Benefits of Energy Technology Innovation

Part 2: Economy-Wide Direct Air Capture Modeling Results

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About the Author

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Executive Summary

The world is on pace to exceed the level of global warming universally agreed to under the landmark Paris Agreement of 2015 unless negative emissions technologies (NETs) are adopted at scale. Unlike technologies that remove emissions from the point source of emissions such as carbon capture and storage (CCS), NETs either remove carbon dioxide (CO$_2$) from the atmosphere or enhance natural methods for removal. Storing one ton of CO$_2$ from NETs has the same impact on the climate system as reducing one ton of emissions and NETs could be used if emissions reductions in some sectors prove too difficult. Due to relatively low costs, most focus has been on NETs, such as afforestation or biomass energy with carbon capture and storage (BECCS). Despite its high current costs of removal as a nascent technology, however, there has been an increasing interest in direct air capture (DAC).

DAC has several benefits relative to other NETs. DAC requires little land (especially relative to afforestation and BECCS), can remove emissions from dispersed sources, such as transportation, and can be placed anywhere, including near geological storage sites. Most importantly, despite a substantial thermal energy requirement, properly designed DAC plants can remove much more carbon dioxide (CO$_2$) from the air than they produce and could theoretically scale to a very large level. By some estimates, the US alone could store 1 - 1.4 trillion metric tons of carbon dioxide underground captured by DACs, BECCS or CCS EPA (2017).

At current costs, DAC is unlikely to be utilized as a method to significantly offset emissions, but innovations that reduce the costs of carbon dioxide removal could drive significant growth in DAC over time. This study uses an economy-wide model of the US to project the deployment of DAC across a range of technological cost and policy scenarios and provides estimates of the net benefits to society of innovation in DAC that lower its future technological costs. These estimates can help inform research, development, and demonstration (RD&D) expenditures on DAC technologies and future research can inform the expected levels of innovation that can be achieved through public RD&D spending on DAC.

In climate policy scenarios where DAC is an option for policy compliance, the use of DAC storage (carbon dioxide pulled from the air and then pumped into underground reservoirs) will depend on its costs relative to alternative compliance costs. Under the economy-wide emissions targets considered in this study (modeled as cap-and-trade programs), firms may comply with the regulation by either: (i) reducing their emissions, (ii) purchasing allowances from the government (or other market participants), or (iii) purchasing offset credits from the DAC sector. In equilibrium, if the DAC costs exceed the marginal abatement cost required to meet the emissions target, then DAC will not be competitively deployed. Alternatively, if DAC is a cost-effective compliance option, the compliance cost will equal the cost of DAC at the level where gross emissions less DAC removals equals the emissions target.
The same logic applies to other policies to reduce emissions where firms can choose to further reduce emissions or pay a compliance cost in lieu of additional reductions. Carbon taxes and nonemissions pricing policies that create compliance markets—e.g., clean electricity standards, tradable performance standards, and low carbon fuel standards—are examples of other policies that could create incentives for DAC storage.

The relationship between the marginal compliance costs of meeting an emissions target and the marginal cost of DAC is the key mechanism that determines the level of DAC storage. With a more stringent policy, the marginal cost of emissions reductions will be higher, and therefore DAC storage is increasing in policy stringency. Because DAC innovation lowers its marginal costs, the amount of anticipated DAC storage increases with greater magnitudes of innovation.

**Benefits of DAC Innovation and Economy-wide Deployment**

First, DAC storage is not projected to be widely used, regardless of future DAC technology costs, unless there is a policy signal, exogenous increases in industrial demand for CO$_2$, or a substantial increase in private offset markets. Under policy scenarios with emissions targets, however, there are significant differences in projected DAC storage deployment across the four innovation scenarios. Low-cost and very-low cost DAC technologies scale up significantly in the modeling analysis; low-cost DAC storage is responsible for 51 percent of abatement in 2049 in the policy with lower marginal abatement costs and 55 percent in the policy with higher marginal abatement costs.

Table ES-1. Benefits of Lower Technology Costs by Policy Stringency

<table>
<thead>
<tr>
<th>Policy Scenario One</th>
<th>Per Net Ton Reduced ($)</th>
<th>Net Reductions in 2049</th>
<th>Marginal Benefits ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>$5</td>
<td>2.05</td>
<td>$11</td>
</tr>
<tr>
<td>Medium</td>
<td>$15</td>
<td>2.05</td>
<td>$31</td>
</tr>
<tr>
<td>Low</td>
<td>$31</td>
<td>2.05</td>
<td>$63</td>
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<tr>
<td>Very Low</td>
<td>$33</td>
<td>2.05</td>
<td>$67</td>
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</table>

<table>
<thead>
<tr>
<th>Policy Scenario Two</th>
<th>Per Net Ton Reduced ($)</th>
<th>Net Reductions in 2049</th>
<th>Marginal Benefits ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>$11</td>
<td>2.23</td>
<td>$24</td>
</tr>
<tr>
<td>Medium</td>
<td>$22</td>
<td>2.23</td>
<td>$48</td>
</tr>
<tr>
<td>Low</td>
<td>$38</td>
<td>2.23</td>
<td>$86</td>
</tr>
<tr>
<td>Very Low</td>
<td>$41</td>
<td>2.23</td>
<td>$91</td>
</tr>
</tbody>
</table>

Second, relative to a scenario in which DAC does not exist, DAC storage reduces compliance costs, displaces reductions in high-abatement-cost sectors, and lowers the policy-induced in-
crease in energy prices, which is beneficial to both firms and households. As a result, the nonenvironmental costs of achieving a net emissions target are decreasing in the level of DAC storage (conditional on adopting it). Innovation increases DAC storage and lowers the costs of meeting an economy-wide emissions targets.

