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Establishing China's Potential for Large Scale, Cost Effective Deployment of Carbon Dioxide Capture and Storage

Regional Opportunities for Carbon Dioxide Capture and Storage in China

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This first-ever comprehensive survey of the potential for large scale deployment of carbon dioxide capture and storage (CCS) in the People's Republic of China finds that China has adequate deep geologic carbon dioxide (CO_2) storage capacity to meet likely demand for more than 100 years, and that these storage reservoirs are in close proximity to a large fraction of large stationary CO_2 point sources in China. This may significantly lower the cost of large scale greenhouse gas abatement for China relative to using other CO_2 mitigation options alone, which is good news for the people of China as well as its economy, its trading partners, and those working to establish a robust, durable and viable framework for reducing global emissions of greenhouse gases.

> ***"What the U.S. and China do over the next decade will determine the fate of the world."***
>
> – Steven Chu, U.S. Secretary of Energy

To date, much of the discussion about China's options for addressing climate change have focused only on coal – its large indigenous reserves and its heavy and increasing use – creating a false dichotomy suggesting that China has two choices: (1) continued domestic use of coal with associated emissions rising unchecked, or (2) forgoing the use of this large domestic energy resource in favor of cleaner, more expensive energy and the resulting economic impacts. However, CCS in China presents a third option: the continued use of cheap, domestic coal within China while supporting CO_2 emissions reductions via the capture and geologic storage of the associated CO_2.

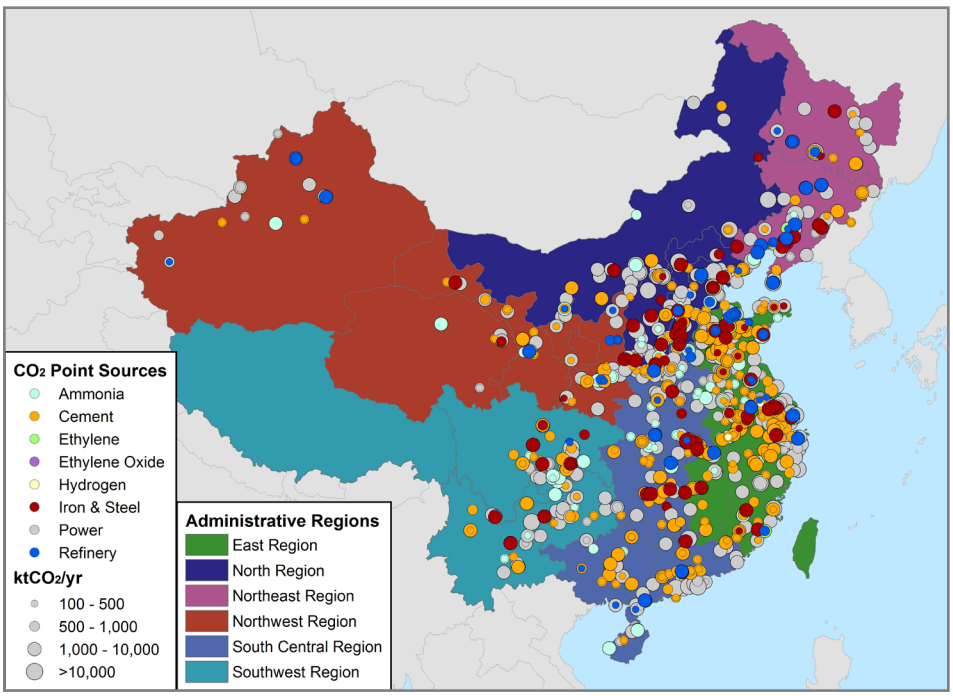
The research reported here demonstrates that China is within the top tier of nations that have both enormous fossil energy reserves and vast potential geologic CO_2 storage resources, which could allow these nations to continue powering their economies with domestic energy supplies while still delivering deep and sustained reductions in atmospheric CO_2 emissions.

