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The impact of CCS readiness on the evolution of China’s electric power sector

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Abstract

In this study, GCAM-China is exercised to examine the impact of CCS availability on the projected evolution of China’s electric power sector under the Paris Increased Ambition policy scenario developed by Fawcett et al. based on the Intended Nationally Determined Contributions (INDCs) submitted under the COP-21 Paris Agreement. This policy scenario provides a backdrop for understanding China’s electric generation mix over the coming century under several CCS availability scenarios. In all scenarios, the electric power sector shifts towards low-carbon generation technologies including significant nuclear, wind, and solar to meet growing demands and emissions targets. The availability and timing of CCS technologies to deploy at scale impacts the resulting generation mix and mitigation costs. Should large-scale CCS deployment be delayed in China by 25 years, the modeled per-ton cost of climate change mitigation is projected to be roughly $420/tC (2010 US dollars) by 2050, relative to $360/tC in the case in which CCS is available to deploy by 2025, a 16% increase. Once CCS is available for commercial use, mitigation costs for the two cases converge, equilibrating by 2085. However, should CCS be entirely unavailable to deploy in China, the mitigation cost spread, compared to the 2025 case, doubles by 2075 ($580/tC and $1130/tC respectively), and triples by 2100 ($1050/tC vs. $3200/tC). However, while delays in CCS availability may have short-term impacts on China’s overall per-ton cost of meeting the emissions reduction target evaluated here, the net impact is much smaller compared with not having CCS available within the century and in each case the carbon price is likely to approach the price path associated with the full CCS availability case within a decade following CCS deployment. Having CCS available before the end of the century, even under the delays examined here, could reduce the total amount of nuclear and renewable energy that must deploy, significantly reducing the overall cost of meeting the emissions mitigation targets.

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1. Introduction

With one of the most rapidly growing economies in the world, the continuing development and expansion of China’s electric generation infrastructure is of global interest as society grapples with how best to address atmospheric greenhouse gas levels. Of particular interest is how China might meet environmental quality and related emissions goals while also using its enormous domestic coal resources and coal-dominant electric generation and industrial infrastructure. CO₂ capture and geologic storage (CCS) is widely discussed in the research and policy communities as an important technology for enabling the transition to low-carbon energy systems. China understands the importance of CCS technologies for lowering their carbon emissions and in a recently released CCS Roadmap [1] outlines and recommends specific actions and activities towards a phased CCS demonstration and deployment approach covering periods to 2020, 2030, and beyond. Yet, constraints including the timing, availability and costs to access CO₂ storage resources in China could significantly impact the degree to which CCS may be utilized effectively within the portfolio of low carbon options. This study examines the impact on China’s electric power sector of variations in timing of CCS deployment readiness, while continuing efforts to reduce carbon emissions.

GCAM-China is a new extension of the Global Change Assessment Model (GCAM)¹ providing enhanced detail for China at the level of each province, autonomous region, and municipality. The China-focused module of this integrated assessment model allows evaluation of multi-sectoral energy supply and demand, coupled resulting emissions, within a consistent energy, economic, and climate modelling framework allowing the impacts of global energy and climate mitigation scenarios to be evaluated over the course of this century at regional levels within China. The level of detail in the electric, transportation, buildings and agricultural sectors facilitates the evaluation of impacts on the deployment of various technologies over time in response to energy, resource, and economic signals. The impact on the deployment of conventional technologies can be compared against those of low-carbon technologies such as nuclear, hydro, renewables, and energy efficiency measures. Building on previous work led by Dahowski [2-5], Dooley [6-8], Edmonds [9-11], Kim [12], and Wei [13], the authors have incorporated province-specific CCS supply curves into GCAM-China to incorporate a more detailed and nuanced evaluation of fossil and biomass coupled CCS technology deployment potential within the mix of available low-carbon energy and electricity generation options.

2. Methodology

In this study, GCAM-China is exercised to examine the impact of CCS availability on the projected evolution of China’s electric power sector. After Fawcett et al. [14], the climate change mitigation scenario selected for this analysis is based upon the Intended Nationally Determined Contributions (INDCs), per national-level COP-21 commitments, for carbon reductions through 2030. Beyond 2030, Fawcett et al. implement a 5 percent annual emissions reduction continuing through the end of the analysis period in 2100. This allows an examination of scenario-specific evolution of China’s generation portfolio over the coming century, under four variations in CCS availability: CCS is fully available for commercial-scale deployment by 2025, 2050 and 2075, and CCS is unavailable for use in meeting the modelled mitigation targets. These four cases are compared against a Reference Case, which reflects existing policy through 2010, but which assumes that no new policies, including those resulting from the COP-21 negotiations, are enacted beyond 2010.

