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A Preliminary Cost Curve Assessment of Carbon Dioxide Capture and Storage Potential in China

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Abstract

This study presents a preliminary assessment of the potential for carbon dioxide capture and storage (CCS) technologies to deploy within China. China has a large theoretical and geographically dispersed geologic carbon dioxide (CO_2) storage capacity in excess of 2,300,000 $MtCO_2$ in onshore basins with deep saline-filled sedimentary basins accounting for over 99 percent of the total. There are over 1620 large stationary CO_2 point sources that emit a combined 3890 $MtCO_2$/year and 91 percent are within 100 miles (161 km) of a candidate deep geologic storage formation. The preliminary cost curve analysis suggests that the majority of emissions from China's large CO_2 point sources can be stored in large deep saline formations at estimated transport and storage costs of less than \$10/tCO_2. This indicates that there is significant potential for CCS technologies to deploy in China and for these technologies to deliver deep, sustained, and cost-effective emissions reductions for China over the course of this century. The research reported here was the result of an unprecedented and highly productive collaboration between researchers in the United States and China.

Keywords: carbon dioxide capture and storage; China; cost curve; climate change.

1. Introduction

The People's Republic of China is the most populous country in the world and has been experiencing tremendous economic and industrial growth [1]. China's population has doubled over the past four decades and now exceeds 1.3 billion people with annual economic growth averaging 9.8 percent since 1980 [2]. The country has abundant domestic coal reserves (the third largest in the world) and it is this coal that powers the economy, supplying an estimated 69 percent of China's primary energy consumption [3]. The majority of China's anthropogenic carbon

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dioxide (CO_2) emissions result from coal combustion and it is estimated that these CO_2 emissions increased some 66% during the relatively short period of 2000–2005 [1]. While historic and per-capita CO_2 emissions remain low compared to more developed nations, the rapid economic development in China, along with the heavy reliance on domestic coal resources, means that overall CO_2 emissions will most likely continue to rise significantly in the coming decades.

While a portfolio of approaches will be necessary to stabilize global atmospheric concentrations of greenhouse gases, carbon dioxide capture and storage (CCS) technologies have been shown to provide great potential economic benefits when included in the overall portfolio of mitigation options [4,5].[1] Until now, there have been no comprehensive bottom-up studies of the CO_2 sources and candidate geologic storage reservoirs in China; this project was designed to catalogue and examine characteristics of large anthropogenic CO_2 sources and candidate geologic storage reservoirs, and analyze opportunities for CCS deployment in this very important region. The goal was to deliver a first-order assessment of the potential for CCS technologies to be deployed in various regions of China, to link large and growing industrial CO_2 sources with available geologic CO_2 storage reservoirs capable of storing CO_2 safely over significant time scales, and perform an initial estimate of costs. The analysis is intended to represent a first step towards a more comprehensive understanding of China's potential opportunities to utilize CCS as a means of cost-effectively controlling CO_2 emissions.

2. China's Large Stationary CO_2 Point Sources

The focus on emissions within this project is on the large, stationary source CO_2 emitters, such as power plants, cement kilns, steel mills, and petroleum and chemical refineries. The goal was to compile an initial dataset that represents the majority of large point-source emitters that emit at least 0.1 $MtCO_2$/yr. As a result, the analysis does not consider all anthropogenic CO_2 emissions, and specifically does not consider those from small industrial CO_2 point sources, transportation, direct energy use in commercial and residential building sectors, land use, agriculture, and similar activities.

2.1. Electric Power Sector

The World Electric Power Plants (WEPP) Asia Database was used as the primary source of information on China's electric power sector [6]. For China, WEPP contains data on 6060 electric power generating units of all types and sizes. Because this analysis is only concerned with power units that could be candidates to adopt CCS, all non-fossil-fueled generating units (e.g., hydro, nuclear, solar, wind) as well as those very small fossil units that did not meet the 0.1 $MtCO_2$/yr threshold were filtered out of the set. Additionally, due to the greater uncertainty associated with planned plants, only the units specified as operating were selected. This screening process left 1984 fossil-fired power units at 629 plants with combined estimated annual CO_2 emissions of 2811 $MtCO_2$. Coal-fired units represent the overwhelming majority of these, accounting for 94 percent of the number and a full 98.5 percent of the total estimated emissions.