An international team of researchers led by Robert T. Dahowski of the U.S. Department of Energy's Pacific Northwest National Laboratory and Professor Xiaochun Li of the Chinese Academy of Sciences' Institute of Rock and Soil Mechanics has completed five years of collaborative research that defines the pivotal role that CCS technologies can play in cost effectively reducing China's

U.S. DEPARTMENT OF ENERGY

China's 1,623 large stationary CO_2 sources collectively emit over 3.8 $GtCO_2$ annually. These include:

- » 629 Fossil-fired power plants (72% of large, stationary CO_2 source emissions)
- » 554 Cement plants (14%)
- » 160 Ammonia plants (3%)
- » 127 Iron & steel mills (7%)
- » 84 Refineries (2%)
- » 69 Other facilities (1%)



Map showing Administrative Regions of China and large, industrial point sources of CO_2, by sector.

greenhouse gas emissions over the course of this century. This international research team evaluated the potential storage capacity in China's major sedimentary basins, and mapped the large stationary power plants, steel mills, cement plants, chemical refineries and other industrial facilities that are responsible for 64% of all Chinese CO_2 emissions to the atmosphere. The research team also compiled the first-of-its-kind CO_2 storage cost curve for China. This work facilitates a fundamentally deeper understanding of how CCS technologies could deploy in China, and at what costs, over the course of this century and beyond.

CHINA'S LARGE POTENTIAL DEMAND FOR CO_2 STORAGE RESERVOIRS

The U.S.-China research team has documented 1,623 large stationary CO_2 emissions sources in China that collectively emit more than 3.8 billion metric tons of CO_2 ($GtCO_2$) per year. These existing facilities – as well as those that are planned or under construction – represent an enormous potential demand for CCS technologies in China.

Coal-fired power plants account for more than 70% of these annual emissions. Cement plants and steel mills make up the vast majority of the remaining emissions, driven by China's rapid economic and industrial development.

For scale, China's 3.8 $GtCO_2$ in annual emissions from these 1,623 existing facilities are equivalent to the cumulative emissions for the entire Chinese economy – including China's transportation sector – over the first half of the 20th century. If CCS could be cost effectively deployed at a significant number of these 1,623 CO_2 sources, as well as at new facilities being built across

China, it could provide a significant contribution to stabilizing atmospheric concentrations of CO_2 and avoiding the worst impacts associated with global climate change.