¹ GCAM is a dynamic-recursive model that projects global energy use, land use, and resulting emissions through the end of the century.
These cases are evaluated within GCAM-China using newly integrated province-specific cost curves. While the methodology and results of the provincial cost curve study will be discussed in detail in a forthcoming manuscript, the resolution these new curves enable for the present analysis is worth noting. In particular, as discussed in previous studies, there is a significant degree of heterogeneity in the spatial distributions of China’s CO₂ source fleet as well as its CO₂ storage resources [15], though there is sufficient co-location across most of China to suggest that CCS could provide an important mitigation option [4]. However, known mismatches exist—particularly in southern coastal provinces such as Guangdong—between the limited availability of onshore geologic CO₂ storage capacity and the potential demand, as reflected by the existing CO₂ source fleet. In this case, the use of provincial CCS cost curves to parameterize storage resources and associated costs within GCAM-China allows a more detailed and nuanced examination of the impacts of different policy and technology scenarios on CCS deployment across regions of China. The mechanics and greater breadth of impacts of this approach will too be treated in greater depth in another forthcoming journal manuscript, while this current analysis focuses on how the availability of CCS, and timing thereof, impact the evolution of China’s electric generation sector.

3. Results

Figures 1 and 2 present the resulting composition of China’s electric power sector through 2100, as modeled under the Reference Case, and Paris—Increased Ambition policy scenario where CCS is fully able to deploy by 2025 (PIA-CCS) or delayed until 2050 (PIA-2050), 2075 (PIA-2075), and 2100 (PIA-X). For each 5-year period through 2100, beginning with actual generation in 1990, the mix of electric power generation in China is shown, to highlight projected changes in generation from technologies including coal and other fossil technologies, biomass, nuclear, hydro, wind, solar, and CCS deployed with fossil and biomass energy. Because policy is fixed across cases, each scenario shown reflects the same degree of emissions abatement, achieved using the technology specifications noted. With the exception of how CCS availability is modeled in each scenario, all other technologies are identically parameterized. The results therefore highlight the impact that the availability of commercial-scale CCS technology has on the structure of China’s electric power sector as well as costs to meet emissions reduction targets in the policy scenarios.

Figure 1. Annual electric power generation (EJ/y) in the Reference Case (top), PIA-CCS (middle) and PIA-X (bottom) cases.
3.1. Policy impact with and without CCS

Figure 1 compares the Reference Case with the PIA-CCS and PIA-X cases. First, it’s important to note that both policy cases result in increased electric generation in 2100, 46 EJ and 53 EJ under PIA-CCS and PIA-X, respectively, compared with 36 EJ under the Reference Case. This is because the power sector has more abatement options than other sectors, and is more amenable to CCS because of economies of scale associated with large power generation facilities. Coupled with more expensive abatement options in the industrial, commercial and residential sectors, this drives a move towards greater electrification in these sectors to displace on-site fuel use. In the PIA-X case, where CCS is entirely unavailable to all sectors, fuel switching options make electric power one of the most nimble sectors, resulting in even larger demands for electricity under this case, and even greater deployments of non-emitting technologies (solar, wind, nuclear).

In addition to changing the overall size of the electric power sector, the availability of CCS technologies dramatically shifts the sector’s fuel mix. Addressing the PIA target with CCS in the portfolio allows China to continue using coal to provide a significant fraction of its electricity generation. In 2050, coal accounts for 50 percent of generation, of which one-sixth is coupled with CCS. By 2100 30 percent of electricity is produced from coal, fully coupled with CCS. Without CCS, coal’s share drops below 40 percent in 2050 and provides less than an exajoule of generation by 2080. Both policy cases reflect reductions over the Reference Case, where coal accounts for 75 and 60 percent shares of the generation portfolio in 2050 and 2100, respectively.

