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Examining CCS deployment potential in China via application of an integrated CCS cost curve

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Abstract

Previously published cost curves focusing on CO_2 transport and storage have helped illustrate the large potential for CCS technologies to deploy in China. This paper examines results from recent work to incorporate the costs of CO_2 capture and compression into integrated cost curves that more fully reflect expected costs across the set of large, industrial CO_2 sources and better illuminate the possible value of CCS to this fast-growing economy. Results show that significant potential exists for large-scale deployment of CCS at costs less than \$70/tCO_2. Mapping the cost curve results confirms that the majority of existing CO_2 point sources may be able to utilize CCS technologies, and that – except for many sources in southern China – onshore storage capacity appears accessible and sufficient for decades of large-scale deployment.

Keywords: Carbon dioxide capture and storage; CCS; cost curve; China; source-sink matching; climate change

1. Introduction

Earlier research by the authors has focused on assessing the magnitude and distribution of existing industrial and power generation emissions as well as the geologic CO_2 storage resource across mainland China [1-3]. This work detailed annual emissions estimates totaling over 3.8 GtCO_2 from 1623 large point sources and estimated CO_2 storage capacities for 90 potential geologic storage formations [1,3]. Spatial analysis has shown good collocation of storage options to most sources, with over 90% of sources having at least one candidate storage option within 160 km [2,3]. This first ever national-scale source-sink matching study for China led to the development of cost curves for CO_2 transportation and storage [2,3]. These cost curves indicated that most of the large industrial and power sector CO_2 emissions sources in

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China should be able to transport and store their CO_2 for many decades and perhaps over a century at costs between \$2-8/tCO_2 [3]. While the results of this preliminary research helped to establish the large potential for CCS to contribute to significant long-term reductions of CO_2 emissions across many regions and industrial sectors of China, it specifically excluded capture and compression, key CCS project costs.

Building upon this previous work, the authors have recently assessed the highly unit- and sector-specific costs associated with the capture and compression of CO_2 from this set of existing large CO_2 point sources. By incorporating these costs into the existing modeling framework alongside transport and storage, this analysis allows for the most comprehensive and realistic examination to date of opportunities and barriers for CCS deployment across China. Fully integrating capture and compression requirements into the source-sink matching enables more accurate economic allocation of geologic storage capacity by considering the full end-to-end costs that projects will face. In most cases, CO_2 capture and compression are expected to be the largest component costs for CCS systems; incorporating these is critical for evaluating more realistic project economics and deployment potential, including the examination of early opportunities across China's varied geological, industrial, and geographical landscape. This paper highlights key findings from the first national-scale cost curve assessment of China to integrate costs across the entire CCS value chain [4] including capture, compression, transport, storage, and MMV, and evaluates more closely what the resulting cost curve suggests regarding the potential for CCS to deploy at scale in China.

2. An integrated CCS cost curve for China

Development of this fully integrated cost curve followed the well-documented source-sink matching methodology described by Dahowski et al. [3,5]. Key characteristics of the 1623 large CO_2 point sources and 2,300 GtCO_2 storage capacity within 90 major Chinese deep onshore sedimentary sub-basins (as shown on the map in Fig. 1 and described by [1,3]) were analyzed within a geospatial techno-economic modeling framework to develop CCS cost curves. Algorithms for estimating CO_2 capture and compression costs were added to the transport and storage cost modules used to produce the previously published cost curves [3], to evaluate end-to-end CCS system costs. Representative costs for *n^{th}-unit* capture systems and compression were estimated using cost relationships adapted from the literature [6-8] based on actual characteristics of each CO_2 source including plant type, process and fuel type, emissions rate, pressure, and location-specific electricity prices [9]. A 90% capture efficiency was applied to all sources, and U.S. and global sourced cost estimates were converted to expected mid-range costs in China by application of adjustment factors based on IEA assumptions [10]. A detailed description of the development of the fully integrated end-to-end CCS cost curve may be found in a recent article published by the authors [4].

