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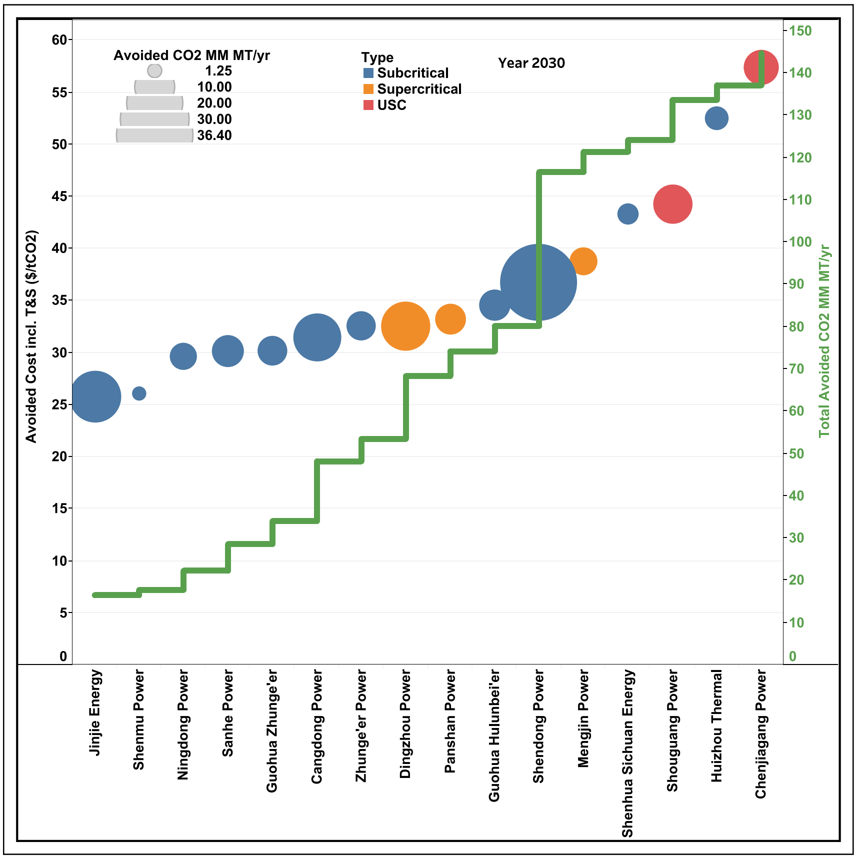

In this study, using a granular analysis of the existing power plant fleet at Shenhua Group, a large power company, we show that local variations in power plant type, operation, geographical location, age, and fuel costs result in significant distribution in the avoided cost of $CO_2$ capture within a single fleet. The fleet analysis initiated in this study is required to estimate the distribution of $CO_2$ capture costs. The strategy addresses the concerns that currently CCS is universally expensive.

## HIGHLIGHTS

One-size-fits-all style of cost estimation is too simplistic

A commercially justifiable pathway to methodically deploy CCS

The avoided cost is as low as $25/$tCO_2$ for the lowest cost plant in the Shenhua fleet

Power plant proximity to T&S sites is critical in assessing CCS deployment pathway

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# Large-Scale Affordable $CO_2$ Capture Is Possible by 2030

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## SUMMARY

**Carbon capture and storage (CCS) is an important option for any "lowest cost" transition to a decarbonized global economy. China, given its large $CO_2$ footprint and strong dependence on coal, is a particularly important player. In this study, we show a pathway for affordable deployment of $CO_2$ capture in the Chinese power sector scaling to greater than 100 million $tCO_2$ per year by 2030 at an avoided cost of less than $\$37/tCO_2$. We show that the distribution of costs across a fleet of power plants presents an underappreciated opportunity to reduce costs and that several avenues are available in the existing policy and market regime to further reduce the net avoided cost of capture to as low as $\$25/tCO_2$ for some plants. This means the rate of deployment of CCS in China will likely be limited by the maturation of transport and storage, rather than the cost of capture.**

## INTRODUCTION

Widespread adoption of CCS technology plays an important role in most integrated assessment modeling studies aimed at identifying the lowest cost trajectories for limiting global climate change.[1,2] Simply put, the ability to affordably transition to a low-carbon economy is greatly improved by having the option to capture and store $CO_2$ from the large existing fossil fuel footprint. Large-scale demonstrations to date show that it is feasible to operate solvent-based capture systems under realistic conditions at selected power plant facilities, but recent weakening of the project pipeline has raised concerns about whether CCS technologies will become a viable commercial option to deliver on its potential for GHG mitigation.[3–6] A primary reason for this is high costs. Cost estimates for $CO_2$ capture have been developed for different capture technologies, different regions, and different operating conditions, but careful attention still needs to be paid to the effects of underlying assumptions.[7–11] Estimates based on technoeconomic modeling of reference power plants and calibrated against demonstration projects suggest significant cost reductions are needed to make CCS affordable in North America and Europe.[7,8] On average, the estimated costs for $CO_2$ capture in China are up to about 30% lower than in Western countries due to a variety of favorable structural features.[9–11] However, these mean values for costs are currently too high to justify deployment at the prevailing rates in China's regional carbon trading markets.

