Rhodium Group

Capturing Leadership

Policies for the US to Advance Direct Air Capture Technology

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About This Report

Carbon 180 commissioned Rhodium Group, to assess the role of Direct Air Capture technology in the US response to climate change and identify near and medium-term policy actions to advance the deployment of this technology in the next decade. The Linden Trust for Conservation and ClimateWorks Foundation provided financial support for this analysis. The research was performed independently, and the results presented in this report reflect the views of the authors and not necessarily those of Carbon180, the Linden Trust or ClimateWorks.

About Rhodium Group

Rhodium Group is an independent research provider combining economic data and policy insight to analyze global trends. Rhodium's Energy & Climate team analyzes the market impact of energy and climate policy and the economic risks of global climate change. This interdisciplinary group of policy experts, economic analysts, energy modelers, data engineers, and climate scientists supports decision-makers in the public, financial services, corporate, philanthropic and non-profit sectors. More information is available at www.rhg.com.

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Table of Contents

1 About This Report

2 Acknowledgements

3 Table of Contents

4 Executive Summary

8 Chapter 1: Why Direct Air Capture and Why Now?

10 Chapter 2: The Scale of the Challenge

20 Chapter 3: The Current Landscape

25 Chapter 4: Achieving Take-off

37 Chapter 5: Supporting Long-Term Deployment

43 Chapter 6: Conclusions and Key Findings

46 Technical Appendix

56 Endnotes

Executive Summary

Growing evidence suggests that limiting global temperature increases to reasonably safe levels will require not only a rapid reduction in carbon dioxide (CO_2) and other greenhouse gas emissions (GHGs) around the world but large-scale removal of CO_2 from the atmosphere as well. Every year that global emissions continue unabated, the required pace of future reductions accelerates, and the quantity of CO_2 emissions that ultimately needs to be removed from the atmosphere grows. Fortunately, thanks to recent technological innovations, the options for CO_2 removal are increasing in number and falling in cost. But significant policy action is required to ensure these technologies are available in time and at the scale required to avoid the worst impacts of global warming.

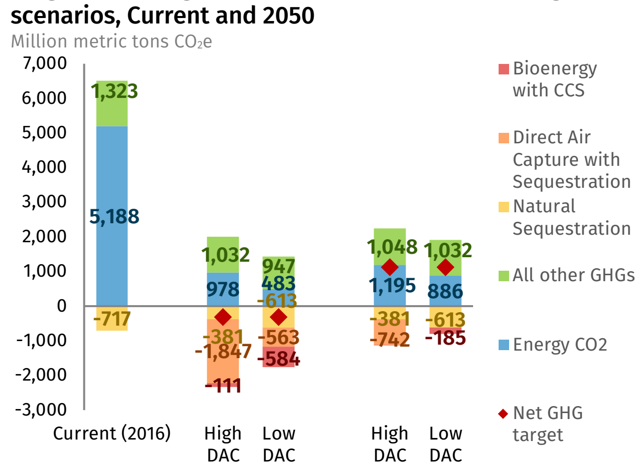
This report focuses on one of these emerging carbon removal technologies: Direct Air Capture (DAC). DAC safely removes CO_2 from the air using chemical filters and produces a concentrated stream of CO_2 for use in products like concrete and fuels or for permanent geologic storage. Carbon180, the Linden Trust for Conservation, and the ClimateWorks Foundation asked Rhodium Group to conduct an independent analysis of the role DAC can play in supporting a decarbonized US future, its cost, and the actions required to achieve deployment at a scale that can have a global impact on reducing GHGs in the near, medium and long term.

We studied the latest peer-reviewed literature and conducted dozens of expert interviews to understand the state of the technology today concerning performance and costs. We modeled DAC's role in a decarbonized US future, using trailblazing analysis to measure long-term need. We then developed a detailed set of policy options that can both accelerate the deployment of DAC and support the technology at the scale required for the US to deliver its contribution toward avoiding the worst impacts of climate change. Our key findings follow.

Getting to Zero Emissions by Midcentury Requires Large-Scale Carbon Removal with Direct Air Capture Technology

Last year, global CO_2 emissions reached an all-time high. Recent scientific research indicates that global emissions need to reach net-zero between 2045 and 2055 to limit global temperature rise to 1.5 degrees Celsius. DAC technology does not make it possible to bypass the difficult work of reducing emissions. We find that even with break-neck electrification of vehicles, buildings, and industry, unprecedented improvements in energy efficiency, completely decarbonized power generation, and carbon removal from enhanced natural sequestration, DAC technology will be essential for the US to decarbonize by midcentury. Our analysis indicates that for the US to reach net-zero emissions by 2045 (our "100by45" scenarios) between 560 and 1,850 million metric tons of CO_2 will need to be removed by DAC technology and then permanently stored underground annually, depending on the availability of other carbon removal options, such as bioenergy with carbon capture and storage (BECCS) and natural sequestration, and the pace of electrification in the transportation, buildings, and industrial sectors (Figure ES.1.).