As a result of the reduced nonenvironmental cost of meeting an economy-wide emission target, the estimated benefits of DAC innovation to society is substantial. The estimated benefits are projected to be between $5 and $41 per metric ton reduced, depending on the size of innovation and the stringency of the emissions targets. Applied to net reductions in 2049, the annualized value of the Low innovation scenarios in 2049 alone is $63 and $86 billion ($2015) in the two policy scenarios. See Table ES-1 for details.

Overall, these results imply quantitatively significant net benefits of DAC innovation when there is sufficiently stringent climate policy, primarily through reduced policy compliance costs. Therefore, a successful DAC RD&D program should be used in combination with policies requiring carbon emissions reductions, including carbon pricing policies, and/or other policies such as increasing tax credits under Section 45Q, clean electricity standards, tradable performance standards, and low carbon fuel standards. Such policies would provide a meaningful demand for DAC’s negative emissions potential and contribute to keeping the world on a pathway towards the Paris Agreement temperature goals.
1. Introduction

In December 2015, 195 countries agreed to limit global warming to 1.5-2°C under the Paris Agreement. There is increasing consensus that pathways to meet these targets would need to include large amounts of negative emissions technologies (NETs), including carbon dioxide removal from the atmosphere by increasing carbon stocks in soils, forests, and wetlands (e.g., afforestation), capturing CO₂ from emitting facilities through carbon capture and storage (CCS), capturing CO₂ directly from the atmosphere (DAC), producing energy from biomass and using CCS to prevent the resulting emissions from entering the atmosphere (BECCS), or converting atmospheric CO₂ into rocks using geological processes (IPCC (2018), National Academies of Sciences, Engineering, and Medicine (2019)).

Each of these NETs has the potential to significantly reduce net greenhouse gas (GHG) emissions, but (with the exception of existing natural carbon sinks) none of these approaches exist at a meaningful scale. As described in detail in the National Academy of Sciences report Negative Emissions Technologies and Reliable Sequestration, these technologies are at various stages of development and the cost estimates vary widely both across NETs and for a given NET.¹

Integrated-assessment models (IAMs), global-scale models that are designed to represent the relationship between the economy and climate, have largely focused on afforestation and BECCS due to their relatively low prices, but there has been pushback against these approaches in recent years (see, for example, McGrath (2018) and Carlton (2020)) due to the sheer scale of land that would be needed to produce the scale of BECCS projected in those models. DAC has received plenty of attention from the public press, but less attention in modeling exercises; there are only a handful of IAM modeling analyses that include DAC (Chen and Tavoni (2013), Marcucci et al. (2017), Strefler et al. (2018), and Realmonte et al. (2019)). These studies find that deploying DAC at scale lowers the costs of meeting the Paris targets by easing near-term constraints on emissions and increasing negative emissions in the long term.

The focus of this study is estimating the welfare benefits of DAC innovation in the United States. I introduce a DAC technology into an economy-wide CGE model of the US and then compare outcomes such as DAC uptake and economic costs across DAC technology cost scenarios and policy scenarios. By comparing the economic costs of meeting an emissions target across a range of technology cost assumptions, I estimate the net benefit to society of innovations that reduce DAC costs and demonstrate how the net benefits change with the stringency of policies to reduce emissions. Such an exercise is designed to inform DAC research, development, and demonstration (RD&D) decisions by US policymakers.

¹For example, the cost estimates for DAC vary from about $100 to $1,000 per ton of CO₂ removed from the atmosphere.
I consider a combination of four different DAC technological cost scenarios and two economy-wide carbon dioxide targets, modeled as cap-and-trade programs. As previously found in the IAM literature, I find that use of DAC storage decreases the cap-and-trade allowance prices, which represent marginal economy-wide compliance costs, and the absolute change in allowance prices is higher in the lower technology cost scenarios. The mechanism driving this result, however, is slightly different than the mechanism in the IAM literature. In those models, increases in the use of DAC storage in the very long term (past 2050) allow for more emissions in the short run. Because temperature change depends on cumulative emissions, more negative emissions in the distant future allow for more positive emissions in the near future. In this current analysis, DAC becomes a method of compliance to meet the cap-and-trade program; when and to what extent it becomes a used method of compliance depends on DAC costs and the stringency of the emissions target. When marginal abatement costs begin to increase significantly and rise above DAC costs, DAC becomes a backstop method of compliance and determines the equilibrium allowance price. The pace at which investment in DAC can scale up determines how much DAC storage is used to meet compliance.

Overall, the economic welfare costs of meeting net emissions targets are lower in scenarios with lower DAC costs, implying that the benefits of reducing the costs of DAC could be substantial. In Policy Scenario One, a cap-and-trade program scenario that produces approximately the same level of cumulative emissions as a cap that linearly declines to 80 percent below 2005 levels, the welfare cost per metric ton is reduced from $76 per ton (in $2015) under no innovation (current costs) to $70, $61, $45, and $43 per ton in the High, Medium, Low, and Very Low cost scenarios, respectively. In 2049, these welfare cost savings are valued at between $11 and $67 billion. The benefits are higher under Policy Scenario 2, with greater compliance costs.

These results imply that RD&D spending decisions designed to drive down the cost of DAC need to be carefully crafted in conjunction with policies to reduce emissions. With no policy that creates either an explicit or implicit price on carbon, DAC is unlikely to be used at any significant level regardless of costs. With a policy that creates either credits or direct payments to DAC plants, my findings show that the benefits increase with the ambition of the policy.2

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2The benefits most likely also vary by type of policy and policy design, though that is beyond the scope of this paper. Inefficient or poorly designed policies may lead to high compliance costs, which would benefit investors in DAC relative to a more efficient policy with lower compliance costs, and increase the benefits of DAC RD&D spending.
2. **A Brief Primer on Direct Air Capture**

DAC uses chemical processes to separate CO$_2$ from ambient air.\(^3\) The energy (and costs) required to separate gases depends on concentrations, air pressure, temperature, and humidity. In particular, thermodynamic laws show that the energy required to separate gases increases as concentration levels fall: the concentration of CO$_2$ in ambient air is about 400ppm, whereas the concentration of CO$_2$ in flue gas from fossil fuel plants is 30,000 - 150,000ppm, depending on the fuel. As a result, the energy requirement required to remove a single ton from the atmosphere is quite high, especially compared to the energy requirement to remove a ton from flue gas.