To offset the reductions in coal-fired power generation and meet additional electricity demand under the PIA policy cases, the GCAM modeling suggests that China would deploy a significant amount of additional nuclear, solar and wind. Table 1 highlights the projected shifts in electricity generation mix under each of the each of the modeled scenarios, at both 2050 and 2100. Nuclear generation in 2100 more than triples from 1.5 EJ in the Reference Case to 5.4 EJ under PIA-CCS; and meeting PIA without CCS could require 11.5 EJ of nuclear generation, a seven-fold increase. Wind would increase from 2.2 EJ/y (Reference) to 5.8 EJ/y (PIA-CCS); without CCS, wind generation is estimated at 14 EJ/y in 2100, making up 27 percent of the generation portfolio, compared with only six percent in the Reference Case. Annual solar generation would increase from 2.9 EJ (Reference) to 8.6 EJ (PIA-CCS); in the absence of CCS, solar generation would rise to 21 EJ annually by 2100. Under PIA-X, solar would account for 40 percent of total electricity generation in China by the end of the century, a five-fold increase.
over its 8 percent share under the Reference Case; with CCS, solar would make up a 19 percent share of the generation mix.

### Table 1. Modelled generation resource mix (% of total generation) for each scenario, 2050 and 2010

<table>
<thead>
<tr>
<th>Generation type</th>
<th>Reference 2050</th>
<th>CCSS 2050</th>
<th>PIA-2050 2050</th>
<th>PIA-2075 2050</th>
<th>PIA-X 2050</th>
<th>Total Generation, EJ/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>75%</td>
<td>61%</td>
<td>43%</td>
<td>0%</td>
<td>39%</td>
<td>35.7</td>
</tr>
<tr>
<td>Coal + CCS</td>
<td>0%</td>
<td>0%</td>
<td>8%</td>
<td>30%</td>
<td>6%</td>
<td>35.8</td>
</tr>
<tr>
<td>Gas</td>
<td>2%</td>
<td>4%</td>
<td>2%</td>
<td>0%</td>
<td>3%</td>
<td>34.6</td>
</tr>
<tr>
<td>Gas + CCS</td>
<td>0%</td>
<td>0%</td>
<td>2%</td>
<td>5%</td>
<td>1%</td>
<td>45.6</td>
</tr>
<tr>
<td>Biomass</td>
<td>1%</td>
<td>4%</td>
<td>1%</td>
<td>0%</td>
<td>2%</td>
<td>35.6</td>
</tr>
<tr>
<td>Biomass + CCS</td>
<td>0%</td>
<td>0%</td>
<td>2%</td>
<td>10%</td>
<td>1%</td>
<td>45.7</td>
</tr>
<tr>
<td>Nuclear</td>
<td>4%</td>
<td>4%</td>
<td>11%</td>
<td>12%</td>
<td>12%</td>
<td>34.7</td>
</tr>
<tr>
<td>Hydro</td>
<td>12%</td>
<td>12%</td>
<td>12%</td>
<td>9%</td>
<td>12%</td>
<td>45.4</td>
</tr>
<tr>
<td>Wind</td>
<td>3%</td>
<td>6%</td>
<td>9%</td>
<td>13%</td>
<td>11%</td>
<td>52.8</td>
</tr>
<tr>
<td>Solar</td>
<td>3%</td>
<td>8%</td>
<td>9%</td>
<td>19%</td>
<td>10%</td>
<td>14%</td>
</tr>
<tr>
<td>Other (oil, geothermal, CHP)</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td><strong>Total Generation, EJ/y</strong></td>
<td><strong>35.7</strong></td>
<td><strong>35.8</strong></td>
<td><strong>34.6</strong></td>
<td><strong>45.6</strong></td>
<td><strong>35.6</strong></td>
<td><strong>45.7</strong></td>
</tr>
</tbody>
</table>