The global variability of costs presents an interesting opportunity to focus on lower cost markets to initiate a supply chain, since reductions in anthropogenic $CO_2$ anywhere in the world contribute equally to efforts to manage the average atmospheric $CO_2$ concentration. Efforts to address the challenge of affordability have focused on a combination of technology development, and policy measures that impose a

### Context & Scale

Given the urgency called for in the recent IPCC 1.5DC report, it is believed that CCS needs to be deployed at larger scale and earlier than generally believed because it could significantly improve the range and affordability of options available to address how the energy ecosystem might evolve in a carbon-constrained future. Previous research holds that CCS is currently too expensive to implement. This study shows the costs can be significantly lower in China to a surprising degree. This is primarily driven by the fact that actual plant parameters are different from reference plant parameters. While a breakthrough would be valuable, our manuscript shows that there are other more impactful factors, such as internal coal pricing, accounting for depreciation of retrofit technologies, breakeven cost basis, priority dispatch for clean power generators, and engineering learning curve and technology development, that can be brought to bear immediately, so the world can get started on CCS now.

sufficiently high price on carbon to motivate action. In the near to intermediate term, additional avenues exist to reduce the cost of $CO_2$ capture so that commercial-scale deployment can begin. In China, efforts to improve urban air quality through the adoption of ultra-low emissions (ULE) pollution controls on power plants over the past few years provide a model for how to bring the costs of introducing CCS at scale into an affordable range.

We observe a number of features from this historical precedent that could apply to the case of CCS. The first feature is the rank order effect, which drives technology adoption at lower cost sites first. For air quality, this occurred in the 1960s in the US and in the 2010s in China as their respective power industries adopted $SO_2$ and $NO_x$ emissions reduction controls.[12–14] Applying this principle to $CO_2$ capture, we note that average values estimated from reference power plants are useful but that actual costs at power plants vary widely due to local differences in system hardware and operation. The importance of variability (due to real differences among power plants) and uncertainty (due to the use of statistical ranges in generalized estimates across populations of power plants) in cost estimates is recognized, but most studies still tend to focus on a single cost value or a probabilistic range estimated using a reference plant.[15] In this study, we show the actual estimated cost distribution for 25 plants in a large power plant fleet. A second feature from the ULE precedent is that the cost structures and operating practices in the Chinese energy sector offer additional opportunities for improving the affordability of $CO_2$ capture. We note five specific aspects: (1) internal coal pricing rather than market price for vertically integrated power companies,[16,17] (2) standardized accounting of capital depreciation for retrofit technologies, (3) a breakeven cost basis for financing of investments that are required by regulation,[18] (4) increased capacity factors and priority dispatch for high compliance generators,[19] and (5) reductions in the cost of capture through technology development and engineering learning curve effects. The effects of these aspects on avoided cost for 25 plants is presented in the results section, and we then discuss the implications of lower $CO_2$ capture costs on the prospects for rapid CCS deployment and energy system decarbonization in China and globally.

## RESULTS

### CCS Avoided Costs for Shenhua Fleet

Figure 1 shows our bottom-up analysis of the cost distribution for retrofitting $CO_2$ capture to a fleet of 25 power plants from Shenhua Group, representing 56 GW of capacity that produced over 260 Mtpa $CO_2$ in 2016.[16] Costs are expressed in terms of the avoided cost of $CO_2$. Details for the calculations and a more in-depth discussion are included as Supplemental Information.[11,20] Results are presented as marginal cost curves, plotting the estimated avoided cost for each plant as a function of the $CO_2$ footprint for a "baseline capture case" (BCC), using standard costing assumptions for hypothetical reference plants while taking into account local design features that are different for each plant (e.g., steam cycle conditions and cooling, power plant size before and after capture retrofit, and utilization hours), and an "affordable capture case" (ACC), which shows the cost reduction potential from costing and operating practices from five aspects mentioned earlier inspired by the example of ULE adoption. The analysis shows that the costs of $CO_2$ capture across the Shenhua fleet follow a distribution where the lowest cost operations can be meaningfully less than the mean, median, and highest costs. The average and minimum avoided costs for $CO_2$ without transportation and storage (T&S) in the BCC scenario are \$69 and \$49/t$CO_2$, suggesting that the lowest cost opportunity is over 29% less expensive than the average. The savings are even more pronounced in the ACC scenario with the average and minimum avoided cost without