Despite this disadvantage, DAC has several advantages relative to flue gas CCS. First, the flue gas CCS is limited to the amount of carbon dioxide flowing through the smokestack, whereas DAC has no limitation to the amount of air that can be subject to it. DAC also does not discriminate on the source of emissions and can be used to offset distributed emissions from sectors such as transportation and home heating (sectors with potentially high abatement costs). Most DAC plant designs also require relatively little land and can be placed away from emissions sources and close to storage sites, avoiding the need for pipeline transportation to geological sequestration sites. DAC operations, despite the high energy cost, generate less emissions than they capture (unless coal is used as an energy source) and could theoretically scale up significantly to remove large amounts of CO$_2$ from the atmosphere and store them underground.

There are two primary types of DAC processes, and they differ primarily by the type of material that is used to absorb CO$_2$ from the atmosphere. Liquid solvent systems use aqueous hydroxide solutions that react with CO$_2$ in the air. Most importantly, the final step needs heat in excess of 800$^\circ$C, a requirement that currently uses natural gas to meet. The firm Carbon Engineering is currently piloting this process.

Solid sorbent DAC systems use a variety of solid sorbents, the most common of which use amine materials (ammonia derivatives). The largest energy use is the electricity needed to run fans to blow air over the sorbent material, and the thermal requirements of the process are much lower and can be met with waste heat.

Ultimately, the economics of DAC systems depend on the energy requirement to pull a stream of pure CO$_2$ from the air and the sources of the energy and their costs. For instance, if coal were used to provide the thermal heat of liquid solvent systems (which is not proposed in practice), the entire process would generate nearly as much CO$_2$ as it pulled from the air. For this reason,

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\(^3\)Sources for this section are Broehm et al. (2015), National Academies of Sciences, Engineering, and Medicine (2019), and Realmonte et al. (2019).
DAC systems are designed to use zero-carbon or relatively low-carbon electricity and thermal sources. Further, the costs of these systems will be impacted by the change in energy prices over time and by the policies meant to reduce gross emissions, making it difficult to accurately pin down future costs. For example, the costs of removing CO$_2$ through a liquid solvent plant using natural gas would increase substantially if its use of natural gas were covered by a price on carbon. Solid sorbent systems powered by solar electricity and waste heat are promising because they do not generate process emissions, but the use of solar for DAC could crowd out investment in solar for electricity sold to the grid.

Outside of storage, a few potential markets exist for pure CO$_2$. The gas can be used in oil and gas operations through the enhanced oil recovery (EOR), though the level of demand for CO$_2$ for EOR is approximately 70 mmt and using DAC to increase fossil fuel production seems counterintuitive. Alternatively, the CO$_2$ could be sold to the beverage industry or used in greenhouses or algae farms. Expanding the opportunities for CO$_2$ utilization in innovative construction materials and synthetic fuels is also an active area of early-stage research.
3. Methodology

3.1. A brief description of the RFF-DR model

The RFF-DR CGE model is a dynamic multiregion and multi-industry intertemporal model of the US economy with international trade. CGE models combine detailed economic data with formulas that describe economic behavior to project how an economy will respond to a policy over time. For each policy scenario, the model calculates the changes in the supply and demand of producer and consumer goods by households and firms in each region and the corresponding changes in market-clearing prices.

The RFF-DR CGE model shares many features with the Goulder-Hafstead Energy-Environment-Economy (E3) model. Each regional economy is modeled as a collection of forward-looking agents: firms representing distinct industries within that region, a single representative household for that region, and regional and federal governments. The model captures the interactions among agents both within and across regions and solves for market-clearing prices in each period. Each agent has perfect foresight, and the model is solved in each period until it converges to a new steady-state balanced-growth equilibrium. The model is benchmarked to replicate 2015 data, and each period represents two years. For the purposes of this analysis, regions are aggregated into a single national region. Please see Appendix A for a description of the RFF-DR model.

Carbon coefficients on fossil fuel expenditures are calibrated by fuel (oil, natural gas, coal) and sector (residential, commercial, industrial, transportation, electric power) to match benchmark fuel-sector energy-related carbon dioxide emissions in the benchmark year. The model is then calibrated to match energy price projections and fuel-sector emissions projections from the EIA (2020) reference case through 2049 by adjusting the model’s exogenous production and preference parameters.

3.2. Adding DAC to the RFF-DR model

DAC output may be purchased by the other sectors or stored underground. In the benchmark year, there is no DAC storage. To effectively add a new production sector to the RFF-DR CGE model, it must produce some positive level of output consistent with a positive level of inputs. In this study, we introduce the DAC sector with minimal levels of output that is purchased by

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4 For a complete description of the E3 model, see Goulder and Hafstead (2017).
5 The model does not currently include industrial process emissions of CO₂ or non-CO₂ greenhouse gases.
the remaining sectors of the model such that the DAC industry’s expenditures match its revenue. The initial DAC industry has 1 mmt annual capacity and DAC inputs of capital, electricity, labor, and materials are consistent with cost assumptions discussed in the following section, assuming 10 percent of variable operating costs are spent on labor and 90 percent spent on industrial goods. For current costs, I assume a price of $325 per metric ton removed following the conservative estimate for a first generation plant from Larsen et al. (2019).

The government can also have positive expenditures on DAC storage in the model. As part of climate policy, the government may purchase an exogenous level of DAC output for storage each period at the market-clearing price, which will primarily be determined by the industry’s marginal costs of removal at that level of storage. To finance these purchases, however, pre-existing taxes on households or firms would need to be raised to balance the government’s budget constraint, which seems like an unlikely policy. This type of policy is not considered in this analysis.