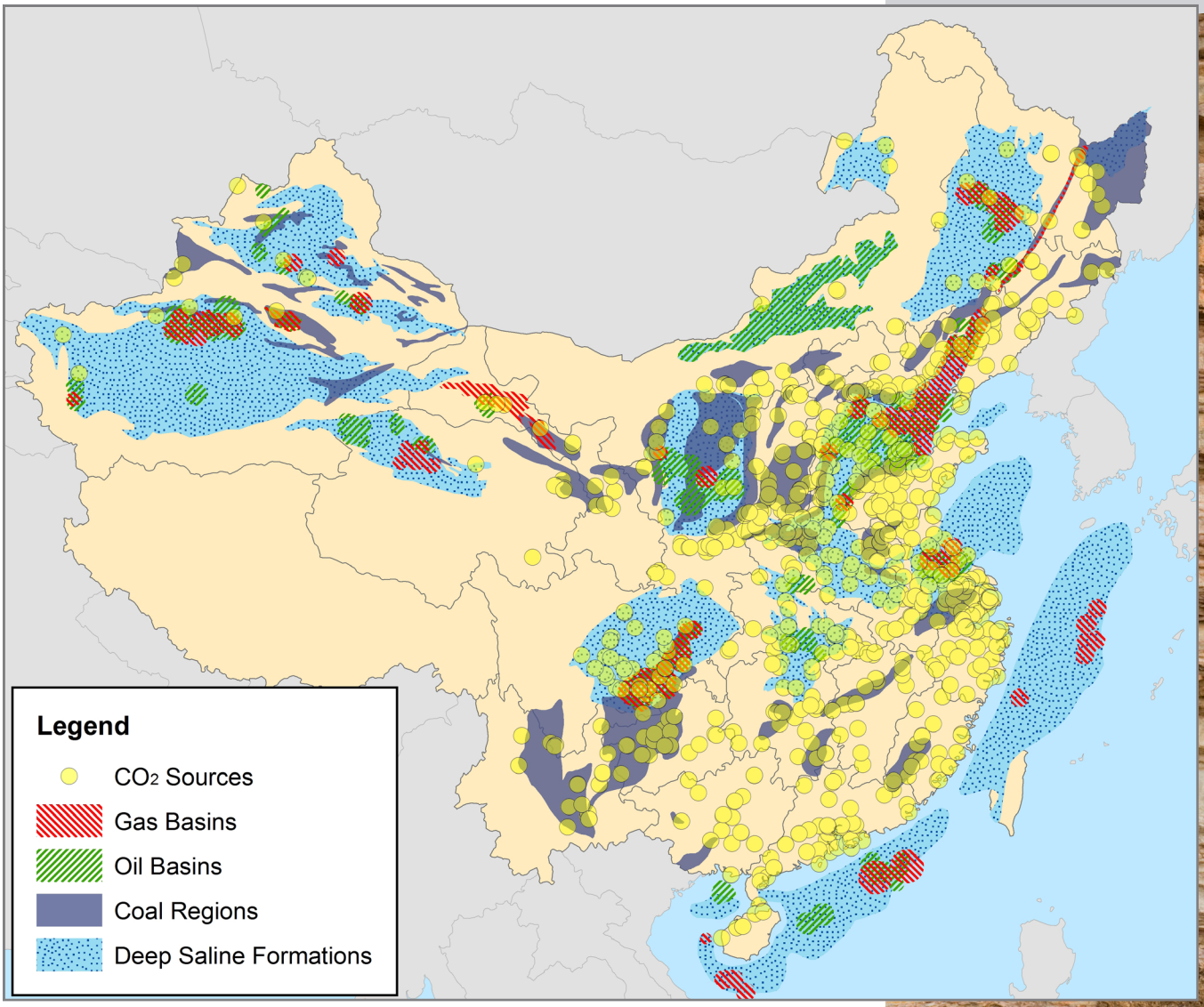
WORLD-CLASS POTENTIAL DEEP GEOLOGIC CO_2 STORAGE RESOURCE

In order for CCS to play a significant role in any nation's portfolio of clean energy technologies, there must be adequate deep geologic CO_2 storage capacity to accommodate the potential demand from existing and future CO_2 sources.

This team of leading U.S. and Chinese researchers has, for the first time ever, mapped over 2,300 $GtCO_2$ of theoretical geologic CO_2 storage capacity in 90 onshore storage formations. This represents a vast and valuable domestic natural resource for China. While the current study focuses on this onshore storage resource, the team has also identified an additional 780 $GtCO_2$ of

China may have as much as 2,300 $GtCO_2$ of onshore geologic CO_2 storage capacity:

- 2,290 $GtCO_2$ in DSFs
- 12 $GtCO_2$ in coal seams
- 4.6 $GtCO_2$ in oil fields
- 4.3 $GtCO_2$ in gas fields
- additional 780 $GtCO_2$ in offshore basins



China's 2,300 $GtCO_2$ of potential deep geologic CO_2 storage capacity is widely distributed throughout the country. An additional 780 $GtCO_2$ of offshore storage capacity may also be available to the industrialized coastal areas.

potential capacity in 16 offshore geologic formations along mainland China's heavily developed coastal regions, which could prove immensely valuable in this part of China where there is strong potential demand for storage relative to existing onshore capacity.

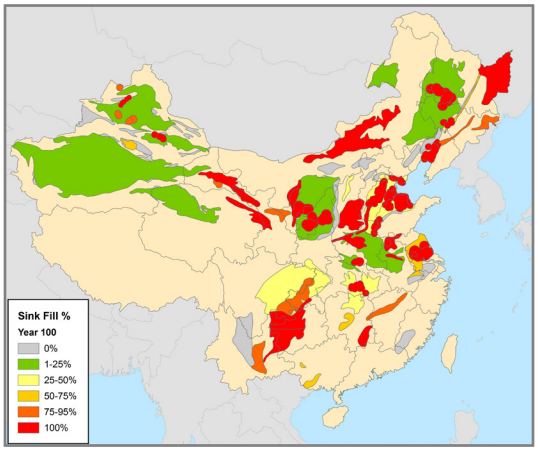
The vast majority of the potential geologic CO_2 storage capacity – within China as well as around the world – is found in deep saline formations (DSFs). China's DSFs account for over 99% of the country's estimated deep geologic CO_2 storage resource.