2.2. Large, Stationary Industrial CO_2 Sources

Additional anthropogenic sources of CO_2 evaluated in this study included those from the following industrial sectors: cement, iron and steel, petroleum refineries, ammonia, ethylene, ethylene oxide, and hydrogen. Data were compiled from a variety of sources, including industry, enterprise, and product databases and websites, plus existing worldwide CO_2 source inventories. Annual CO_2 emissions were estimated based on IPCC Guidelines for national greenhouse has inventories using available plant capacities and productivities as described in Li et al. [7]. Results for the non-power sectors indicate that there are 994 large (0.1+ $MtCO_2$/yr) plants, emitting a combined 1081

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[1] Note that the cost-effectiveness of CCS technologies as a significant CO_2 emissions mitigation option will rely not only on technical feasibility and relative economics to other mitigation options, but also on a positive value either implicit or explicit on carbon emissions.

$MtCO_2$/yr (one-half of which is from cement production). Latitude and longitude of each plant were assigned based on city center of each location.

2.3 Summary of Large, Stationary CO_2 Sources

Figure 1 is a map showing the location of the 1623 CO_2 point sources that each emit at least 0.1 $MtCO_2$/yr. The combined annual CO_2 emissions from these sources is estimated at over 3890 $MtCO_2$. Power generation accounts for 73 percent of the total annual emissions from these sources. Cement plants contribute 14 percent, followed by iron and steel (7%), ammonia (3%), refineries (2%), ethylene (1%), ethylene oxide (<1%), and hydrogen (<1%). The majority of the sources are concentrated along the coastal zones, with 58 percent of the sources being located within the east and south central regions.

