China’s 2060 carbon neutrality goal will require up to 2.5 GtCO\textsubscript{2}/year of negative emissions technology deployment

Jay Fuhrman\textsuperscript{1}, Andres F. Claren\textsuperscript{1}, Haewon McJeon\textsuperscript{2}, Pralit Patel\textsuperscript{2}, Scott C. Doney\textsuperscript{3}, William M. Shobe\textsuperscript{4}, Shreekar Pradhan\textsuperscript{*}

\textsuperscript{1} Department of Engineering Systems and Environment, University of Virginia, Charlottesville, Virginia, USA
\textsuperscript{2} Joint Global Change Research Institute, University of Maryland and Pacific Northwest National Laboratory, College Park, Maryland, USA
\textsuperscript{3} Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia, USA
\textsuperscript{4} Batten School of Leadership and Public Policy, University of Virginia, Charlottesville, Virginia, USA
\textsuperscript{*}Corresponding author, email: shreekar@virginia.edu

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Comments are welcome by contacting the corresponding author directly.

Abstract

China’s pledge to reach carbon neutrality by 2060 is ambitious and could provide the world with much-needed leadership on how to achieve a $+1.5^\circ$C warming target above pre-industrial levels by the end of the century. But the pathways that would achieve net zero by 2060 are still unclear including the dependence on negative emissions technologies. Here, we use the Global Change Analysis Model (GCAM 5.3), a dynamic-recursive, technology-rich integrated assessment model, to simulate how negative emissions technologies, in general, and direct air capture (DAC), in particular, will contribute to China’s meeting this target. Our results show that, for China to be net-zero in 2060, it would need to deploy negative emissions technologies (NETs) at very large scales, on the order of 2.5 GtCO\textsubscript{2} negative emissions per year with up to 1.5 GtCO\textsubscript{2} per year of that coming from DAC. DAC, like other forms of negative emissions, such as bioenergy with carbon capture and storage and afforestation is an emerging technology that has not been demonstrated at a commercial scale. Deploying NETs at this scale will have widespread impacts on financial systems and resources availability such as water, land, and energy in China and beyond.
1. Introduction

On September 22, 2020 China announced that it would pursue a plan to achieve “carbon neutrality” in its economy by 2060. While the number of countries, regional governments, and corporations that have been making carbon neutrality commitments has been accelerating, China’s announcement stands out because of its size as the world’s currently-largest greenhouse gas emitter, and ambitious timeline. China today produces approximately one-third of global greenhouse gas emissions, but much of these emissions result from production of products that are exported to other regions of the world. In addition, primary power consumption in China is currently very carbon intensive with most of the primary fuel supply coming from coal combustion. In order to achieve their target, China will need to decarbonize its power, transportation, and industrial sectors in the near term and seek opportunities for negative emissions in the long term. To achieve carbon neutrality, an institution needs to balance emissions and sinks. For any large and complex economy, there will be sources of emissions that will be recalcitrant to decarbonization, such as aviation, freight transport, and high temperature heat applications in industry. For this reason, there is growing interest in approaches for actively removing emissions from the atmosphere. So-called negative emissions technologies (NETs) are a suite of engineered or natural approaches such as direct air capture or bioenergy with carbon capture, that can play an important role in offsetting recalcitrant emissions, and/or reaching net-negative emissions globally. There has not yet been modeling performed to understand how much China will need to rely on negative emissions to achieve its climate ambitions. While China is distinct from many of the other institutions making decarbonization pledges because of its size, its announcement was similar to other plans that have provided few details about how it might achieve its target.

At a global scale, integrated assessment models (IAMs) have been actively utilized for exploring deep decarbonization pathways. IAMs incorporate economic, geophysical, demographic, and climate modules to study future policy scenarios. The International Panel on Climate Change (IPCC) uses a suite of IAMs to explore different scenarios and inform international commitments, including those laid out in the 2015 Paris Climate Accord. Over the past several years, IAMs have been used to explore what it would take to limit future anthropogenic climate change to +1.5°C warming relative to pre-industrial levels. In order to meet these aggressive decarbonization scenarios, all IAMs rely on NETs to help offset recalcitrant emissions. Bioenergy with carbon capture (BECCS) and afforestation (AR) are the most widely modeled technologies, but a few models have begun to look at engineered NETs such as direct air capture.