Smaller geologic CO_2 storage potential can be found in depleted oil fields (4.6 $GtCO_2$), depleted natural gas fields (4.3 $GtCO_2$) and deep coal beds (12 $GtCO_2$). While a significant resource in their own right, some of these formations also have the potential to generate additional oil and natural gas as a result of CO_2 injection. Storing CO_2 in these hydrocarbon fields could potentially yield as much as 6,700 million barrels of additional oil and 16 trillion cubic meters of additional natural gas over the course of this century, further enhancing China's energy security.

THE IMPACT OF VARIATIONS IN CO_2 STORAGE CAPACITY DISTRIBUTION IN CHINA

More than 90% of the existing large power plants and industrial facilities in China are within 100 miles of a candidate geologic CO_2 storage reservoir. This suggests that there will be little need to build extensive and costly long distance CO_2 pipeline infrastructure.

The large CO_2 sources and candidate storage reservoirs are particularly well-matched in the North and Northeast Regions of China where the team's modeling reveals that virtually all point sources should be able to access adequate capacity in nearby candidate CO_2 storage reservoirs through this century and beyond, even when taking into account the depletion of available CO_2 storage capacity in these regions as reservoirs are gradually filled over time.



Projected utilization of China's candidate onshore CO_2 storage reservoirs after 100 years of full scale CCS deployment. Many of the filled (red) reservoirs are in close proximity to reservoirs that still have ample remaining capacity, providing options for continued cost effective CO_2 emissions mitigation in these regions.

Other regions may see more competition for large CO_2 storage reservoirs, but this research shows that the significance of this heightened competition for available deep geologic CO_2 storage capacity varies considerably from region to region.

In the heavily industrialized East and South Central Regions, competition for available CO_2 storage space is likely to be greater, with a larger fraction of the region's CO_2 sources unable to access a nearby storage reservoir. There are nearly 200 sources within these two regions that either do not have any known onshore geologic storage options available within the applied 150 mile search distance, or are unable to utilize the nearby storage resource having been outcompeted by other sources for the limited capacity. However, if the offshore CO_2 storage capacity identified by the research team in this part of China should prove technically and economically achievable, it would likely provide significant value for the CO_2 sources in these regions.

Of the remaining regions, the Southwest Region of China is likely to experience more competition for available CO_2 storage space, as 24% of the sources there are unable to access sufficient capacity within the search distance. The Northwest Region appears to have ample CO_2 storage capacity, yet a number of sources compete for available storage capacity in the eastern part of the region and longer pipelines may be needed to reach more distant storage options to the west. Such insights may enable Chinese decision makers to consider planning where new power plants and industrial facilities might be located to better utilize available storage reservoirs.

90% of China's large stationary CO_2 emissions sources are located within 100 miles of at least one identified storage formation; 85% have at least one storage option within just 50 miles.