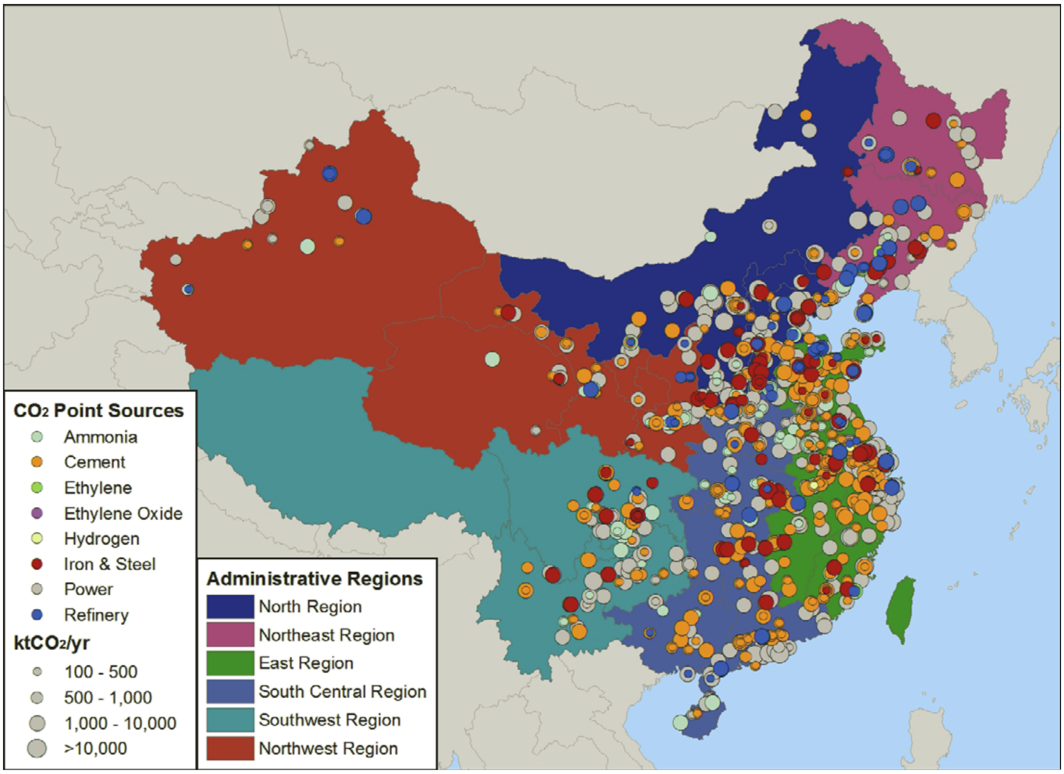

Figure 1. Map of Large CO_2 Point Sources by Type, Size, and Administrative Region

3. China's Candidate Geologic CO_2 Storage Reservoirs

Four major classes of deep geologic reservoirs present within China have been identified and evaluated as candidates for the long-term storage of anthropogenic CO_2—deep saline sedimentary formations, depleted gas basins, depleted oil basins with potential for CO_2-enhanced oil recovery (EOR), and deep unmineable coal seams with potential for enhanced coalbed methane recovery (ECBM). The focus of this research project is primarily on onshore basins at this time, although some initial data have been collected and reported for offshore basins. This study applied a basin-scale capacity estimation similar to methods used in previous studies (e.g., for North America, see Dahowski et al. [8]) as described in greater detail in Li et al [7].

China has a large theoretical and geographically dispersed deep geologic CO_2 storage resource in excess of 2,300,000 $MtCO_2$ in onshore basins with potentially an additional 780,000 $MtCO_2$ in relatively close offshore basins. Deep saline-filled sedimentary basins account for over 99 percent of the total calculated storage capacity. Figure 2 shows the location and areal extent of the 106 deep geologic formations examined in this research project.

3.1. China's Deep Saline Formation CO_2 Storage Capacity

Deep saline-filled sedimentary formations (DSFs) tend to be the largest, most widely distributed and highest-capacity candidate geologic CO_2 storage formations. Data on the spatial extent of the major sedimentary basins in China were derived primarily from geospatial data of the sedimentary basins published by the United States Geological Survey [9] and supplemented by higher-resolution basin boundaries and locations of additional basins taken form the Atlas of Oil and Gas Basins in China [10]. In the absence of high-resolution data on the key factors driving storage capacity in Chinese DSFs—including basin geometry, fractional lithology, porosity, and geochemistry—capacity was evaluated using an approach that incorporates both volumetric and solubility parameters, as described by Brennan and Burruss [11]. Results of this research identified 16 onshore and 9 offshore sedimentary basins with capacity in onshore deep sedimentary basins estimated at 2,288,000 $MtCO_2$; offshore capacity was estimated at 779,000 $MtCO_2$.

3.2. China's CO_2 Storage Potential in Depleted Gas Fields

Location and key characteristics of major Chinese gas basins were compiled using data taken primarily from the second Atlas of Oil and Gas Basins in China [10]. Capacity estimates were calculated at the basin level; however, field locations were used to develop sub-basin coverage of locations and capacities to provide greater storage-zone resolution for the spatial and economic analyses. Also, to facilitate source-reservoir pairing and the associated costing methodology, basins or sub-basins with less than 2 $MtCO_2$ storage capacity were eliminated from evaluation.[2] The 13 major onshore and 4 offshore gas basins assessed in this study offer a total of more than 5100 $MtCO_2$ in total estimated CO_2 storage capacity.

3.3. China's CO_2 Storage Potential in Depleted Oil Fields

The approach for depleted oil fields is similar to that for the gas fields. However, in addition to location, depth, and capacity estimates, the recoverable oil from tertiary CO_2-flood EOR was also estimated for each major oil-producing basin and resulting sub-basin. Sixteen major onshore and 3 offshore depleted oil basins evaluated here have a total estimated CO_2 storage capacity of 4800 $MtCO_2$—of which 4600 $MtCO_2$ is found onshore. If CO_2 injection is successful in stimulating additional oil recovery in these reservoirs, as much as 7 billion barrels of incremental oil could eventually be recovered in this fashion.