China has previously committed to achieving peak CO₂ emissions by 2030. The new carbon neutrality commitment far strengthens its nationally determined contributions (NDCs) in the Paris agreement. What these commitments mean, practically is that China will need to undergo
a dramatic transformation in its economy in the very near term, even while some activities move in the opposite direction, for example, China recently rolled back its previous policies to ban new coal-fired power plants.\textsuperscript{12,13} There are several studies that have attempted to explore China’s decarbonization pathways.\textsuperscript{12,14–18} However, not much attention has been given to the role that negative emissions technologies can play in the country’s decarbonization pathways, especially the availability of advanced technologies like direct air capture with carbon storage (DAC). In our recent paper, we have assessed the negative emission technology needs for meeting a +1.5°C target globally. Our results indicate that this will require substantial deployments of negative emissions with much of that activity concentrated in the US and China because of their estimated capacity to carry out geologic carbon storage.\textsuperscript{10}

The goal of this paper is to estimate the range of negative emission needs for China to meet its carbon neutrality goal and to specifically understand whether negative emissions technologies are likely to play an important role in these plans. In particular, we sought to understand how the availability of different NETs might impact the required decarbonization of different sectors and the extent to which each NET needs to be deployed. We also sought to quantify the costs of some of these approaches recognizing that the scale at which they would be needed in order to meet this target is quite large and so understanding the tradeoffs these technologies would represent is important to understand today. To perform this analysis, we used the Global Change Analysis Model (GCAM)\textsuperscript{19}, a technology-rich integrated assessment model with embedded simplified versions of global climate and carbon dynamics. Using several different scenarios, we modeled the ways in which China might achieve its carbon neutrality target in 2060 to provide insight about the technological transitions, financial impacts, and resource constraints this might bring about internationally.

2. Methods

We used the latest release of GCAM 5.3\textsuperscript{19}, enhanced with NET capabilities, to simulate four possible future emissions trajectories shown in Figure 1. We modeled the 2060 net-zero China and world scenarios following the near-term to net-zero ("NT2NZ") approach described in Kaufman et al.\textsuperscript{20} We assumed a linearly declining net CO\textsubscript{2} emissions trajectory from 2025 until reaching zero net CO\textsubscript{2} emissions in 2060 for both China separately and the rest of the world together. This approach of getting to net-zero CO\textsubscript{2} emissions accommodates uncertainties and measurement difficulties while also helping guide policy design.\textsuperscript{20} For example, the constraint on net CO\textsubscript{2} emissions follows the “NT2NZ” approach in the scenario where China and the rest of the world net CO\textsubscript{2} emissions decline on a linear trajectory to net-zero emissions by 2060. For the 1.5 °C scenarios, emissions continue to decline below net-zero after 2060. Across the four CO\textsubscript{2} constraints, we permuted three parametrizations for the cost, efficiency and availability of DAC (i.e., high-cost DAC, low-cost DAC, and no DAC available), for a total of 12 scenarios.
Table 1. Four scenarios were run in GCAM to simulate future trajectories of emissions reductions.

| Scenario Name                          | Description                                                                                                                                                                                                 |
|----------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| No climate policy                      | A reference scenario with no climate mitigation policy (i.e., pricing or constraints on CO₂ or other GHG emissions), but improving technological efficiency                                                                                 |
| China only net-zero 2060              | China achieves net-zero CO₂ emissions by 2060, with no climate policy in the rest of the world. This scenario is intended to illustrate the limitations of China - or any other country - acting alone with ambitious mitigation, in achieving the international objective of limiting warming to well-below +2ºC in 2100. |
| China + rest of the world (ROW) net-zero 2060 | China, along with the rest of the world achieve net-zero CO₂ by 2060 in a linearly declining emissions trajectory. China’s emissions are individually constrained, but emissions from the remaining regions in the rest of the world are allowed to be individually greater than or less than a separately imposed emissions constraint, so long as their sum is less than or equal to this constraint. |
| Achieve +1.5ºC limit                  | Same scenario as above up to 2060. After 2060, net CO₂ emissions continue to decline below the net-zero by 2060 target on a linear trajectory for all regions.                                                                 |

We modeled DAC as a process that uses an aqueous reaction between atmospheric CO₂ and a hydroxide solution and has evaporative water losses at the air contactor. The DAC technology requires energy input in the form of process heat and electricity, and financial inputs for capital expenditure and non-energy operations and maintenance, given in Table 2. We assume that the process heat is high-temperature heat from natural gas combustion and not lower temperature waste-heat or renewables. While there are other DAC archetypes that can use renewable electricity and/or waste heat input and do not consume water, we focused our analysis on this high temperature process because it appears to be the most inexpensive and commercially mature at present. Carbon storage costs are endogenous in our model. Note that DAC is assumed to behave as a quasi-backstop technology, with no external constraints on its deployment outside the availability of energy, carbon storage, and its cost relative to other mitigation and negative emissions technologies in meeting a binding cap on CO₂ emissions. No other technological, institutional or legal limitations are modeled with respect to DAC, which therefore can be deployed rapidly at scale in the model under appropriate conditions.
Table 2. Input parameters for direct air capture and carbon sequestration technology\textsuperscript{10,21}