The resulting CCS cost curve is shown on the right panel of Fig. 1. Each individual point on the curve represents a unique pairing of a specific CO_2 source and its selected lowest-cost available storage option, subject to capacity constraints and competition amongst sources for nearby storage capacity. The color of each point identifies the type of CO_2 storage formation selected, and the position on the curve reflects the net CCS cost (y axis) and contribution to the cumulative annual CO_2 stored (x axis) from each paired CCS project. The curve shows that based on the set of existing CO_2 sources and candidate storage options, over 2,900 million tons of CO_2 could be stored annually within onshore geologic formations at costs ranging from as low as -\$60/tCO_2 to more than \$200/tCO_2. More importantly, however, the bulk of the CCS potential, representing over 80% of the combined annual emissions from all existing sources, could be achieved at costs less than \$70/tCO_2. This suggests that CCS could represent a significant greenhouse gas mitigation option for China [4]. Further, there may be as much as 175 million tons of CCS potential available at very low and potentially even negative net costs, if enhanced oil recovery (EOR) based CO_2 storage can be as successfully developed in China as modeled here.

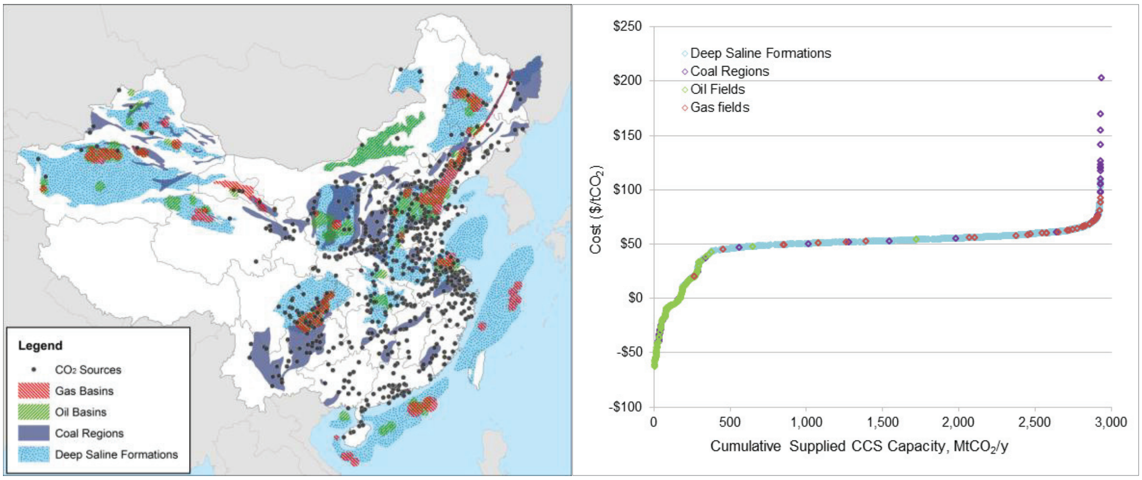

Figure 1. Map of large CO_2 point sources and CO_2 storage reservoirs in China (left) and resulting integrated CCS cost curve incorporating component costs for CO_2 capture, compression, transport and storage, colored by storage reservoir class (right)

The cost curve shown in Fig. 1 represents deployment potential for CCS within the first 20-year modeled time-step of full-scale deployment (i.e., all CO_2 sources simultaneously seek to capture their CO_2 and store it within an accessible storage formation at the lowest net cost). Subsequent 20-year analysis intervals have been examined which have shown that the overall supply of moderately priced CCS capacity around \$40-70/tCO_2 is sufficient for many decades of full-scale CCS deployment and well over a century of more realistic deployment, although the lowest net cost options are used up more quickly [4]. This is because there appears to be a relatively limited supply of storage capacity in depleted oil fields and coal bed methane fields that may be suitable for CO_2-enhanced hydrocarbon recovery, compared with the vast and widespread capacity that is estimated to be available in deep saline formations (DSFs).

