both countries might collaborate on, for example, linking new renewable power to existing hydropower (which can be used as a storage medium). Finally, considering the high degree of urbanization in the United States, rapid urbanization occurring throughout China, and the role of motorized vehicles in both countries, there may be an opportunity for deeper collaboration on electric vehicles,

particularly vehicle-to-grid technologies that enable battery storage.

Substantial U.S.-Chinese collaboration in renewable energy development could have significant impacts in the near-term (e.g., cost reductions) and the longer-term (e.g., by supporting research, development, and commercialization of frontier technologies). Progress on this front will most certainly benefit the global community, by slowing and then reducing greenhouse gas emissions, and enabling more renewable energy to be harnessed cost-effectively in every country. The United States and China will continue to pursue

national priorities of economic development and energy security, and there will be ongoing multilateral dialogues about ways to mitigate climate change. As both countries increasingly acknowledge, though, their leadership and cooperation on renewable energy development will be one of the keys to addressing these challenges.

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## ENDNOTES

<sup>1</sup> The bilateral study (and this commentary) draws significantly upon the report, *Electricity from Renewable Resources: Status, Prospects, and Impediments*, a U.S.-focused study published by the National Research Council in 2009.