Under a carbon tax policy or subsidy, the government provides direct payments to DAC firms for sequestering carbon dioxide underground (such a payment already exists under section 45Q) at the level of the tax. If the level of the direct payment is below the marginal cost of DAC storage, the DAC industry will not supply any storage. If the level is above the marginal cost of DAC storage, that will offer a large incentive to build out new DAC plants. The overall level of DAC investment will depend on how quickly plants can be built and whether the cost of storage increases with the overall amount of CO₂ already stored underground.

Under cap-and-trade programs, regulated firms have the option to (a) reduce emissions, (b) use an allowance (purchased through a government auction, received through direct allocation, or bought on a secondary allowance market), or (c) purchase a “DAC credit” from a DAC supplier, which they are legally allowed to submit in lieu of submitting an allowance. Under such a policy, DAC producers receive a “DAC credit” from the government for each metric ton of CO₂ they store underground. If allowance prices are below the DAC marginal costs, profit-maximizing firms will choose to purchase allowances and the demand for DAC credits will be zero. If the allowance price is equal to the DAC marginal cost in RFF-DR model, then regulated firms are indifferent between purchasing an allowance or a credit. Of course, the allowance price can never exceed the marginal cost of DAC in equilibrium; if it did, regulated firms would choose to purchase only DAC credits for compliance and the demand for allowances would fall until the price was equalized with the DAC credit price. In equilibrium, the allowance price must be less than or equal to DAC marginal costs and net emissions cannot exceed the net emissions cap set by the policy.

There is currently a relatively small offset market for firms and households, and DAC may play a role in those markets in the future. The model does not include this market. The extent that DAC could serve this offset market is reserved for future research.
Finally, the RFF-DR model assumes long-run constant returns to scale technology for DAC production. As a result, the very-long-run supply of DAC storage becomes infinite in any scenario where the price received by DAC producers exceeds their marginal costs of production, as would be the case in a carbon tax scenario with a long-run tax greater than the DAC sector’s (endogenous) long-run marginal costs. In this current study, we only consider cap-and-trade policies to limit economy-wide emissions. Under such a policy, the allowance price can never exceed DAC marginal costs in equilibrium.

\[\text{In the short run, due to capital adjustment costs, there are decreasing returns to scale.}\]
4. Technology and Policy Scenarios

I consider four innovation scenarios for solid sorbent systems. Current costs are assumed to be $325 per metric ton in 2021 (Larsen et al. (2019)). Long-run costs follow Shawhan et al. (2020); High and Low long-run cost scenarios are derived from mid-high and mid-low cases from Sinha and Realf (2019), with an additional electricity requirement for onsite CO₂ compression for The Medium scenario averages costs from these two scenarios and Very Low represents a 12.5 percent decrease in all cost inputs relative to the Low scenario. For each solid sorbent system, I assume thermal requirements are met by a combination of solar steam and waste heat. Finally, in each scenario productivity increases over time (at a fixed annual rate) such that costs converge to the long-run assumptions by 2049.

<table>
<thead>
<tr>
<th></th>
<th>High</th>
<th>Medium</th>
<th>Low</th>
<th>Very Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>18</td>
<td>15</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Variable OM</td>
<td>13</td>
<td>11</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Capital (annualized)</td>
<td>125</td>
<td>77</td>
<td>30</td>
<td>26</td>
</tr>
<tr>
<td><strong>Total Costs</strong></td>
<td><strong>157</strong></td>
<td><strong>104</strong></td>
<td><strong>51</strong></td>
<td><strong>45</strong></td>
</tr>
</tbody>
</table>

In this analysis, I use cap-and-trade programs to achieve cumulative emissions targets. The policies are economy-wide programs that cover all energy-related CO₂ emissions. Firms are allowed to cover emissions with either allowances or DAC credits. The model includes no other forms of offsets. Allowances are auctioned, and the revenues are returned to households through lump-sum dividend payments (as is common in many current policy proposals). The policy starts in 2021.

Policy Scenario One is meant to approximate a cap-and-trade program with banking and borrowing that achieves net emissions that are 80 percent below 2005 levels by 2050 (assuming a linear rate of decline from 2021 emissions). Policy Scenario Two increases marginal abatement costs, in absence of DAC, by 25 percent each period. Figure 1 displays both the reference case emissions in the absence of policy and the net emissions caps.

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8 For more details on cost assumptions, see Shawhan et al. (2020).
9 I find a banking and borrowing consistent price path that meets the cumulative emissions goal in the absence of DAC and apply the resulting emissions path as the annual cap.
Figure 1. Net Emissions Under Alternative Policy Scenarios (mmt CO₂)
5. Results

5.1. DAC Storage and Gross Emissions

The level of DAC storage depends on both DAC costs and policy scenario. For example, in the absence of an emission reduction policy, there is no DAC uptake under any innovation scenario, and results from these scenarios are not reported. Further, there is zero DAC storage in either policy scenario in the absence of innovation (holding current costs fixed). Finally, in each innovation scenario, DAC storage varies substantially across technology costs; Low and Very Low cost scenarios include significant growth in DAC through 2049. DAC storage levels under the different DAC technology cost assumptions and policy scenarios are reported in Figure 2.

In both policy scenarios, DAC storage is introduced between 2031 and 2037 and grows through 2049. In Policy Scenario One, DAC storage is 112, 472, 1045, and 1116 mmt in 2049 under the High, Medium, Low, and Very Low scenarios; DAC is responsible for 5, 23, 51, and 55 percent of compliance under the four scenarios. In Policy Scenario Two, DAC storage is 265, 667, 1224, and 1295 mmt in 2049 under the High, Medium, Low, and Very Low scenarios; DAC is responsible for 12, 30, 55, and 58 percent of compliance.