| Technology   | Natural Gas (GJ/tCO\textsubscript{2}) | Electricity (GJ/tCO\textsubscript{2}) | Water (m\textsuperscript{3}/tCO\textsubscript{2}) | Non-Energy Cost (2015 $/tCO\textsubscript{2}) |
|--------------|--------------------------------------|--------------------------------------|--------------------------------|---------------------------------|
| Low cost DAC | 5.3                                  | 1.3                                  | 4.7                           | 180                            |
| High cost DAC| 8.1                                  | 1.8                                  | 4.7                           | 300                            |

3. Results

Figure 1 presents the results for (a) global average temperature anomaly, (b) atmospheric CO\textsubscript{2} concentrations, and (c) CO\textsubscript{2} emissions trajectories obtained from running GCAM under our four CO\textsubscript{2} emissions constraint scenarios. The CO\textsubscript{2} emissions trajectories follow directly from the constraints imposed. Although China currently emits the most CO\textsubscript{2}, its unilateral commitment to reach net-zero emissions by 2060 will be insufficient to limit warming to anything close to the +2\textdegree C target, and would result in over +3\textdegree C of warming relative to preindustrial levels (Figure 1a). Without a global climate policy or if China acts alone, the global atmosphere CO\textsubscript{2} concentration continues to increase but stabilizes if the rest of the world (ROW) follows China’s lead or agrees to a below +2\textdegree C warming target (Figure 1c). If China and the ROW together reduce their emissions to net-zero by 2060, this results in approximately +1.8\textdegree C of warming in 2100. Limiting warming to +1.5\textdegree C or below by end-of-century would require CO\textsubscript{2} emissions to continue to decline to net-negative emissions globally after 2060, reaching nearly 20 GtCO\textsubscript{2} net removal globally in 2080 before stabilizing at these levels thereafter (Figure 1c).

Our results show that getting China and the rest of the world to net-zero by 2060 without DAC, would require China to deploy at least 1 Gt-CO\textsubscript{2} per year of negative emissions from BECCS and AR, which is inline with the recent study.\textsuperscript{6} Scenarios in which DAC is deployed show slightly higher warming in 2100 despite meeting the same CO\textsubscript{2} emissions cap, owing to fugitive methane emissions from the production of natural gas, which DAC takes as an input. Lower costs for DAC lead to its higher deployment and thus higher fugitive methane emissions. Achieving the +1.5\textdegree C target without DAC available, that is relying only on BECCS and AR, would represent a marginal cost of US$ 675 per tCO\textsubscript{2} in 2060. With DAC available, the world along with China could achieve net-zero CO\textsubscript{2} emissions by 2060 at much lower marginal costs, in the range of US$ 350 - 545 per tCO\textsubscript{2} (See Figure 2). Because DAC would reduce the burden on land and water imposed by an over reliance on BECCS and AR for negative emissions, the cost and some of the environmental tradeoffs of climate mitigation would be lower under DAC deployment.
Figure 1: Model results show very different trajectories for (a) Global temperature, (b) CO$_2$ concentration, and (c) net CO$_2$ emissions under the four scenarios simulated here.
Figure 2: CO\textsubscript{2} price paths in China for net-zero CO\textsubscript{2} by 2060 scenarios. If only China commits to meeting net-zero emissions by 2060, China is able to import inexpensive biomass for mitigation and negative emissions, and the CO\textsubscript{2} price never reaches the point at which it is financially viable to deploy DAC (orange line). In this scenario, the CO\textsubscript{2} price declines slightly after peaking around 2060, due to an exogenously-defined population peak in China and improving technological efficiency. When all countries take ambitious action to meet a net-zero (green) or net-negative (blue) emissions target, the CO\textsubscript{2} price is much higher but the availability of DAC can substantially reduce it.