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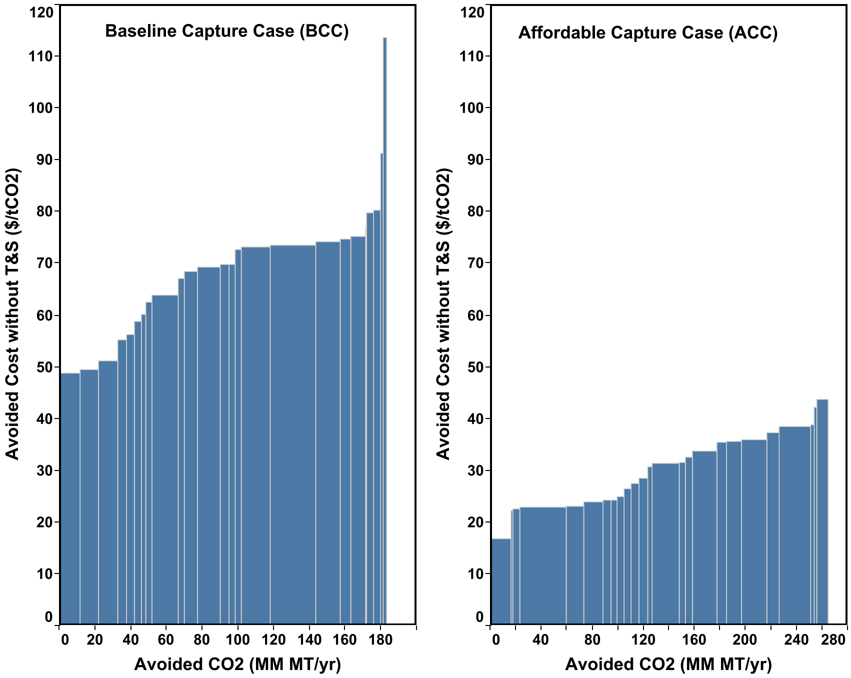

**Figure 1. Marginal Cost Curves for Shenhua Fleet under Baseline Capture Case (Left) and Affordable Capture Case (Right) without T&S**

T&S to $30 and $17/tCO$_2$ captured, respectively. The lowest quartile corresponds to an avoided CO$_2$ of 45 MM tpa at a cost lower than $56/tCO$_2$ for BCC and an avoided CO$_2$ of 66 MM tpa at a cost lower than $23/tCO$_2$ for ACC without T&S. An exchange rate of 6.5 RMB:1 USD was assumed throughout this study.

## Pathways for Reduction in CCS Avoided Costs

Figure 2 shows cost walks from the baseline case to the affordable case for five power plants from the Shenhua fleet, corresponding to the minimum, 25th percentile, median, 75th percentile, and maximum avoided cost of CO$_2$. To minimize confusion, we only included the Shenhua plants with T&S costs that are within 50% of the capture costs. This more granular presentation of the results highlights the relative contributions from each of the cost reduction factors. The first bar shows the avoided costs for the BCC. The intermediate bars show the potential savings associated with each of the cost reduction factors introduced earlier, culminating in the ACC cost. For context, the maximum trading value for CO$_2$ in regional emissions trading pilots in China in 2017 was about $10/tCO$_2$ (70 RMB/tCO$_2$), and incentives for compliance for the retrofitting of ULE to power plants were 10 RMB/MWh for early adopters before 2016 and 5 RMB/MWh for later movers.[21,22,23] The values of these prices relative to the costs of CCS for a particular plant, and the cost of alternatives for low-carbon electricity will determine the ultimate affordability and deployment of CCS across the power sector.

Figure 3 shows distributions for the cost savings factors from all of the plants in the analysis. The highest contributions are from the use of internal pricing for fuel and increased capacity factor. Fuel costs are a meaningful contributor to overall electricity costs, and their importance is amplified by the efficiency penalties associated with retrofitting a power plant for CO$_2$ capture. Internal coal pricing is representative of the true costs of CO$_2$ capture, and coal prices vary widely across the country (22–80$/ton in