CO_2 STORAGE COST CURVE ILLUSTRATES SIGNIFICANT POTENTIAL AND IMPORTANCE OF CCS FOR CHINA

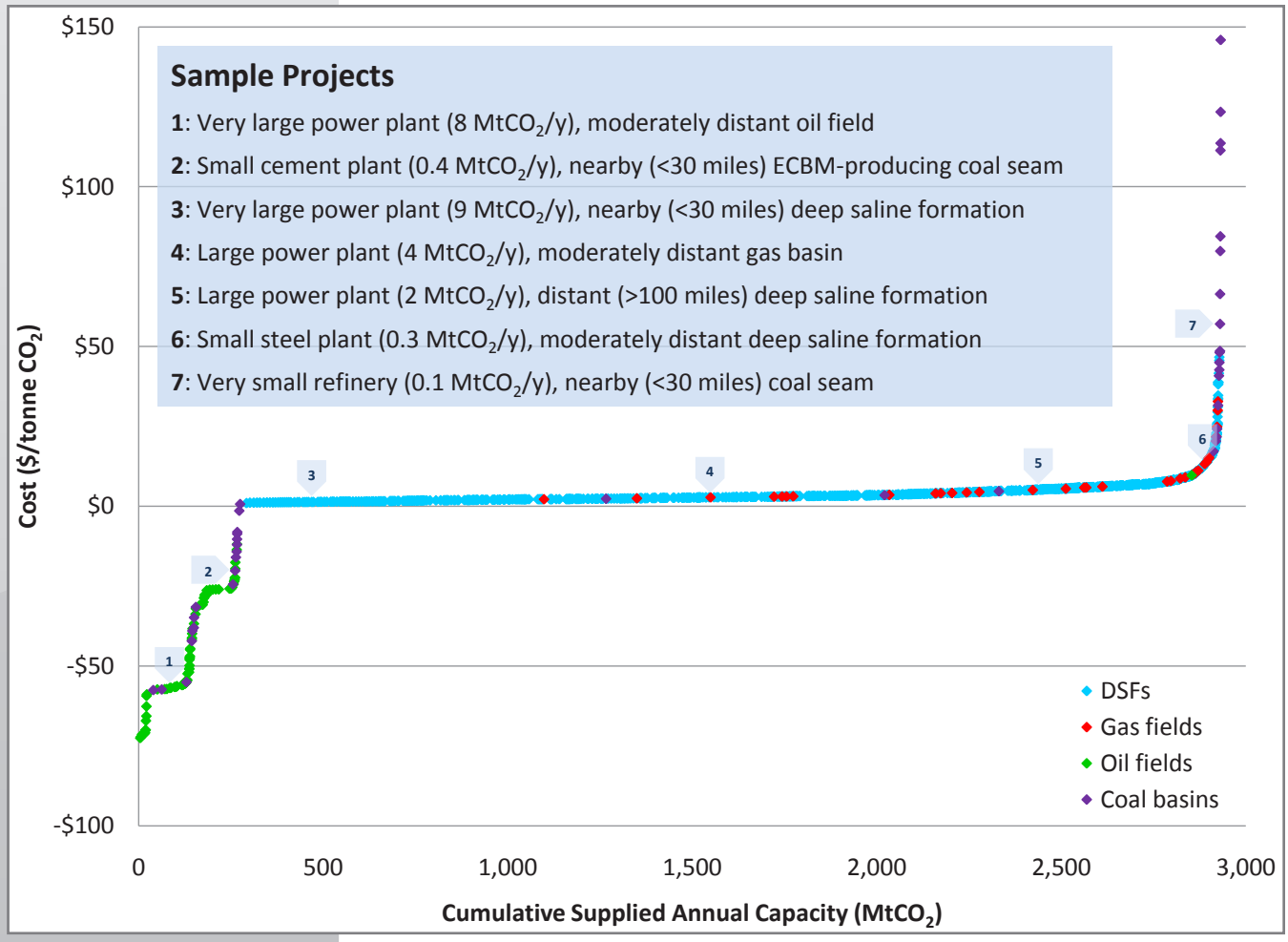
The ultimate role of CCS technologies in global efforts to cost effectively reduce greenhouse gas emissions will be determined by a combination of the stringency and timing of future greenhouse gas emissions reduction policies, the full costs of employing end-to-end CCS systems, and how those costs compare to other methods of bringing about large scale decarbonization of the economy. It is therefore essential to understand the costs of deploying CCS relative to other emissions mitigation technologies. To that end, this cost curve addresses the costs of transporting CO_2 from each point source to its matched CO_2 storage reservoir and injection of the CO_2 into a suitable deep geologic reservoir, including site characterization and long-term measurement, monitoring and verification of the stored CO_2. This analysis intentionally omits the cost of CO_2 capture, compression, and dehydration in order to focus on the storage side of CCS. Future analyses will incorporate these significant additional cost components to provide a more complete picture of estimated end-to-end CCS system costs.