With a fixed net emissions cap in each period, DAC storage displaces gross emissions reductions from high-abatement-cost sectors like transportation. Conditional on the policy stringency, this leads to higher gross emissions in scenarios with lower DAC costs, as shown in Figure 3. The difference between gross emissions is simply equal to the difference in DAC storage across scenarios. The increase in gross emissions due to DAC storage leads to an increase in associated noncarbon air pollutants. The difference in noncarbon air pollutant levels across emissions or DAC cost scenarios will depend on where (i.e., fuel/sector) gross emissions are being displaced by DAC use for policy compliance. Unfortunately, the RFF-DR model does not currently have the capability to estimate the change in noncarbon air pollutants.

5.2. Allowance Prices and Overall Economic Costs

Figure 4 displays the path of allowance prices over time. In the policy’s second decade, as DAC begins to be implemented, the allowance price represents the marginal costs of DAC and allowance prices decrease as DAC costs continue to decline to the long-run cost assumptions in Table 1. DAC costs in the model are endogenous. Solar costs are projected to decrease and long-run DAC costs in the RFF-DR model are lower than costs predicted in Table 1.

10 The RFF-DR model does not currently include existing state policies that could drive DAC uptake.
Changes in the technology cost assumptions have significant impacts on allowance prices, especially in Policy Scenario Two. In 2049, the allowance price falls from $247 under constant DAC costs (not displayed) to $175, $98, and $34, and $29 under High, Medium, Low, and Very Low cost scenarios, respectively.
With substantially lower allowance prices, the auction revenue generated by a given cap-and-trade program is substantially different across technology cost scenarios. For example, in 2049, auction revenues are $482, $289, $98, and $82 billion (2015$) in 2049 under High, Medium, Low, and Very Low cost scenarios in Policy Scenario One.
As mentioned, the auction revenue in this analysis is returned to the representative household in the form of lump-sum payments (or dividends). This representative household in fact prefers lower dividend payments, lower allowance prices, and lower energy price increases and benefits from the lower technology costs, as will be shown below, but important distributional effects may occur that are beyond the scope of this paper. Further research on the trade-off between lump-sum payments and energy prices for particular household groups is necessary to address.
the distributional consequences of significant DAC storage as a compliance mechanism under cap-and-trade programs.

Of course, policymakers could choose other options for the revenues (cut pre-existing taxes or fund green investment programs) or could allocate the allowances freely to firms. The free versus auction decision and the revenue use of any auction revenue is one of the most important determinants of overall policy cost and the distribution of those costs across households (Goulder and Hafstead (2017)). Further research will be necessary to investigate how DAC storage, and DAC storage cost assumptions in particular, impact the trade-offs between free vs auctioned allowances and the potential uses of (any) auction revenue.

Table 2. Economic Costs by Policy and Technology Scenario

<table>
<thead>
<tr>
<th>Policy Scenario</th>
<th>Per Net Ton Reduced $2015</th>
<th>As a fraction of wealth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Policy Scenario One</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Innovation</td>
<td>$76</td>
<td>0.49%</td>
</tr>
<tr>
<td>High</td>
<td>$70</td>
<td>0.46%</td>
</tr>
<tr>
<td>Medium</td>
<td>$61</td>
<td>0.40%</td>
</tr>
<tr>
<td>Low</td>
<td>$45</td>
<td>0.29%</td>
</tr>
<tr>
<td>Very Low</td>
<td>$43</td>
<td>0.28%</td>
</tr>
<tr>
<td><strong>Policy Scenario Two</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Innovation</td>
<td>$87</td>
<td>0.62%</td>
</tr>
<tr>
<td>High</td>
<td>$77</td>
<td>0.55%</td>
</tr>
<tr>
<td>Medium</td>
<td>$66</td>
<td>0.47%</td>
</tr>
<tr>
<td>Low</td>
<td>$49</td>
<td>0.35%</td>
</tr>
<tr>
<td>Very Low</td>
<td>$47</td>
<td>0.33%</td>
</tr>
</tbody>
</table>

Notes: Economic Costs are equal to -1*EV, where EV = the equivalent variation measure of the policy-induced change in welfare. See footnote 12 for explanation of EV. Economic costs do not include benefit from reductions in GHG emissions or local air pollutants.

Economic welfare is a broad measure of how changes in prices and income affect household utility through changes in consumption and leisure. Because environmental benefits of reduced GHG emissions or local air pollutants do not enter the household’s utility function in the RFF-DR model, economic costs represent the nonenvironmental costs of the policy and do not

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Reported economic costs are calculated using equivalent variation (EV), which is the adjustment in income that changes the consumer’s utility equal to the level that would occur IF the policy were implemented. Negative EV implies an economic cost (welfare loss). EV is calculated as a present discounted value over the infinite horizon. In each technology scenario, the appropriate reference case for each technology is the no policy scenario with the same technology.
include any climate or nonclimate health benefits through reduced local air pollution.  

For a given policy stringency, Table 2 shows that the policy has lower costs in scenarios with lower technology costs. The introduction of DAC can impact household welfare through multiple channels. The use of DAC storage lowers allowance prices and therefore mitigates the impact of the cap-and-trade program on energy prices. It also increases labor demand, increasing the real wage, all else equal. Both of these factors would lead to higher economic welfare. On the cost side, DAC usage also significantly reduces income households receive through rebates of auction revenues and diverts resources (capital and labor, in particular) from other sectors, which could increase prices in capital- and labor-intensive industries. Because welfare costs decline when DAC is used and welfare costs decline more when more DAC is used, households clearly value the decline in energy prices induced by DAC use.

Further, the difference in welfare costs across technology scenarios is increasing in the stringency of the cap. The Low cost scenario is $31 per metric ton cheaper than the no innovation scenario under Policy Scenario One and $38 per metric ton cheaper under Policy Scenario Two.

5.3. Benefits of Lower Technology Costs

The benefits of lower technology costs are measured by comparing the welfare costs in different technology scenarios for a given policy scenario. These do not represent true “net benefits,” as the model exogenously imposes DAC technological change and has no costs associated with the changes (households will always prefer costless technology changes). These benefits, however, can be compared to proposed RD&D spending proposals to get a rough estimate of the benefits such RD&D could provide relative to its costs.