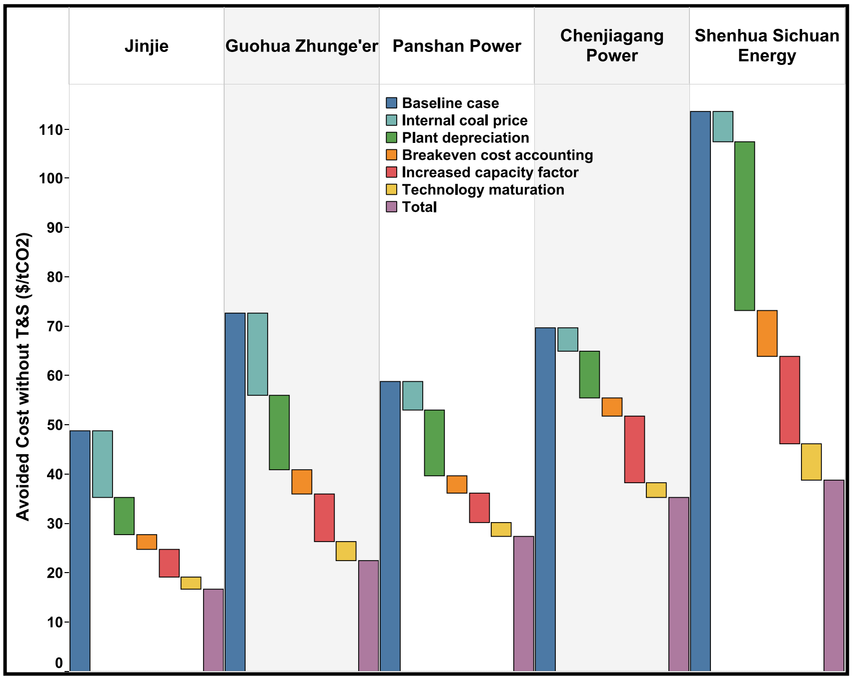

**Figure 2. Cost Waterfalls Showing the Relative Contributions of Internal Coal Price, Plant Depreciation, Breakeven Cost Accounting, Increased Capacity Factor, and Technology Maturation to the Difference between Avoided Costs in the BCC and ACC Scenarios**

2016).[17] The second and third bars correspond to benefits related to investment required for compliance with regulation. Adjustments in cost bases related to plant depreciation accrue disproportionately to older plants, which may benefit from extended life after retrofitting.[18,24] In China, power plants follow a straight-line depreciation method over 15 years. The power plant capital is amortized over the same number of years. The plants that are older than 15 years are treated as fully depreciated units. For plants that are less than 15 years old, an amortization factor is calculated based on the ratio of plant age to 15 years.[24] Hence, the plants that are older benefit from reduction in power plant capital and results in lower COE. It should be noted that lower COE is calculated for both the retrofitted plant with carbon capture and the baseline "reference" plant for each case. A second option of treating the plant capital cost would be to treat it as sunk capital and remove it from the estimation of COE. The sunk capital method is a more optimistic case and will further reduce the COE's and the avoided costs. The "breakeven" cost metric represents a company's internal cost of generating low-carbon power and provides a proper basis for comparison against other forms of low-carbon power generation, and the proper basis would be the "generator's cost."[25] The generator's cost would include internal fuel costs, which is shown as a separate factor. In Chinese electricity markets, annual electricity output is still regulated, and so, an increase in the capacity factor to compensate for the reduced efficiency could be accommodated by provincial transmission authorities. Such a change would improve the annual cost basis for electricity generation.[26] Here, we show the results for normalizing the total annual electricity output to the baseline output before retrofitting with $CO_2$ capture. The high variability in both of these factors is tied to the underlying variation in coal prices across the country and the different types of power plants in the fleet.

The final bar shows the potential cost savings from a 30% reduction in capital costs over existing solvent-based technology. We do not specifically define the nature of

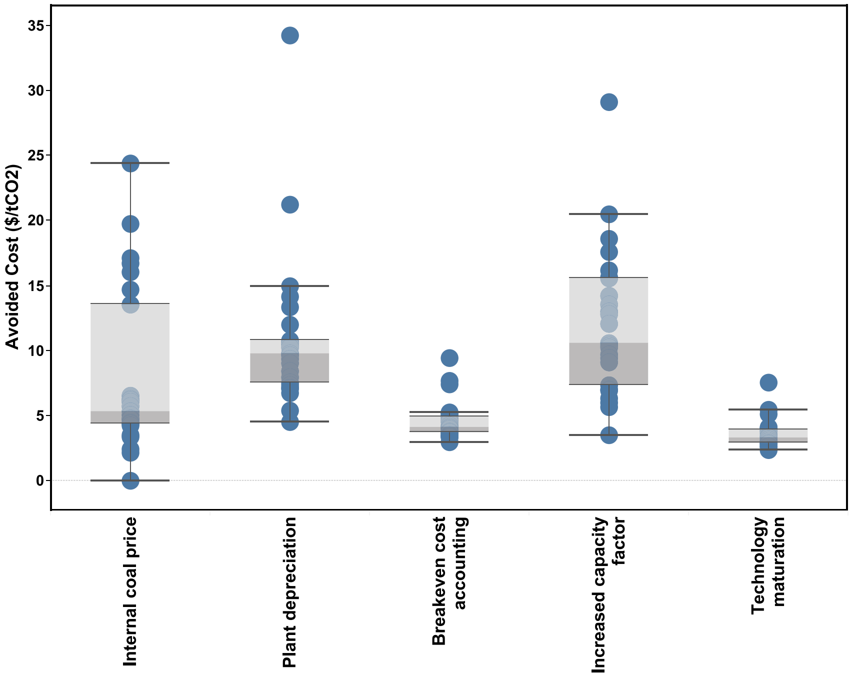

**Figure 3. The Distribution of Avoided Cost Savings across the Shenhua Fleet from the Five Factors Analyzed in This Study**