Largely due to the vast size of China's candidate deep geologic CO_2 storage reservoirs and their wide geographic distribution, the cost of transporting, storing and monitoring CO_2 for the majority of China's large stationary CO_2 point sources falls in the range of \$2-8/ton CO_2. While there are some CCS projects (depicted as individual points on the curve) that might see their costs offset by revenues from enhanced hydrocarbon recovery resulting from CO_2 storage in

Cost effective CO_2 transport and storage options appear robust even if ultimately achievable storage capacities prove lower than projected.

depleted oil fields and coal seams, the opportunity to exploit these "value-added" reservoirs is limited by technical factors such as field readiness for CO_2-driven enhanced recovery, remaining uncertainties for CO_2 storage in coals, and the relatively small total storage capacity available in each field. There are also some facilities that could see transport and storage costs that are many times larger than those in the \$2-8/ton CO_2 range but in general, these represent relatively small CO_2 point sources that are quite distant from their nearest candidate CO_2 storage reservoirs. For these sources, it is likely that there could be more cost effective ways for reducing or offsetting their CO_2 emissions.

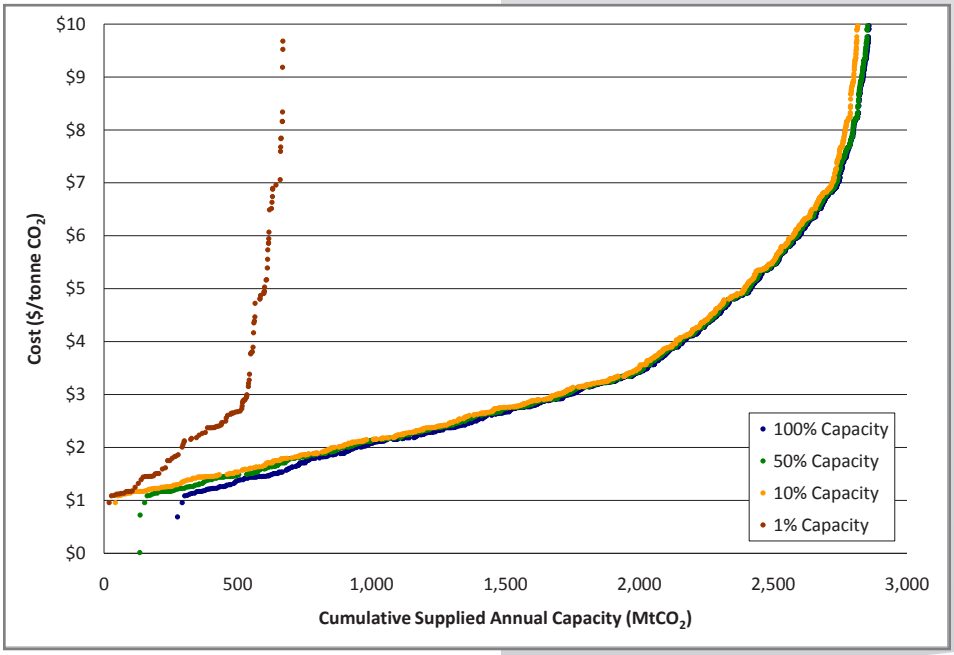
Remarkably, this narrow range of potential CO_2 transport and storage costs appears to hold true for the vast majority of China's power plants and industrial facilities across a number of different scenarios explored in this analysis. For example, storage is likely to be available in this cost range for all regions of the country for at least a few decades of large scale CO_2 storage, and indeed throughout much of this century for all but the South West. In the South West Region, the limited supply of CO_2 storage capacity could lead to higher



China's Cost Curve for CO_2 transport and storage (excluding capture) shows that the vast majority of Chinese power plants and industrial facilities should face transport and storage costs less than \$10/tonCO_2. Each point here represents an existing CO_2 point source and its paired lowest cost geologic storage reservoir (see full report for the assumptions employed for this analysis).