The four panels of Fig. 2 highlight the variation in CCS component costs for the individual projects that make up the overall cost curve (displayed for reference in dark blue on each chart). As shown, capture costs range from \$0 (for high purity CO_2 emissions sources) to more than \$55 per ton (for sources emitting lower concentrations of CO_2). Compression costs vary over a narrower range, estimated at \$7-15/tCO_2 for this set of sources, driven mostly by electricity price followed by CO_2 flow rate and inlet pressure [4]. Costs to transport the CO_2 via pipeline from each industrial facility or power plant to its storage reservoir range from \$0.23-33.00/tCO_2 due primarily to a combination of CO_2 flow rate and transportation distance. Storage costs are the most highly variable and incorporate capital and O&M costs associated with site characterization; CO_2 injection infrastructure; production and CO_2 recycling infrastructure for oil and coalbed methane fields; plus MVA. Storage results span a range of nearly \$200; lowest costs fall in the negative range due to offsetting revenues from CO_2-enhanced hydrocarbon recovery and the highest modeled costs exceed \$100/tCO_2 for distant storage formations with low injectivity and limited capacity.

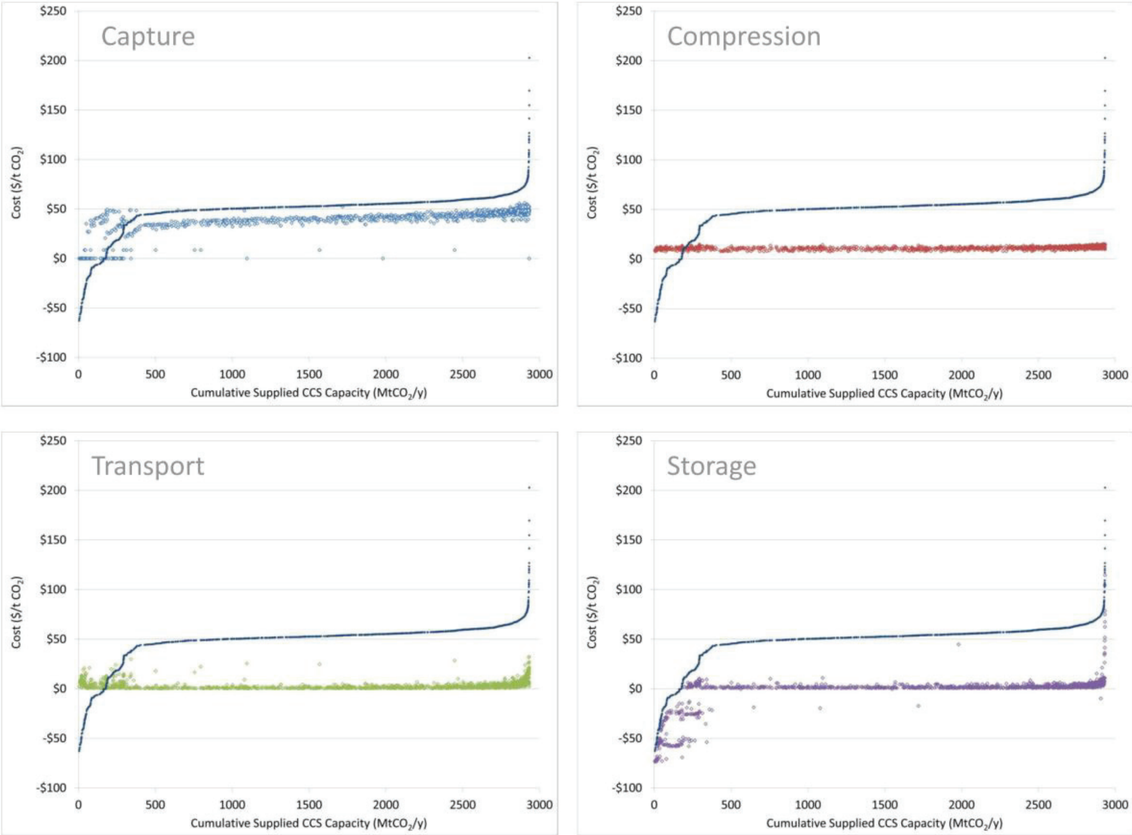

Figure 2. Total integrated CCS cost curve for China (dark blue) displayed with each individual contributing component cost for capture, compression, transport and storage. The net cost and resulting position on the cost curve for each source-sink pair depends on the unique combination of characteristics that define the each contributing component cost.