3.4. China's CO_2 Storage Potential in Coal Seams

CO_2-driven enhanced coalbed methane recovery (CO_2-ECBM), while not yet a commercial technology, is being investigated for the concurrent storage of CO_2 and recovery of coalbed methane resources. ECBM-based storage is included in this assessment to provide a basis for understanding the potential role that it may play in China should the technology become mature enough for wide-scale use. Spatial data on China's major coal-bearing regions were obtained from the U.S. Geological Survey [9] and supplemented by additional and higher-resolution data where available. Key characteristics of the coal resource within each basin were used to estimate CO_2 storage capacity and potential for recovery of additional coalbed methane via CO_2-ECBM. Total capacity in deep, unmineable coal seams via ECBM in China is estimated at approximately 12,000 $MtCO_2$ within 45 major coal basins.

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[2] This threshold value for reservoir capacities is driven by the combination of the 20-year commitment requirement and the minimum annual emissions cut-off for sources of 0.1 $MtCO_2$/yr. Thus, 2 $MtCO_2$ is the minimum capacity required of a formation that could be used to store the emissions from the smallest CO_2 source for the 20-year time commitment required by the base assumptions employed in this analysis.

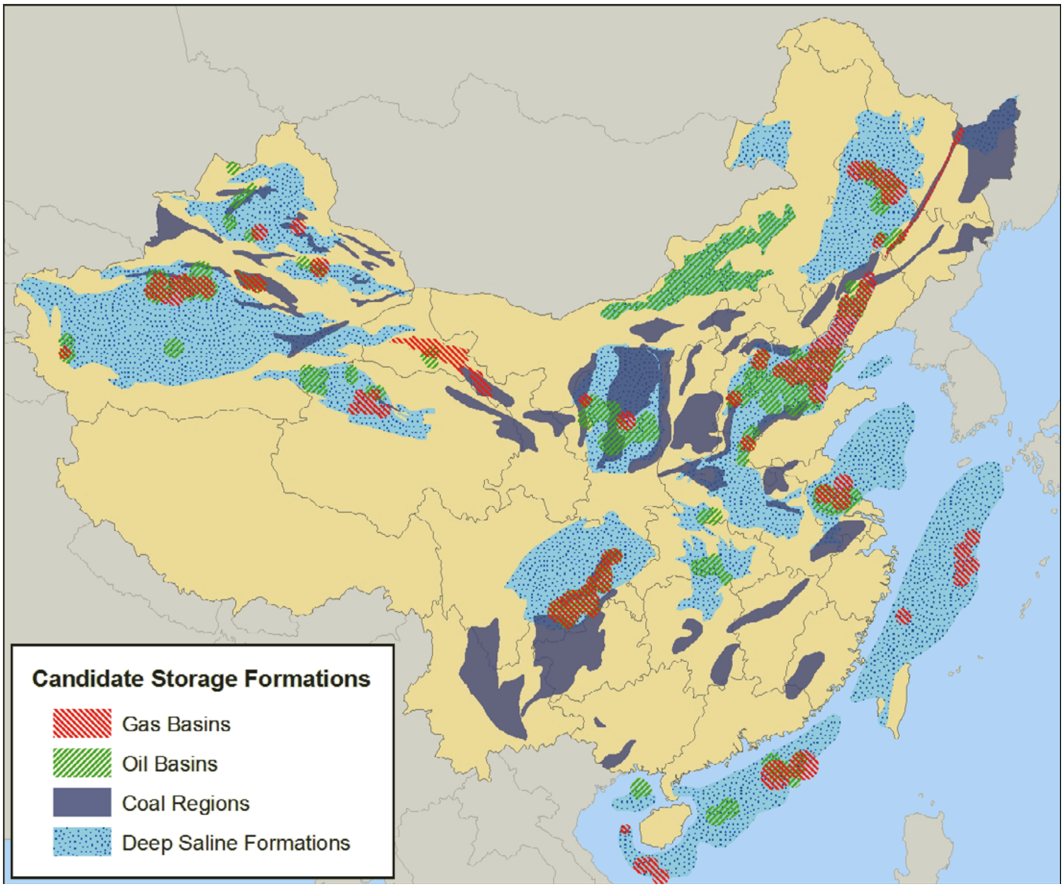

Figure 2. Map Showing the Combined Location and Extent of Candidate Geologic CO_2 Storage Formations Analyzed in This Study