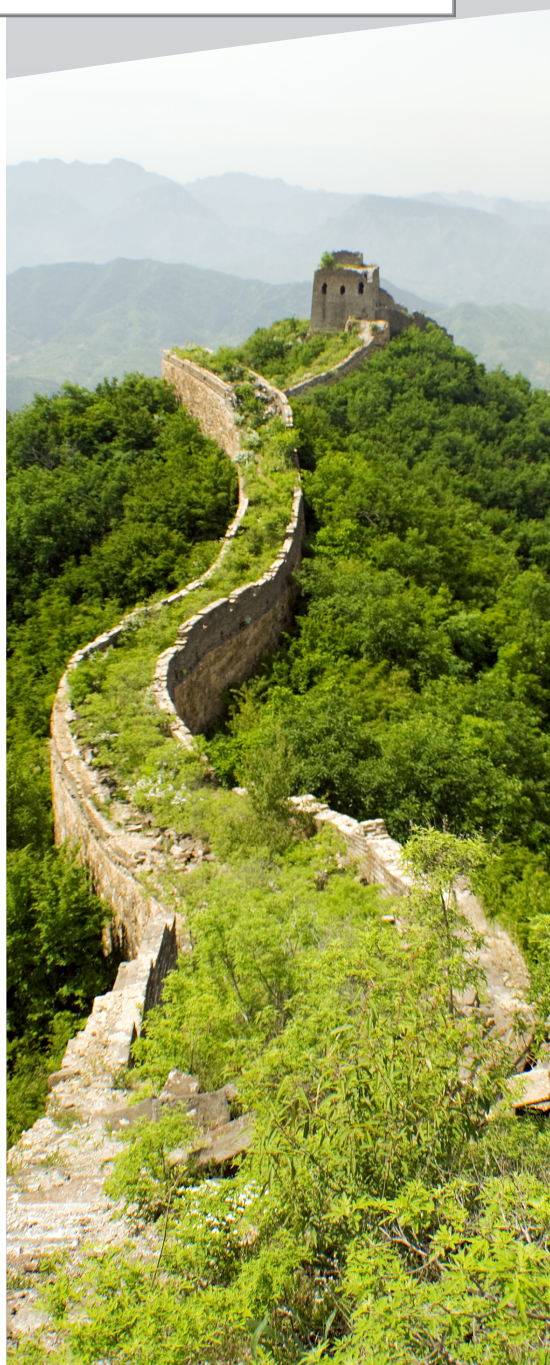
per-ton transport and storage costs as time progresses. Ultimately, this could allow non-CCS based emissions mitigation technologies to play a larger role in this region.

Though in-depth field and laboratory studies will be needed to validate current capacity estimates, this cost range holds true even if there proves to be only half as much usable storage capacity as projected. The research team analyzed cases in which only 50%, 10% and 1% of the indentified 2,300 $GtCO_2$ of onshore storage capacity were available for use. Only in the most pessimistic and unlikely scenarios, in which the 2,300 $GtCO_2$ identified by this study is overestimated by a factor of 10 or 100, do significant constraints develop on the cost effective long term deployment of CCS in China.



A sensitivity analysis shows that if only 50% or 10% of the estimated geologic CO_2 storage capacity in China proves suitable, the ability for CCS to deploy and offer significant impact remains strong and the majority of resulting transport and storage costs remain within the $2-8/ton CO_2 range. (Note: curve zoomed in to this range of costs for greater clarity of this point).

Still, in all but the most pessimistic case, in which only 1% of the capacity proves suitable, CCS could be able to supply between 0.5 and 3.0 $GtCO_2$ in annual emissions reductions for decades to come. For all but this very lowest capacity case examined, CCS appears able to provide a significant tool for addressing China's CO_2 emissions while at the same time preserving the energy and economic security provided by China's large, domestic industry and fossil fuel resources.



Endnotes

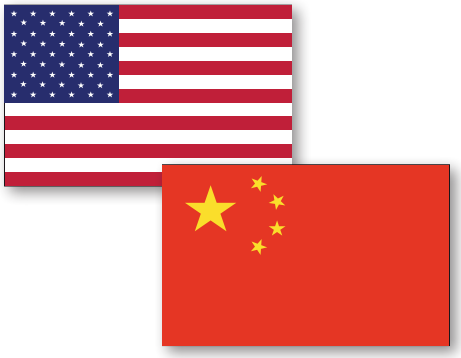
This short synopsis of the research performed by this international collaboration over the past five years was prepared to coincide with the awarding of the Carbon Sequestration Leadership Forum Recognition Award, bestowed upon this project during the CSLF Ministerial Conference on October 13, 2009 in London.