This work demonstrates that, while broad generalizations of CCS component costs are often made, component costs can indeed be highly variable and depend on the unique combination of characteristics for the specific CO_2 source and geologic storage reservoir under consideration. Such costs are strongly influenced by the type and size of CO_2 source, distance to its selected storage location, and a number of characteristics of the storage reservoir itself, among other factors. In fact, while most high purity CO_2 sources appear at the low cost end of the curve, there are a significant number of high purity sources with higher net CCS costs as well, including one in the very high cost tail of the curve. Further, a number low-purity sources fall in the low-cost portion of the curve, highlighting the importance of considering candidate project characteristics in totality when assessing deployment potential. While CO_2 capture often represents the largest component cost for most CCS projects, having a high-purity CO_2 source is not sufficient to guarantee a low-cost CCS project; nor does lower CO_2 purity necessarily preclude a source from being considered attractive for early demonstration or commercial projects.

3. Mapping the resulting CCS costs

By evaluating both the underlying component costs and their influence on the total net CCS cost of potential projects, the cost curve provides a valuable tool for understanding the potential magnitude and cost of emissions mitigation across key sectors of China's economy. The curve provides unique insight into which projects may represent true low-cost opportunities for early CCS deployment, as well as the regional distribution of possible expanded commercial deployment. Fig. 3 presents a map of the distribution of CO_2 source-sink pairings that make up the integrated cost curve, highlighting net CCS cost by CO_2 source size and location. The main map and accompanying maps, providing greater clarity on the results within each cost range, illustrate that potential CCS projects of varying sizes and costs appear possible across most regions of China.

Low-cost CCS options (shown in green, with net costs less than \$25/tCO_2) may be present within parts of 26 provinces, municipalities and autonomous regions across China. There are multiple pairings within most areas, although Shandong Province, where the large Shengli oilfield and other oilfields of the Bohai Basin are located, contains the largest number. This abundance of relatively low-cost CCS options suggests that, at this level of analysis, a number of areas appear economically attractive and invite further study to identify those regions and sites best suited for pilot and early commercial projects. As seen in Table 1, most of these pairings involve high purity CO_2 sources, but other types of sources are also represented. All of the projects with net costs below \$0/tCO_2 target CO_2-EOR and CO_2-ECBM storage processes; the current modeling of these value-added storage options suggests that revenues produced from enhanced recovery of oil and coalbed methane might result in as much as 174 MtCO_2/yr of economically attractive storage, primarily in areas from northeast China through the south central region. The true magnitude and cost potential of these options may well prove more moderate given China's complex geology, and efforts are underway to evaluate the assumptions underlying EOR- and ECBM-based storage costs more closely. The set of pairings with estimated costs up to \$25/tCO_2 includes a more diverse set of CO_2 sources and sinks, although high purity CO_2 sources continue to dominate this part of the curve.

It is in the \$25-50/tCO_2 range where DSF-based storage begins to contribute the largest portion of CO_2 storage, accounting for 88% of the projects and 98% of the annual stored CO_2. A broad mix of CO_2 source types are represented, although this group of projects reflects the overall transition from smaller high-purity sources to larger lower-purity sources. In fact, the set of pairings in this group has the highest average annual CO_2 flow of all of the groups, at over 5.5 MtCO_2/project captured and stored; it is the large CO_2 flow rates from these sources that also contribute to lower costs via economies of scale associated with many of these processes. However, the \$50-75/tCO_2 cost range contains the largest number of candidate CCS projects. These 925 pairings of CO_2 sources and storage reservoirs are capable of storing 1,968 MtCO_2/yr, primarily into DSFs although again all types of storage options are represented. Of these sources, 46% are power plants, 39% cement, and 7% iron & steel facilities. The sources are smaller on average than individual sources in the \$25-50/tCO_2 range, leading to higher costs, however the average source-sink transportation distance lowest of all categories. These CCS pairings largely represent smaller lower purity sources injecting their CO_2 into nearby DSFs with somewhat lower injectivities. As can be seen from the map in Fig. 3, this group of sources (in orange) is not only the largest but also the most broadly distributed across regions of China, with the greatest concentrations in the highly industrialized eastern provinces.