the technology maturation effect—it can be achieved through either new technology introduction or the engineering learning curve. Savings of 30% are consistent with research and development (R&D) roadmaps from the United States Department of Energy (USDOE) and more conservative than the 67% reduction estimated by Sask Power in progressing from its Boundary Dam project to Shand power plant.[27] The noteworthy implication here is that technology maturation, while important and necessary for CCS to reach its full cost potential, need not be the prime pathway for achieving affordability in CCS in the near term.

The combined impact of the factors is that cost-competitive $CO_2$ capture may be available within China coinciding with the announced start of a national emissions trading market in 2020.[22] An initial key feature of the market is an obligation for the power sector to participate, with an initial fleet-averaged $CO_2$ intensity target of 550 $gCO_2$/kWh.[28] Power companies can reach the goal of 550g/kWh through a combination of renewables (e.g., hydro, wind, and solar) or nuclear generation and CCS. For individual coal power plants, reaching the intensity target will require a $CO_2$ capture rate of about 50%. With a current cumulative global CCS capacity of about 40M tpa, the deployment of CCS in the lower quartile of the Chinese power sector could more than double the world's existing installed base.

## DISCUSSION

Low $CO_2$ capture costs reduce one of the primary barriers to large-scale CCS deployment. This section considers three additional questions related to establishing commercial supply chains in China. First, how are our results impacted by the additional costs associated with offtake of captured $CO_2$? Second, how representative is the Shenhua fleet of the overall fleet in China? Third, what do our results mean for the role of CCS in energy system decarbonization in China? A final consideration is what our results might mean for the development of CCS outside of China.

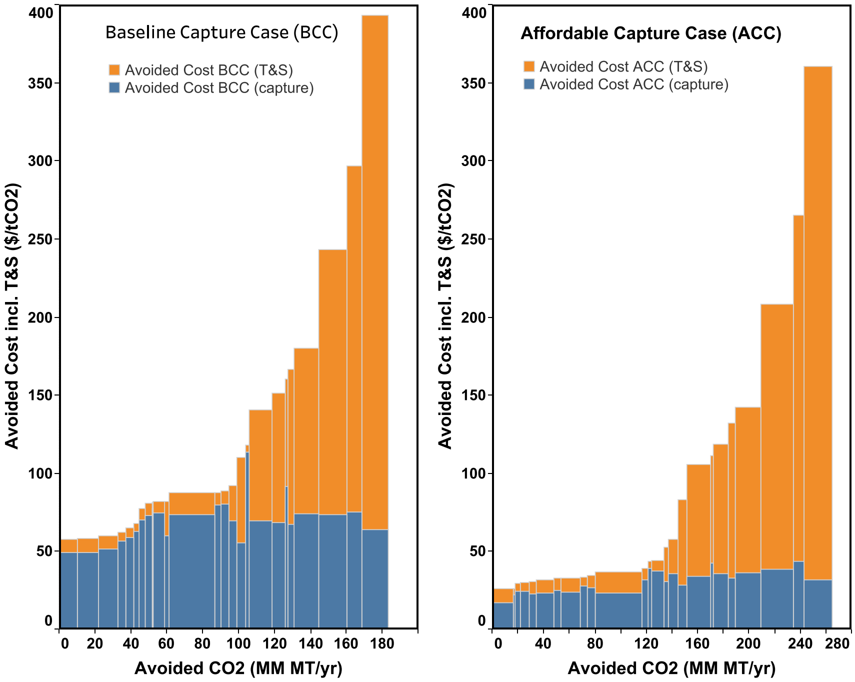

**Figure 4. Marginal Cost Curves for Shenhua Fleet under Baseline Capture Case (left) and Affordable (Right) Capture Cases with T&S (Orange)**

## Path to Large-Scale Deployment of CCS in China

A whole chain perspective is needed when considering actual CCS deployment. Power plants with low capture costs but are located far from storage options become less favorable once T&S costs are included. China must continue to mature its capabilities for T&S or utilization of captured $CO_2$. This need is well recognized by the Ministry of Science and Technology (MOST) and is a point of emphasis in China's recently released roadmap for CCS.[29]