4. CO_2 Source-Reservoir Matching and Resulting Cost Curves for CO_2 Transport and Storage

A central aspect of the research presented here was to model the economic competition between the large number of China's stationary CO_2 point sources and China's large theoretical CO_2 storage capacity in these deep geologic reservoirs. Most large stationary CO_2 point sources in China are in relative close proximity to at least one candidate deep geologic CO_2 storage reservoir. For example, 54 percent have a candidate storage formation in the immediate vicinity; 83 percent have at least one storage formation within 50 miles (80 km); and a full 91 percent have the potential to reach a candidate storage formation within 100 miles (161 km). Variations in proximity do occur from region to region across China with large numbers of CO_2 sources in industrialized coastal zones not having as ready access to abundant CO_2 storage capacity as do the more interior regions. In the north, northwest, and southwest regions, candidate storage formations are particularly well-positioned to be accessed by CO_2 sources, with over 90 percent of the sources having at least one potential storage option within just 50 miles (80 km). At least 80 percent of the large CO_2 sources in the east and northeast have a candidate storage option within this distance, falling to 65 percent for the south central region.

The computation of cost curves for CO_2 transport and storage in China was performed following the methodology outlined in Dahowski et al. [8] with updated costs and assumptions as new information and data have become available. The core of the computation of the cost curve is the pairing of each of the 1623 large CO_2 sources to the candidate CO_2 storage reservoirs that could be reached within the specified maximum search radius, which in this analysis was set to 150 miles (241 km). For each resulting source-reservoir pair, the costs of CO_2 transport and various components of CO_2 storage were estimated, based on the combined characteristics of the individual source and selected reservoir (e.g., annual CO_2 flow rate, transport distance, reservoir type, depth, allowable injection rate). The primary costs evaluated in the analysis include transport of the CO_2 from the source to the reservoir via pipeline; storage-site characterization, injection well and well-field infrastructure; oil and coalbed methane recovery and CO_2 recycling infrastructure; and measurement, monitoring, and verification requirements for the injected CO_2. The costs associated with CO_2 capture, dehydration, and compression at each source have been intentionally excluded to focus on the net cost of CO_2 transport and storage.[3] Capture and related costs can be added at a later time to examine their impact on the overall costs and cost curves. A least-cost optimization process was performed to determine which sources would be allowed to store their CO_2 into which target reservoirs, subject to filling constraints over a 20-year period.

Figure 3 shows the resulting preliminary cost curve for CO_2 transport and storage for China. Each individual point on the curve represents a unique CO_2 source and its selected CO_2 storage reservoir. The amount of CO_2 stored into the formation each year is represented on the x-axis (in $MtCO_2$), and the estimated net cost for CO_2 transport and storage for each pair (in $\$/tCO_2$) is represented on the y-axis. As can be seen, the cost curve for CO_2 transport and storage for China is comprised of three distinct sections. First, there appear to be a number of potential opportunities for low and even negative cost CO_2 transport and storage in nearby candidate value-added CO_2 storage formations that exhibit promising CO_2-enhanced hydrocarbon recovery characteristics.[4] The next and largest part of the curve is a long, slowly increasing stretch that spans the next 2600 $MtCO_2$/yr of stored CO_2, with costs increasing to approximately $\$10/tCO_2$. The 1050 pairs in this region consist of a broad mix of source types and reservoir classes; however, the overwhelming majority are large sources such as coal-fired power plants storing their CO_2 into the high-capacity deep saline formations that are broadly distributed throughout many parts of China.[5] Lastly, at the far right side of the cost curve is the vertical high-cost region comprised of some 200 pairs whose CO_2 point sources are typically quite small and distant from a suitable storage reservoir.[6]

Overall results of this preliminary cost curve analysis indicate that the majority of emissions from China's large CO_2 point sources can be stored in these large DSFs at estimated costs of less than $\$10/tCO_2$. In fact, nearly 90 percent of the CO_2 stored in this analysis—from sources that were able to locate an available storage target—gets stored into one of the regional DSFs modelled in this study.