The benefits of lower technology costs vary by both policy stringency and the technology scenarios considered (Table 3). For example, under Policy Scenario One, I find benefits per ton reduced of DAC technology improvement, relative to no innovation, of $5, $15, $31, and $33 under High, Medium, Low, and Very Low cost scenarios; under Policy Scenario Two, the benefits are $11, $22, $38, and $41.

To gain a sense of the scale of the potential gains from technology improvements, Table 3 also displays net benefits per ton for each of the four technological cost scenarios (relative to the No Innovation scenario) the annualized level of potential benefits in 2049 (multiply benefit per ton reduced times reductions in 2049). This implies that the benefits of innovation are between 12.

As shown in Goulder and Hafstead (2017), environmental benefits often vastly exceed economic costs and, depending on the Social Cost of Carbon used to monetize the value of emissions reductions, monetized values of reductions in local air pollutants often exceed the climate benefits.
Table 3. Benefits of Lower Technology Costs by Policy Scenario

<table>
<thead>
<tr>
<th>Policy Scenario One</th>
<th>Per Net Ton Reduced $2015</th>
<th>Net Reductions in 2049 bmt</th>
<th>Benefits $2015 billions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>$5</td>
<td>2.05</td>
<td>$11</td>
</tr>
<tr>
<td>Medium</td>
<td>$15</td>
<td>2.05</td>
<td>$31</td>
</tr>
<tr>
<td>Low</td>
<td>$31</td>
<td>2.05</td>
<td>$63</td>
</tr>
<tr>
<td>Very Low</td>
<td>$33</td>
<td>2.05</td>
<td>$67</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Policy Scenario Two</th>
<th>Per Net Ton Reduced $2015</th>
<th>Net Reductions in 2049 bmt</th>
<th>Benefits $2015 billions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>$11</td>
<td>2.23</td>
<td>$24</td>
</tr>
<tr>
<td>Medium</td>
<td>$22</td>
<td>2.23</td>
<td>$48</td>
</tr>
<tr>
<td>Low</td>
<td>$38</td>
<td>2.23</td>
<td>$86</td>
</tr>
<tr>
<td>Very Low</td>
<td>$41</td>
<td>1.23</td>
<td>$91</td>
</tr>
</tbody>
</table>


### 5.4. Capital Adjustment Costs

In the long run, DAC production is constant returns to scale and has no specific limit in the RFF-DR model. In a cap-and-trade equilibrium, production will be set such that the allowance price equals DAC marginal costs and the allowance market clears. In the short run, capital adjustment costs in the RFF-DR model restrict how quickly firms can adjust their capital stock (up or down). The quadratic specification of investment costs also implies that these costs will be quite significant for the DAC industry as it attempts to quickly ramp up investment spending. Further, because adjustment costs are denominated in output, huge investment spending reduces net output and raises the marginal cost of production. In addition to constraining the growth of the DAC industry, this also implies, all else equal, that adjustment costs will lead to allowance prices overshooting the long-run DAC marginal cost.

To investigate the role of capital adjustment costs in the uptake of DAC in the RFF-DR model, I simulate an alternative set of scenarios in which adjustment costs for the DAC industry are 50 percent lower. Figure 5 displays the DAC storage and allowance prices in Policy Scenario One with the Medium and Low cost technology scenarios.

DAC storage is only slightly higher in these two scenarios when adjustment costs are reduced and the difference in allowance prices, indicating that these levels of adjustment costs are not significantly limiting DAC storage. Of course, as adjustment costs converge to zero, DAC stor-
Figure 5. Impact of Adjustment Costs Assumptions on DAC Storage and Allowance Prices

(a) DAC Storage (mmt CO₂)

(b) Allowance Prices ($2015 per ton CO₂)

...will immediately converge to its steady-state level and allowance prices will be capped by the marginal cost of DAC in the steady state.
6. Key Assumptions and Limitations

CGE models provide a useful laboratory for qualitatively and quantitatively evaluating how changes in policy design or technology assumptions impact firm and household behavior, holding fixed baseline forecasts and price elasticities. With that said, quantitative projections are not forecasts because they depend on these baseline forecasts and price elasticities, whose future values are uncertain. Thus, results should not be regarded as firm predictions of what actually will occur, and changes to any single assumption may alter projections.

Changes to either baseline forecasts or price elasticities may impact the results presented here in a variety of ways. For example, solar electricity is a major input for solid sorbent DAC plants in the model, and the relative cost of solar technology will impact the profile of DAC costs over time, regardless of improvements in DAC technology, while also impacting the economy’s aggregate marginal abatement costs. Benchmark price elasticities largely dictate the shape the economy’s aggregate marginal abatement costs, and an important determinant of DAC uptake is the marginal cost of DAC relative to marginal abatement costs.

If key elasticities for consumer or producer demand are low compared to actual values, the model’s abatement curve would increase and the model would overpredict the amount of DAC uptake for any given technology level, leading to an overestimate of the benefits of DAC innovation. On the other hand, if elasticities are too high, the model would underpredict DAC uptake and the benefits of DAC innovation. Unfortunately, our elasticity estimates are based on past relationships and we have no way to know what elasticities will be in the future given broader changes to technology across all sectors and broader changes to household preferences. The COVID-19 pandemic is a stark reminder of this, as we cannot yet say whether transportation habits will return to normal or fundamentally shift.