Figure 3 shows the extensive transformation China will need to make to its economy in order to achieve its 2060 net-zero target. The panel on the left shows the dominant current emissions sectors transportation, industrial, and electric power. On the right, show the results of three permutations of the China only net-zero 2060 scenario, one in which no DAC is available, one in with DAC is available but continues to be expensive (US$ 300/tonCO\textsubscript{2}), and one in which DAC is available and is less expensive (US$ 180/tonCO\textsubscript{2}) (see Table 2). In all three cases, China will rely on significant deployments of negative emissions to achieve its net-zero target. Under the low cost DAC deployment, China would require about 2.5 GtCO\textsubscript{2} of negative emissions to attain net-zero by 2060 much of it coming from DAC with the remainder coming from BECCS and AR. If DAC continues to be expensive, it would make up a smaller percentage of the negative emissions
portfolio, which would still total 2 GtCO₂. The difference between these two scenarios would be made up through decarbonization of “hard-to-mitigate” sectors: transportation and industry. The availability of low-cost DAC effectively reduces the need to decarbonize some sectors.

![Figure 3: Pathways for China to reach net-zero CO₂ emissions by 2060 all involve deep emissions reductions and CO₂ removal. The availability of direct air capture technology in China enables less use of BECCS, and also offsets emissions from difficult-to-mitigate sectors such as transportation and industry, allowing higher emissions from these sectors relative to the no DAC case. Results shown here are for the China + rest of the world (ROW) net-zero 2060 scenario, which results in approximately 1.8⁰C of warming from preindustrial.](image)

Figure 4 shows the primary energy consumption transition that is likely to result from a China only net-zero 2060 scenario. Under present conditions, China relies heavily on coal and oil for its primary energy. To achieve net zero will require a significant rollout of renewable energy over the coming 40 years in addition to very large deployment of fossil-based carbon capture and storage. For the three negative emissions cases described in Figure 3 for the China only scenario (no DAC available, high cost, and low cost DAC) we see important differences in energy consumption patterns. Notably, the deployment of DAC creates primary energy demand on the same order of magnitude as all of China’s present day natural gas consumption. This natural gas is used to supply process heat to DAC. The primary energy consumption of coal would decline from 67% share in 2020 to 21% in 2060 without DAC. This includes 2% conventional coal and 19% coal based carbon capture and storage. With low cost DAC deployment, the share of coal would decline to 22% in 2060 with 4% conventional coal and 18% coal based carbon capture and storage.
Figure 4: Historical and projected primary energy consumption by fuel for China showing values for recent historical periods and for net-zero emissions in 2060 scenarios. Process heat for DAC (i.e., the primary energy supply from natural gas CCS devoted solely to CO$_2$ removal) is reported separately in indigo (dark purple at top of bars).

4. Conclusions

In 2018, the IPCC released a report describing what it would take to limit end-of-century warming to $+1.5^\circ$C above preindustrial levels, recognizing this target would require ambition and coordination far beyond what we have seen to date. The recent pledge from China to achieve carbon neutrality by 2060 provides a major contribution towards limiting climate change. To achieve this goal, first China needs to demonstrate that they are on track to carbon neutrality. Second, the rest of the world should also join the coalition of carbon neutrality. Third, efforts to stabilize the climate system should continue beyond 2060. We modeled these different futures in an effort to understand the role of negative emissions technologies (NETs) in helping to achieve the net-zero by 2060 target. Negative emissions technologies are being developed in order to offset recalcitrant emissions from transportation and industry, even though they are generally considered to be more expensive than conventional decarbonization activities. We analyzed China’s options to go net-zero using the Global Change Assessment Model (GCAM) with three major sources of negative emissions: bioenergy with carbon capture (BECCS), afforestation (AR), and direct air capture with carbon storage (DAC).
Our findings show that the NETs lower the cost for China to achieve its net-zero emissions target. This is particularly true if the rest of the world is decarbonizing alongside China. The extent to which NETs are deployed depends on their cost, which is expected to go down over time as technologies improve once their use is incentivized. However, some of the radiative forcing benefit of CO\textsubscript{2} removal with DAC is offset by fugitive methane emissions. If the leakage rate of the natural gas supply chain is higher, the net radiative forcing benefit of large-scale natural gas-fired DAC deployment would be correspondingly lower. We found that, without DAC, China can possibly get to net-zero CO\textsubscript{2} emissions by 2060 with 1.5 GtCO\textsubscript{2} negative emissions, but this would need to come from BECCS and AR at an increasingly higher marginal cost per tCO\textsubscript{2} than if DAC could be deployed alongside them. With DAC widely available, China’s carbon neutrality can be supported by more than 2-2.5 GtCO\textsubscript{2} negative emissions to get to the net-zero CO\textsubscript{2} emissions by 2060. Our results indicate that up to 30-60% of the negative emission needs would be fulfilled by DAC, while rest would be fulfilled by BECCS and AR. This level of scale up of DAC would require investment in the order of US$ 200-280 billion in 2060 which is about 1-2% of China’s GDP in 2019.

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