#### 3.2. Impact of delayed deployment

Beyond having CCS as an available technology to meet emissions reduction targets, the timing of having the ability to deploy CCS at scale has an impact on China’s transforming electric generation sector and costs. Figure 2 shows the mix of generation technologies used to meet the Paris—Increased Ambition policy target under two delay scenarios in addition to the scenario where CCS is available to deploy fully by 2025. With a 25-year delay, 47 percent of total generation is CCS-enabled by 2100, but abatement costs through the end of the century show the impact of the other, more expensive low-carbon generation technologies deployed in its absence—increasing total cost of addressing the PIA target by 15 percent over the PIA-CCS case. With a 50-year delay, though, even when all CCS resources are fully available beginning in 2075, and despite the discrete jump in CCS deployment in that timestep, there is already a considerable long-lived capital investment in nuclear, solar and wind generation assets. Thus, even if CCS is available at lower prices, the power sector has largely committed to other generation technologies over the earlier part of the century, and CCS use is limited to replacing retiring coal units and meeting new demand, both of which occur at a slower rate in the last quarter of the century. With a delay in availability of large-scale CCS to 2075, there is 7.9 EJ of nuclear representing 17% of total generation in 2100 and 15 GJ of solar and wind comprising a combined 33% of generation. This compares to 5.4 EJ (12%) and 14 EJ (31%) by 2100 under the no CCS delay scenario. In this longer delay scenario, while carbon prices end the century below those for the other cases, overall abatement cost is increased by 33 percent over the PIA-CCS case. Further, as expected, the cumulative economy-wide demand for CO₂ storage capacity decreases as the delay to availability increases: 41 GtCO₂ under PIA-CCS, 35 GtCO₂ under PIA-2050, and 16 GtCO₂ for PIA-2075.
3.3. Carbon price paths

Figure 3 shows the evolution of carbon price ($/tC, 2010 US dollars) under each CCS availability case. Note that each delay case is associated with higher carbon prices—consistent with the PIA-X price path—until CCS becomes available. However, in each case where CCS becomes available before the end of the century, per-ton carbon prices drop and eventually converge on prices similar to those seen in the case where CCS is fully available throughout the analysis period. In fact, by 2090, carbon prices under the PIA-2075 case drop below the other cases. This is due to investments made under the period between 2050 and 2075, when much higher carbon prices drive installation of additional durable capital in wind, solar and nuclear that persists through the end of the century.

Despite the equilibration of carbon prices toward the end of the century for all cases in which CCS is available, the higher-price periods associated with CCS delays to 2050 and 2075 result in higher overall abatement costs. Where CCS is delayed until 2050, abatement costs in the electric power sector through 2100 increase by 15 percent (NPV); where the delay persists until 2075, abatement costs increase by a third. Where CCS is unavailable through the end of the century, abatement costs for China’s electric power sector could increase by half, as China addresses both increased demand for electricity from other sectors and curtailment of fossil fuel use.

3.4. Provincial impacts

As noted above, under each of the scenarios where CCS is available to deploy at scale at some point during the century, strong demand for the technology ensues with significant CO₂ storage capacity demanded. GCAM-China provides the ability to observe interactions including demand for CCS at the province level. Initial results show that while CCS is demanded to some limited degree in most all provinces, the deployment is not uniform, and driven by unique mix of characteristics including access to suitable onshore storage. Provinces exhibiting the highest levels of CCS-enabled technology and CO₂ storage under these modeled scenarios include Hebei, Henan, Inner Mongolia, Shandong, and Zhejiang. Increasing the time delay for deploying CCS results in modified CCS demand across provinces, most notably towards a relative increase in Sichuan and decrease in Inner Mongolia, among others, due to a shifting role for CCS when available in the latter half of the century when coal use has already been significantly curtailed and a greater focus on biomass with CCS develops in industries outside the power sector.

4. Discussion

This study reinforces the value that CCS technologies have for cost effectively helping meet emissions reduction targets through a balanced portfolio of low-carbon electricity generation technologies. The results suggest that not having CCS available to meet the modelled mitigation targets results in a 49% increase in costs over having CCS ready to deploy within the coming decade, along with significantly more nuclear, wind, and solar energy. Further, while delays in availability of CCS in China may have short-term impacts on the overall per-ton cost of meeting the emissions reduction target evaluated here, and thus will increase the overall cost of doing so, the per-ton carbon price is likely to approach the price path associated with the full CCS availability case within a decade of CCS becoming available. Having CCS available before the end of the century, even under the delays as examined here, could still result in significant savings to the cost of overall climate abatement in China’s electric power sector. Having CCS available to fully deploy in the electric power sector before 2025 could reduce the overall sectoral abatement cost by as much as 33 percent, but even deploying CCS as late as 2075 could result in an 11 percent cost
savings over the PIA-X case, suggesting that, while sooner is better than later for CCS deployment in China, later is better than never. In all cases, having CCS available to deploy significantly reduces the total amount of nuclear and renewable energy that must deploy, and reduces the overall cost of meeting the emissions mitigation targets.

References