The model is also only able to consider fixed paths of innovation and does not include increasing return to scale technologies for any sector. This is important for three reasons. First, policy-induced innovation is excluded from the model in all sectors, and it cannot capture the impact of carbon prices on innovating emissions reducing technologies. Second, the model cannot capture endogenous improvements in DAC technology that may occur through processes such as learning by doing. All else equal, adding increasing returns to scale in DAC technologies would increase both DAC uptake and the benefits of moving to lower-cost technologies. Third, the model cannot capture the interactions between innovation in DAC technology and innovation in other technologies that could be used to reduce emissions. If DAC can become commercially viable at scale by midcentury at $40 per ton or less, the incentives to innovate in sectors such as transportation become very low, making it harder to decarbonize those sectors.
7. Conclusion

In this paper, I quantitatively examine the benefits of improvements in DAC technology over time. Using the RFF-DR CGE model, I simulate DAC technology cost assumptions scenarios and emission target policies.

In the RFF-DR model under emissions target policies, DAC storage is only used when the equilibrium compliance cost equals the marginal cost of DAC production. If a compliance market can clear at compliance costs prices below the marginal cost of DAC production, then DAC is never implemented. If compliance costs were greater than DAC marginal costs, regulated firms would simply shift demand to DAC credits and the market would find a new equilibrium such that compliance costs are equal to the marginal cost of DAC production.

The relationship between compliance costs and the marginal cost of DAC production is the key mechanism that determines the level of DAC storage. With a more stringent emissions target, compliance costs will be higher, all else equal, and therefore DAC storage is increasing in policy stringency. Because innovation lowers marginal costs of production, DAC storage is increasing in innovation that lowers costs.

Quantitatively, DAC storage is unlikely to be used extensively at current cost levels, even with relatively stringent emissions targets, because firms will find it less-expensive to reduce emissions than purchase DAC compliance credits. Yet, under a range of scenarios with cost-reducing innovation in DAC, it could play a major role in a portfolio of cost-effective compliance options. For example, in 2049, storage is projected to be 112 mmt under the High cost scenario and 1045 mmt under the Low cost scenario under the primary policy scenario, and is responsible for only 5 percent of compliance in High cost scenario and 51 percent in the Low cost scenario.  

DAC storage impacts the broader performance of economy-wide carbon policies in several ways. Relative to a no DAC scenario, it reduces compliance costs, displacing reductions in high-abatement-cost sectors, and lowers the policy-induced increase in energy prices, which is beneficial to both firms and households. Further, carbon-intensive industries tend to be capital-intensive, DAC storage allows for more production for these industries, and this diminishes the negative effect of the cap-and-trade program on capital income.

Finally, DAC storage decreases the allowance price but also the overall demand for allowances, leading to a substantial reduction in the value of allowances. In this analysis, allowances are auctioned with the revenues returned to households through rebates. DAC storage decreases

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13 The cost scenarios in this paper represent a range of potential future costs from the DAC literature on potential costs of different DAC technologies; more research is necessary to determine which innovation scenario is most likely and what type of impacts RD&D research can have on future technology costs.
Economic welfare measures combine all of these impacts into a single cost estimate, and I find that DAC storage (when used) decreases the economic costs of meeting the cap. Further, I show the decrease in welfare costs is increasing in level of DAC innovation. In other words, households would pay a substantial amount to move from a current cost DAC scenario to the innovation scenarios. For example, the household would be willing to pay $15 or $31 per net metric ton reduced ($2015) to move from the current cost scenario (with no innovation) to the Medium cost scenario, depending on policy scenario, and $22 or $38 per net metric ton reduced to move from the current cost scenario (with no innovation) to the Low cost scenario. Applying these willingness to pay numbers to 2049 levels of emissions reductions, innovation that reduced long-run DAC costs to the Medium cost scenario would generate $31 billion or $63 billion ($2015) in benefits in 2049 alone and innovation that reduced long-run DAC costs to the Low cost scenario would generate benefits of $48 billion or $96 billion in the two policy scenarios included in this analysis.

Overall, these results imply quantitatively significant benefits of DAC innovation when combined with meaningful climate policy through reduced compliance costs. Therefore, a successful DAC RDD program should be used in combination with policies that provide strong price signals to DAC producers. The price signal in this analysis comes from a strict cap-and-trade program but the price signal could be derived explicitly through alternative policies such as the 45Q tax credit system currently in place or a carbon tax. Alternatively, the price signal could come from compliance markets created by policies such as clean energy standards, performance standards, or even low carbon fuel standards.

14Further research is necessary to determine the interaction of DAC with other forms of allowance allocation and/or revenue use
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IPCC. 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable


A. Appendix on RFF-DR CGE Model

The RFF-DR CGE model shares many features with the Goulder-Hafstead Energy-Environment-Economy (E3) model. Each regional economy is modeled as a collection of forward-looking agents: firms representing distinct industries within that region, a single representative household for that region, and regional and federal governments. The model captures the interactions among agents both within and across regions and solves for market-clearing prices in each period. Each agent has perfect foresight, and the model is solved in each period until it converges to a new steady-state balanced-growth equilibrium.

The model is benchmarked to 2015 and each period represents two-years. For the purposes of this analysis, we focus on results through the year 2049.

Two features of the Goulder-Hafstead E3 and RFF-DR CGE models distinguish them from other national or regional dynamic environment-related CGE models. These features make them especially well-suited for analysis of carbon pricing policies at the national or state level. First, the models combine relatively detailed treatment of energy supply and demand with a detailed treatment of the tax system. This detailed treatment allows the model to evaluate the critical interactions between climate policy and state and federal taxes and spending. These interactions play a fundamental role in determining the economic costs of climate policy.

Second, the models include the adjustment costs associated with the installation or removal of physical capital at the region-industry level. These costs affect the pace of capital reallocation across industries within and across regions and ultimately affect the speed at which each regional economy responds to a new national or regional climate policy. In addition, the adjustment costs are necessary to model the differential impacts of environmental policy on profits and asset values across industries and regions. For this analysis, regional specificity would require adding a pipeline network from DAC sites to storage locations and for simplicity, and without loss of generality, aggregates the data into a single national region (as in E3 model).

Regional social accounting matrices (SAMs) from the IMPLAN Group provide information on market flows and nonmarket financial flows among firms, consumers, and the government, IMPLAN (2017). For this analysis, industrial sectors are aggregated into 15 industries that produce distinct commodities.