For the purposes of this analysis, a "large stationary CO_2 point source" is one that emits at least 100,000 metric tons of CO_2 per year. This de minimus criterion is widely used to exclude facilities that are likely too small to make CCS a cost effective emissions mitigation solution.

The figure reporting "Projected utilization of China's candidate onshore CO_2 storage reservoirs after 100 years of full scale CCS deployment" represents an intentionally conservative view of how long China can rely on CCS technologies. In this analysis, all existing facilities immediately begin to store their CO_2 in nearby CO_2 storage reservoirs and continue to do so for 100 years. This is not intended to be a realistic deployment scenario and will be unnecessary in practice as China has a broad portfolio of available CO_2 emissions mitigation options (e.g., wind and solar power and improvements in energy efficiency throughout the economy). Moreover, it is highly unlikely that any enacted climate policy would be so stringent at the outset as to require immediate adoption of CCS for 100% of the captured CO_2 stream for all facilities. The purpose of the full scale deployment assumption is to assess the maximum potential for CCS to deploy and estimate the resulting costs, and for these reasons this figure represents a conservative estimate of how long CO_2 storage capacity would last in China. It is very likely that these formations will be able to accept CO_2 for significantly longer time periods than the scale of this graphic suggests.

ABOUT THIS U.S.-CHINA CLEAN ENERGY COLLABORATION

This research is the result of an unprecedented collaboration between leading institutes and scientists from the U.S. and China, each pioneers in certain aspects of the study of CCS technologies and their deployment potential. The success of this highly productive joint research effort would not have been possible without participation and support from a large number of people and institutions since the project's inception in 2005. The U.S.-China research team would specifically like to acknowledge the critical support of: the United States Department of Energy; the Ministry of Science and Technology of the People's Republic of China; the multilateral Carbon Sequestration Leadership Forum; the many public and private sector sponsors of the PNNL-led Global Energy Technology Strategy Program; and Leonardo Technologies, Inc.



ABOUT THE PACIFIC NORTHWEST NATIONAL LABORATORY

The Pacific Northwest National Laboratory (PNNL) is located in Richland, Washington, and is one of the U.S. Department of Energy's (DOE's) ten national laboratories, managed by DOE's Office of Science. PNNL also performs research for other DOE offices as well as government agencies, universities, and industry to deliver breakthrough science and technology to meet today's key national needs. PNNL is a multidisciplinary laboratory that is focused on making major contributions in the areas of: reducing the effects of energy generation and use on the environment and increasing U.S. energy capacity and reducing dependence on imported oil through research of hydrogen and biomass-based fuels. PNNL currently has approximately 4,200 staff members and a business volume of $881 million per year. ***www.pnl.gov***

ABOUT THE CHINESE ACADEMY OF SCIENCES INSTITUTE OF ROCK AND SOIL MECHANICS

The Institute of Rock and Soil Mechanics, Chinese Academy of Sciences (IRSM) was founded in 1958. IRSM performs research on the fundamentals of rock and soil mechanics and develops technical solutions for geotechnical engineering, such as mining, hydropower, transportation, energy recovery, and energy and waste geological storage. IRSM is the leading institution in the field of geomechanics and geotechnical engineering in China. ISRM is home to the Chinese Society of Rock Mechanics and Engineering, hosts four independent academic committees, and houses the editorial offices for four academic journals. IRSM is located in Wuhan, China. ***www.whrsm.ac.cn***

The complete details of this research effort, the data collected, the methodologies used in the analysis, and the research results are documented in RT Dahowski, X Li, CL Davidson, N Wei, and JJ Dooley. 2009. "Regional Opportunities for Carbon Dioxide Capture and Storage in China: A Comprehensive CO_2 Storage Cost Curve and Analysis of the Potential for Large Scale Deployment of CCS in the People's Republic of China." Pacific Northwest National Laboratory. Richland, WA.

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