Figure 4 shows the estimated T&S costs for each plant in our study, using both the BCC and ACC scenarios. T&S cost methodology follows the method of Wei et al.[30] Transport costs were estimated using a published model of transport cost as a function of $CO_2$ mass flow rate and pipeline length. The average annual $CO_2$ capture rate was used to estimate the mass flow rate and the geographic distance from the plant to geographic center of the closest onshore sedimentary reservoir was used in our calculations. A source-sink matching was used for the Shenhua fleet and sedimentary basins in China. We assume saline aquifer injection is a mature commercial technology by 2035. A flat storage cost of 2.93$/t$CO_2$ was used for Shenhua fleet.[31] The transport costs for the Shenhua fleet ranges from $4–$360/t$CO_2$. Additional details are provided in the Supplemental Information section. The key conclusions of our analysis concerning the width of the distribution and the absolute costs at the low end of the distribution are unchanged; the addition of T&S costs widens the cost distribution, but the lowest cost opportunities still remain less than $32/t$CO_2$ for at least 25% of the fleet. Figure 4 also shows that there are some plants with low capture costs but high T&S costs, primarily due to the proximity of the plants to sequestration sites.

In our analysis, we assumed sequestration in saline aquifers as a conservative option for $CO_2$ offtake. We note that there is widespread global interest in the use of

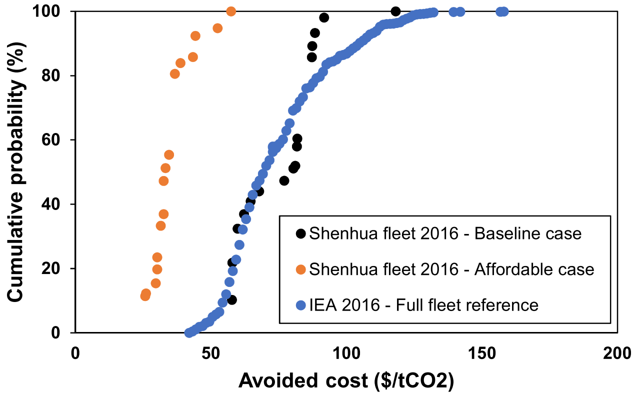

**Figure 5. Cumulative Distribution Function for Avoided Cost for the Shenhua Fleet and Relative to a Broader Study of the Entire China Coal fleet from 2016**

captured $CO_2$ in applications that could generate an offsetting revenue to further improve the economics of CCS; a similar dynamic also applies in China. A recent International Energy Agency (IEA) study estimated that EOR applications in China could value $CO_2$ at up to \$30/t$CO_2$.[32] Such levels would be enough to offset the capture costs at a significant number of early mover power plants. Demonstration projects have been completed in China for both storage and EOR at the scale of 0.1 Mt$CO_2$ per year, and our analysis shows that further scale-up into a comprehensive transport and storage network, rather than $CO_2$ capture costs, is likely to be the rate determining step in CCS deployment.

The power plants in the Shenhua fleet are qualitatively representative of the overall Chinese fleet in that they reflect the breadth of configurations and are geographically distributed across the country. Figure 5 quantitatively compares the cumulative distribution functions (CDF) for the BCC and ACC scenarios of the Shenhua fleet to the CDF computed from an earlier, but less granular, study of costs across the entire China Coal fleet comprising 560 GW of capacity from 2014.[10] The distribution of baseline capture costs from the entire Shenhua fleet align well with the IEA data, indicating that results from the Shenhua fleet are consistent with general situation across China, particularly at the low cost end of the distribution. However, we did observe a significant divergence in the total cost at the high end of the cost curve due to differences in how we calculate T&S costs, suggesting that further attention is needed to understand T&S costs and that geographic proximity to adequate geological sequestration may be the limiting factor in how many plants in the fleet will ultimately participate in CCS. Again, to minimize confusion, we only included the Shenhua plants with T&S costs that are within 50% of the capture costs. Assuming that the low cost tail in the distribution is comparable, extrapolation of the results from the Shenhua fleet (56 GW) across the entire Chinese power sector (1,000 GW) suggests that well in excess of 100 MM t$CO_2$ per year of emissions from coal-fired power plants could be captured at costs less than \$37/t$CO_2$ including T&S in the timeframe needed to establish the ACC market and financial incentives.

## CCS Deployment in the Context of Energy System Transformation in China

China is in the process of aggressively expanding its installed base of intermittent renewable generating capacity; for example, the 13th Five-Year plan calls for wind generation capacity to expand from 149 GW in 2016 to 210 GW by 2020.[33] This aggressive expansion is accompanied by electricity market reform, motivated in part by a desire to facilitate the integration of renewable electricity onto the grid.