Table A-1 displays the unique industries and commodities in the RFF-DR CGE model. The IM-
PLAN data are augmented with information on production, physical consumption, and total expenditures by energy good from the US Energy Information Administration’s State Energy Data System, EIA (2018a), EIA (2018b), EIA (2018c). For this modeling exercise, the regional SAMs are aggregated into a single national; SAM

Finally, we use Bureau of Economic Analysis data to convert personal consumption expenditures by commodity into consumption spending on 10 distinct consumer goods, BEA (2018). All data are from 2015.

Table A-1. Industry and Consumer Goods in the RFF-DR CGE Model

<table>
<thead>
<tr>
<th>Industry</th>
<th>Consumption Goods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Extraction</td>
<td>Motor Vehicle: New and Used</td>
</tr>
<tr>
<td>Gas Extraction</td>
<td>Motor Vehicle: Services</td>
</tr>
<tr>
<td>Coal Mining</td>
<td>Motor Vehicle: Fuels</td>
</tr>
<tr>
<td>Electricity Generation: Fossil</td>
<td>Motor Vehicle: Electricity</td>
</tr>
<tr>
<td>Electricity Generation: Nuclear, Hydro, Other</td>
<td>Non-Personal Transportation</td>
</tr>
<tr>
<td>Electricity Generation: Solar and Wind</td>
<td>Housing</td>
</tr>
<tr>
<td>Electric Transmission and Distribution</td>
<td>Electricity (non-vehicle)</td>
</tr>
<tr>
<td>Natural Gas Distribution</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>Petroleum Refining</td>
<td>Fuel Oils and Other Fuels</td>
</tr>
<tr>
<td>Industrial Sector (Non MV Manufacturing)</td>
<td>Other Goods and Services</td>
</tr>
<tr>
<td>Motor Vehicle Manufacturing</td>
<td></td>
</tr>
<tr>
<td>Wholesale and Retail Trade</td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
</tr>
<tr>
<td>Commercial (Finance, Communication, Services)</td>
<td></td>
</tr>
<tr>
<td>Real Estate and Owner-Occupied Housing</td>
<td></td>
</tr>
</tbody>
</table>

A.1. Production

Output from each industry stems from a nested structure of constant-elasticity-of-substitution (CES) production functions. Figure A-1 displays this structure. Variable intermediate inputs of energy (oil extraction, gas extraction, coal mining, electricity generation, electricity transmission and distribution, natural gas distribution, and petroleum refining) and of materials (industrial sector, motor vehicle manufacturing, trade, transportation, commercial sector, and real estate and owner-occupied housing) are aggregated into an energy composite, E, and a materials composite, M. At the next level of the nest, the variable energy and material composites are aggregated into an intermediate input composite using function h. At the next level, the intermediate input composite $H = h(E, M)$ is aggregated with labor using function g, $G = g(L, H)$ and at the next level the variable input composite is combined with capital using function x, $X = x(K, G)$. For each of these CES nests, elasticities of substitution for each
industry are taken from common estimates from the economic literature.

For each industry, specific intermediate inputs are considered fixed proportion inputs: the input must be in proportion to output (for example, crude oil input into petroleum refining). A fixed Leontief function \( f \) combines these inputs, \( F_E \) and \( F_M \), with the other inputs, \( F = f(F_E, F_M, X) \).

Fixed natural resources are required to produce outputs for certain industries (For extraction industries (oil, gas, coal) and Electricity Generation: Nuclear, Hydro, Other). For these industries, inputs are combined with natural resources via a CES production function, \( Y = y(R, F) \). For extraction industries, the elasticity of substitution is calibrated to match fuel supply elasticities calculated by comparing production across EIA’s AEO alternative reference case scenarios (0.15 for oil, 0.2 for gas, 3.8 for coal) and the Electricity Generation: Nuclear, Hydro, Other elasticity is calibrated such that the fuel price elasticity is approximately zero to limit significant increases in these types of generation in response to policy. For industries without natural resources, output is simply \( Y = F \).

Capital adjustment costs are modeled as the sacrifice of output associated with the process of investing in capital. Specifically, net output is equal to gross output minus adjustment costs, \( \Phi(I/K) \times I \), represents the adjustment costs (in terms of lost output). Adjustment costs have the same functional form as Goulder and Hafstead (2017), where net output \( \tilde{Y} = Y - \Phi(I/K) \times I \) and adjustment costs are quadratic in deviations from the level of investment consistent with the steady state growth path, \( \Phi(I/K) = \frac{\upsilon(I/K-(\delta+gr))^2}{I/K} \), where \( \upsilon \) is the primary adjustment cost parameter (equal to two) and gr represents exogenous steady state growth.

### A.2. Consumer Behavior

RFF-DR modeling of consumer behavior captures several key aspects of consumer choice: the choice between work hours and leisure time, the choice between current consumption and saving for future consumption, and the allocation of current consumption expenditure across various consumer goods and services.

There is a single, representative household for each region. RFF-DR modeling of household consumption follows Goulder and Hafstead (2017) with the exception of the aggregation of consumer goods and services into a consumption bundle. Goulder and Hafstead (2017) used a Cobb-Douglas aggregation of goods and the RFF-DR uses a nested utility structure as specified in Figure A-2.

Elasticities of substitution are common values taken from the literature. Elasticities of substi-
tution between motor vehicle fuels and electricity and between vehicle expenditures and fuels are chosen such that the model approximates the demand response to fuel use from RFF’s transportation model (provided by Josh Linn).

**A.3. Government**

There is a federal government and state/local governments in each region. The governments collect taxes to finance expenditures on goods, services, and labor used to produce a government service. The production function is Leontief and the level of government services provided remain fixed over time. Adjustment to lump-sum taxes are used to balance the government budget constraint as is standard in the CGE literature.
Figure A-2. Consumption Bundle Nest