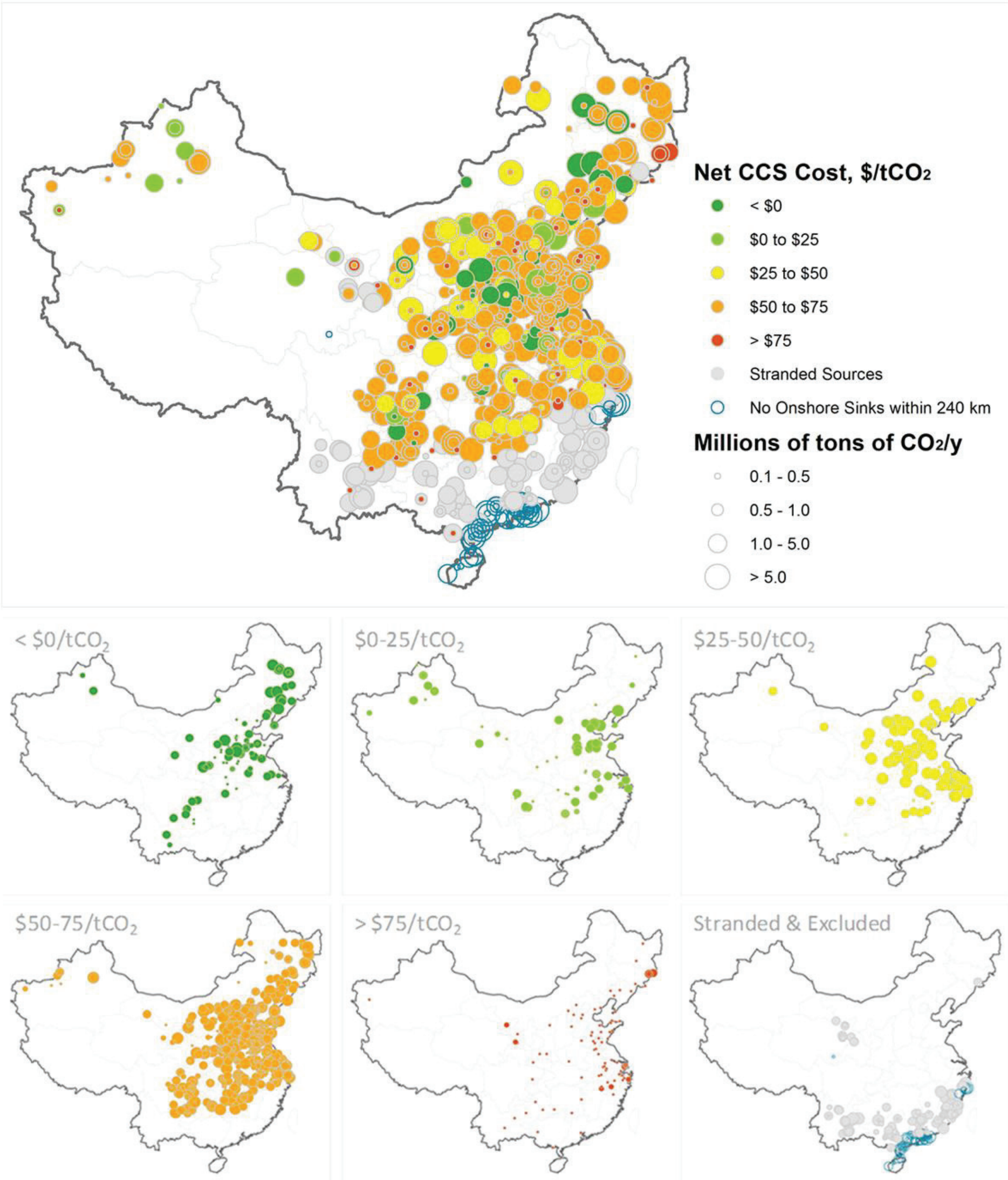

Fig. 3. Map of resulting net CCS cost for each cost curve project pairing, by CO_2 source location and size (top) with separate maps for each specified cost category plus stranded and excluded sources that were unable to access a suitable storage option (bottom)