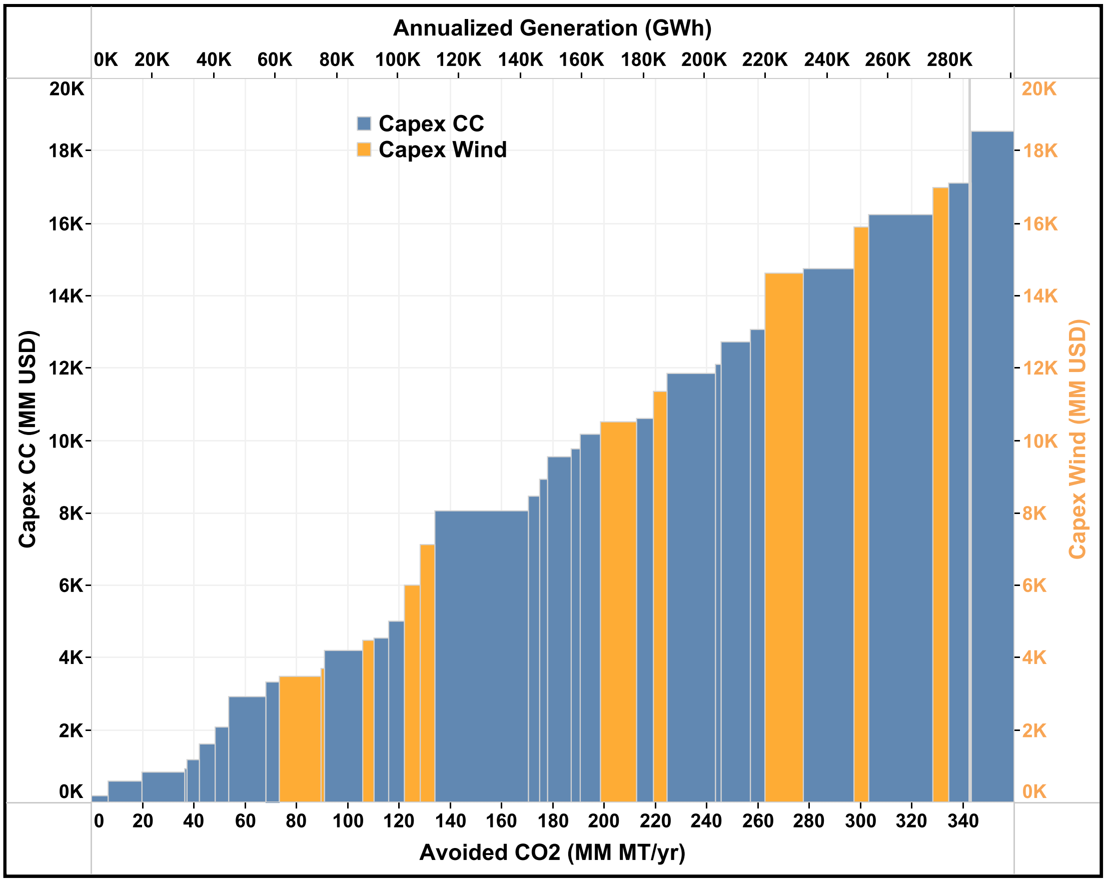

**Figure 6. Marginal Cost Curve Showing Carbon Capture and Wind as Complementary Options for Decarbonization**

As in other parts of the world, technical barriers related to flexibility and economic barriers such as market and institutional inefficiencies make this a difficult challenge. Cost-competitive, dispatchable, low-carbon energy from coal plants equipped with CCS could aid efforts to expand renewable energy generation by providing additional system flexibility. Studies performed for the UK suggest that even limited amounts of dispatchable energy from power plants equipped with CCS provide significant value in this regard.[1]

From the perspective of decarbonization, the most affordable path involves a merit-order of deployment based on cost. One implication of our cost analysis is that a wide cost distribution for CCS creates opportunities for the cooperative deployment with other options, such as renewable energy, as part of a broader effort to decarbonize the energy system. In other words, CCS could be affordably deployed in a cooperative manner alongside expanding renewable capacity. To illustrate this point, Figure 6 shows a marginal cost curve for the Shenhua fleet with estimates for the co-deployment of wind power capacity. For this example, we use a "generic" estimate of wind farm costs in China; the general principle of cost distributions applies to wind installations as well, but for the purposes of this illustration, it is ignored. Details for the calculations and a more in-depth discussion are included as Supplemental Information. The capital investment required for wind power is computed from the specific capital investment and the capacity factor. Liu et al. estimated that a wind installation in China would need a specific capital investment of $677/kWh[34] in 2020 with operation ranging from 1,500 to 2,300 h per year corresponding to a capacity factor of 0.17 to 0.26. Wind installed capital costs in China have been projected between $600–$1,115/kWh by other sources.[35] In our judgment, a 20% capacity factor is reasonable and a 30% capacity factor is aggressive. The cost curve shows that mixed deployment strategy involving both wind and CCS can offer a lower cost approach toward decarbonization than a "CCS -only" or "wind-only" approach.