In addition to the source-reservoir pairs represented on the cost curve, there are also over 250 large CO_2 sources that are "stranded" without access to sufficient available CO_2 storage capacity in onshore basins. These are predominantly located in the coastal regions and highlight an important finding, or confirmation, of this study that the heavily industrialized coastal areas of the east and south central regions appear to have less access to large quantities of onshore storage capacity than many of the inland regions. Indeed, many of these sources are unable to access any suitable CO_2 storage capacity within the 150-mile (241-km) search radius. Storage options do appear to be present in nearby offshore basins, which would likely offer great benefits to these regions; however, a detailed examination of the cost associated with utilizing these offshore basins was outside the scope of the present study.

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[3] Net storage costs include any revenues from incremental oil or coalbed methane recovered as a result of CO_2 injection. Assumed future wellhead oil and natural gas prices of \$60/bbl and \$6.60/mcf (in 2006 dollars) were applied to estimate the value of recovered hydrocarbons (based on EIA 2030 price projections, [12]).

[4] However, it is important to keep in mind that when costs of capture, dehydration, and compression are added, the resulting costs may or may not be negative. Also, many of these "value-added" formations may not be ready for CO_2 injection immediately and the timing of reservoir availability along with more specific reservoir conditions and expected duration of successful recovery would need to be evaluated prior to assuming that resulting costs from these operations would really be net negative.

[5] The CO_2 stored by this section of the curve represents a full two-thirds of the total CO_2 generated by all of the modeled sources and indicates that there is significant potential for many of China's large CO_2-emitting facilities to utilize nearby deep saline formations for emissions reductions.

[6] The CO_2 sources that make up the tail section of the cost curve produce on average one-tenth of the CO_2 per year as the sources in the first two sections of the curve. Not only are these much smaller sources, which suffer higher per-tonne costs for transport and storage, but they also tend to be farther from their selected storage reservoirs (averaging over twice as far as the sources in the lower-cost parts of the curve), requiring longer pipelines.

Future work will need to examine the potential for this offshore storage capacity to provide needed options for the large CO_2-emitting industrial and power facilities in these areas.