Table 1. Cost curve characteristics by net cost category

Net Cost Category	# Sources	Avg. Source Emissions, $MtCO_2/y$	Total CO_2 Stored, Mt/y	High Purity Sources	Power Sector Sources	Avg. Transport Distance, km
< $0/tCO_2$	120	1.61	174	95	8	145
$0 - $25/tCO_2$	85	1.48	113	50	3	112
$25 - $50/tCO_2$	131	5.55	655	19	52	106
$50 - $75/tCO_2$	925	2.36	1968	5	426	98
> $75/tCO_2$	112	0.23	24	2	21	146
Stranded & Excluded	250	2.53	632*	14	119	NA

*CO_2 from stranded and excluded sources represents emitted CO_2, not stored

As noted in the authors' recent paper, this large grouping of potential projects with costs between $50-75/tCO_2$ remains largely intact when modeled over additional 20-year analysis intervals assuming full-scale CCS deployment, suggesting that costs in this range may represent a long-term greenhouse gas mitigation backstop in China [4]. Therefore, projects in the cost range extending above $75/tCO_2$ are unlikely to be called upon or needed for CO_2 emissions mitigation in China given the abundance of long-lasting CCS options at lower costs. This highest cost range includes 112 pairings, mostly represented by very small sources able to access more marginal storage options via long pipelines. In many cases, these sources are outcompeted for closer, more attractive storage formations by sources with lower per-ton costs.

The final group highlighted in Fig. 3 and Table 1 consists of 67 sources for which the modeling showed no known storage reservoirs within 240 km and were in effect excluded from the cost-optimized pairing analysis (blue circles) and 183 more for which suitable matched storage capacity could not be obtained over the modeled period (gray dots). While a small grouping of these sources occurs in north-central China, the vast majority are present in southern China and particularly near the highly industrialized coastal zones. While both sets reflect a lack of identified nearby storage capacity based on the maximum modeled transport distance, the stranded and excluded sources in north-central China may be able to access suitable onshore storage reservoirs via longer pipelines, whereas the ability of sources in southern China to do the same may be more limited given the already strong demand for storage capacity by the high concentrations of CO_2 sources to their north. To utilize CCS these sources may either have to pay much higher transport costs to move their CO_2 over very long distances to more available storage reservoirs, or secure storage in closer offshore storage basins. The examination of offshore storage has thus far been outside the scope of this study; however, this key result stresses the importance of evaluating the technical and economic feasibility of offshore storage in China. Early estimates suggest that between 70 $GtCO_2$ [1,3] and 308 $GtCO_2$ [11] may be present in the nearby Pearl River Mouth Basin, and work is underway to integrate offshore storage into the cost curve modeling framework to assess the likely impact on CCS deployment in these coastal regions.

4. Summary

This new comprehensive CCS cost curve, incorporating costs for the full range of CCS component systems – CO_2 capture, compression, transportation, storage, and MVA – offers a valuable and unique perspective from which to examine CCS deployment potential. The integrated cost curve for China suggests that significant CO_2 storage potential exists within onshore storage formations for many decades of large-scale deployment at costs less than \$70/tCO_2. While CO_2 capture costs typically drive the overall net CCS system costs of a project, other individual component costs can play a significant role; the inclusion of a high-purity CO_2 source does not by itself assure a low-cost CCS project or attractive early opportunity. Examining the details of the cost curve more closely and mapping potential projects by size and cost category helps to illuminate the characteristics and distribution of potential options. The analysis confirms that significant CCS potential exists across most of China across a range of costs, but also highlights potential for low-cost opportunities and the strong mismatch between CO_2 sources and onshore storage options in southern China – a region which could greatly benefit from demonstrating the viability of near-offshore geologic storage options. Overall, these results reinforce the key message that CCS appears to offer a significant and valuable greenhouse gas mitigation option for China, over multiple decades, across the varied industrial and geographical landscape, at costs up to around \$70/tCO_2.

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