We conclude the discussion on China with a brief comment on electricity pricing and electricity market reform in China. Currently, electricity dispatch and pricing are regulated according to guidance from planning authorities. Efforts to introduce more dynamic mechanisms are underway, with active pilots in several jurisdictions. However, reform is a complicated process, and the evolutionary trajectory and final structure of the market are still not clear. This framework presents headwinds to CCS deployment, in the form of uncertainty. However, it may also offer opportunities to establish incentives to further accelerate CCS adoption.

During the ULE deployment process, power plants were offered increased operating hours and a power tariff incentive for early adoption, along with stiff penalties for violations of absolute limits on $NO_x$, $SO_2$, and particulate emissions.[19,23] It is not difficult to imagine a similar incentive being offered for plants equipped with CCS, as part of or independent from the national emissions trading system. In addition, different power tariffs are offered to different forms of power generation in Chinese energy markets, with wind and solar receiving a premium over coal, hydroelectric, and nuclear generation.[36,37] Power tariff premiums for wind and solar over coal power ranged from 160 to 250 RMB/MWh in 2017, equivalent to about $27 to 43/t$CO_2$ avoided.[22] Interestingly, natural gas power plants are offered higher tariffs approaching 110 to 340 RMB/MWh, worth $29 to 88/t$CO_2$ avoided. While the primary purpose of these premiums was to establish a market for renewable energy and to offset the higher fuel costs for natural gas-based generation in China, they establish a valuable historical precedent for apply a similar, appropriately scaled incentive to make coal-CCS plants with carbon intensities consistent with natural gas (about 65% capture equivalent) or renewables (>90% capture equivalent) fully competitive against other forms of low-carbon electricity.

## Implications for Global Deployment of CCS

A final note concerns the generalizability of our findings to countries outside of China. A similar approach in considering CCS cost distributions could be useful in identifying lowest cost paths toward to decarbonization in other countries. We stress that our approach is not a new methodology but rather a proper application of existing methods to understand and appreciate the implications of variability across actual assets in a power generation fleet.

While many of the factors driving a significant opportunity with absolute costs below $30/t$CO_2$ are unique to the Chinese system, incentives exist in other countries that might be incorporated into "ACC" scenarios for other parts of the world. For example, an ACC scenario for the US might focus on natural gas power plants and take into account available tax incentives. The 45Q tax credit is offered for geologically stored $CO_2$ and could be considered a cost offset (akin to EOR revenues) in the framework presented in this study. It would impact financial viability of projects but would not change the underlying economic structures of the $CO_2$ capture process. A more applicable parallel in the US is the 48A tax credit, which is offered for capital investment in advanced coal generation technologies. Here, the incentive offsets some of the capital costs of the project but does not alter the financing terms or operating conditions of the facility. Ultimately, lowest potential costs will depend on the width of the cost distribution and the value of applicable incentives.

The approach to use prevailing conditions in existing methodology as suggested by this study can be used to identify pathway to accelerate CCS deployment worldwide. Commercial CCS hubs at larger than 1 million $tCO_2$ per year, as called for by the MOST roadmap, could offer valuable lessons for CCS deployment in other parts of the world. Economies of scale in manufacturing have benefited a number of other technologies, and large-scale deployment of CCS technologies in China might confer similar cost savings in this arena that could be exported to other countries as well.

### Conclusions

The cost of $CO_2$ capture across power plants in China has been shown to have a wide distribution due to a combination of technical and market factors. In China, several avenues in the existing policy and market regime can be applied reduce the avoided cost of $CO_2$ to as low as \$25/$tCO_2$. Extrapolation of our results from our case study fleet of 25 power plants across the entire Chinese power sector suggests that significant volumes of $CO_2$ could be captured using CCS retrofits at coal-fired power plants for costs on par with other options for low-carbon energy. The actual rate of deployment of CCS in China will likely be limited by maturation of transport and storage capabilities rather than the cost of capture and could coincide with other developments in the transformation of the energy system such as renewables deployment. Globally, this approach could be used to identify lower cost opportunities to accelerate CCS deployment in other countries but could have the most impact through its contribution to maturation of the CCS supply chain in China.

## EXPERIMENTAL PROCEDURES

Full experimental procedures are provided in the Supplemental Information.

## SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.joule.2019.08.014.

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## AUTHOR CONTRIBUTIONS

A.Y.K., S.P.S., H.L., and C.W. developed the original concept. S.P.S., P.H., H.L., and A.Y.K. developed the cost estimates and performed the analysis. Key assumptions for the affordable capture case were validated by C.W., W.Q.X., and X.L. S.P.S., P.H., and A.Y.K. created the figures and wrote the majority of the paper along with help from all the other authors. P.H., N.W., and X.L. estimated the storage costs for each power plant. S.P.S. and A.Y.K. estimated the cost competitiveness of C.C.S. and wind. All authors contributed to data review and consistency checks.

## DECLARATION OF INTERESTS

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