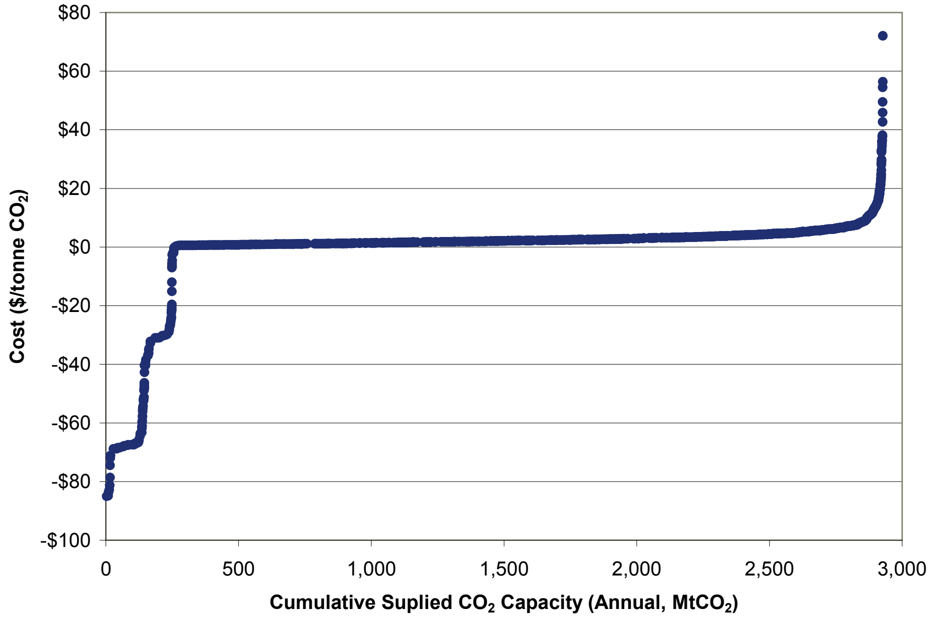

Figure 3. Cost Curve for CO_2 Transport and Storage in China

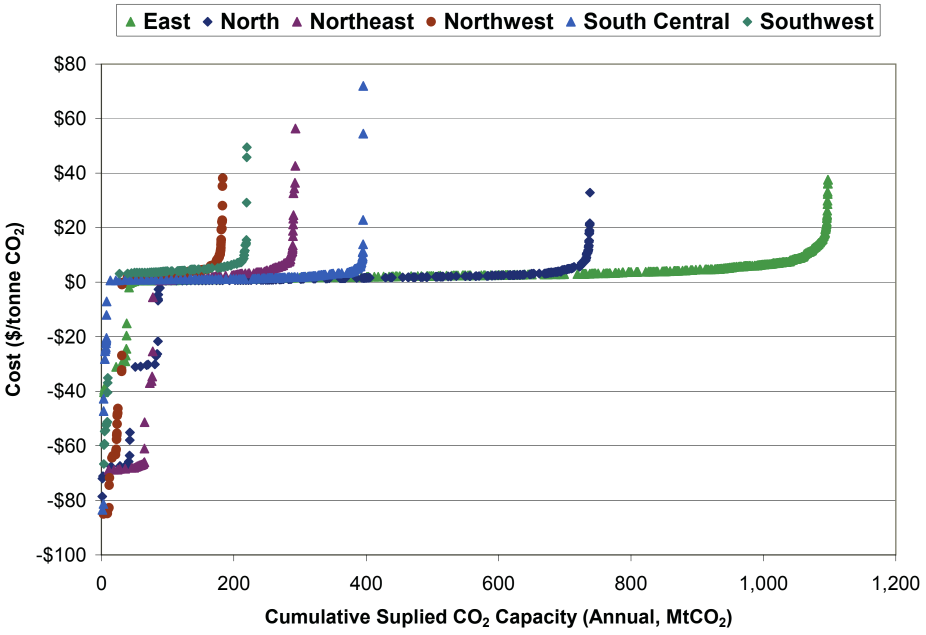

Figure 4. Regional Cost Curves for CO_2 Transport and Storage in China

Figure 4 shows preliminary CO_2 transport and storage cost curves for each of the six major regions of China as identified on the map in Figure 1. This provides a more detailed look at the demand for and costs of CO_2 storage across different parts of the country. The first thing that stands out is the relative difference in total potential annual demand for CO_2 storage from one region to the next. The east region has the largest number of sources and the most CO_2 paired with nearby prospective CO_2 storage formations; the northwest has the fewest. The southwest region has only one more paired CO_2 source than the northwest; yet, overall, the sources there are larger, and 36 $MtCO_2$ more is modeled to be stored there per year; even though a larger number of sources are also left stranded.

5. Future Research

This study performed a first-order evaluation of CO_2 storage options and costs within China, and there are numerous additional areas for future research on the potential for CCS technologies to deploy within China. Some of these include an ongoing effort to update CO_2 source data for both existing and emerging industries and estimating potential impacts on continued growth patterns. Continued development of core data and understanding of basin and sub-basin scale geology as it pertains to the capacity, injectivity, suitability, timing of availability, and economics of CO_2 injection and storage will be important, as it continues to be in all regions of the world where CCS is being studied. Finally, while the model used in this study was significantly updated, better understanding of component costs, specific Chinese market conditions, and other factors impacting costs of deployment in China will be important to consider in greater detail. This work and follow-on research will be critical to helping define global climate and energy-related policy agendas, understand opportunities as well as potential barriers and challenges for CCS, and identify and coordinate potential pilot projects leading toward possible commercial-scale deployment of this class of technologies.

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