FIGURE ES.1.
US greenhouse gas emissions under DAC bounding scenarios, Current and 2050



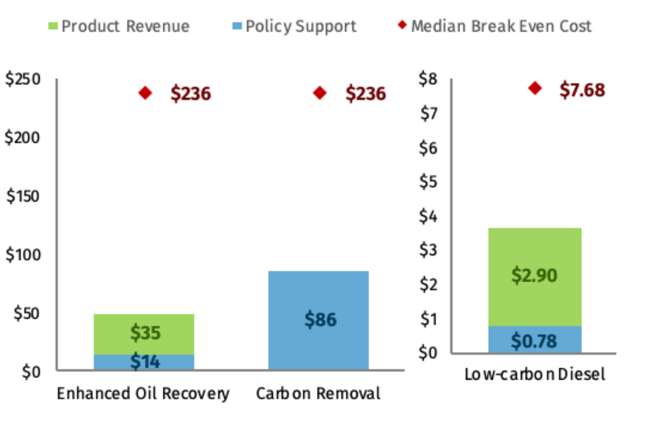
Source: Rhodium Group and Evolved Energy Research analysis.

Even under a less ambitious US target of 83% below 2005 levels in 2050 (our "83by50" scenarios), carbon removal technology remains necessary to offset stubborn sources of CO_2 such as long-haul aviation and shipping, and energy-intensive industrial activities. There is growing scientific evidence that US forests and soils may absorb a smaller share of this carbon without widespread adoption of new agricultural and forestry practices. The same holds true for methane and nitrogen oxide emissions from farming and livestock, which if not tackled will also hinder progress toward eliminating GHG emissions. Achieving 83by50 requires unprecedented speed in transforming the energy sector, consumer patterns, and land use across the US. If carbon removal from other options falls short, up to 740 million tons per year of DAC with sequestration may be required by 2050.

DAC Deployment Is Achievable, and Technology Is Set to Break Through

Investing now in research and development would set the US on track to innovate and improve DAC technology today, so it's ready for deployment when we need it most. Dedicated academic researchers and three commercial DAC companies have worked diligently over the last decade to improve the performance of the technology. Collectively, these companies have built 11 DAC plants around the world, the largest of which is located in Alabama and is designed to capture 4,000 tons per year. However, while some niche opportunities may exist now where DAC is economic, current market opportunities and policy incentives do not provide enough support for the first large-scale DAC plant to break even. This is the case across multiple DAC technology applications, even after accounting for existing policy incentives like California's Low Carbon Fuel Standard (LCFS) and the Federal Section 45Q tax credit (Figure ES.2.). Drawing the historical deployment pathways of key electric power sector technologies, such as natural gas combined cycle power plants, wind, and solar, we find evidence to demonstrate the potential for policy to propel DAC to market. The US has done it before. It can be done again.

FIGURE ES.2.
DAC costs exceed current revenue opportunities
30 year $2018 levelized values



Source: Rhodium Group analysis. Note: Costs are for a first-of-a-kind megaton-scale plant.

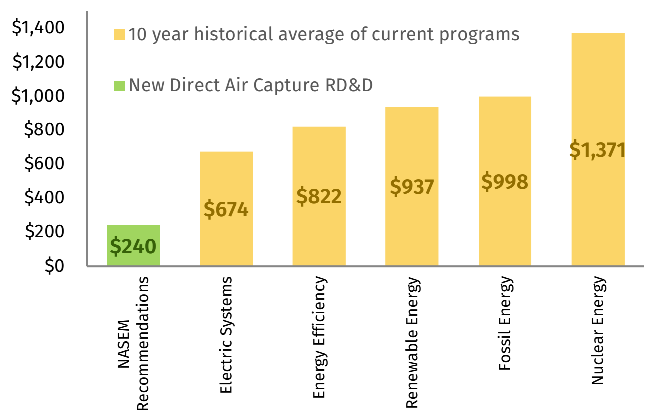
Federal Action Is Needed to Push and Pull DAC Into the Marketplace

To become a leader in DAC technology, the US must prioritize the construction of DAC plants to increase scale and reduce costs through learning and experience. We estimate that at least nine million tons of DAC capacity need to be operational in 2030 to get the US on track for meeting mid-century carbon removal requirements. The specific application of DAC—for use in fuels, products, enhanced oil recovery, or sequestration—matters little at this early stage as long as it advances progress toward the 2030 deployment goal. To ensure this happens, the federal government can pursue policy action on multiple fronts.

Enact and Fully Fund a Comprehensive Research, Development, and Demonstration (RD&D) Program for DAC

Among its developed-country peers, the federal government ranks in the middle of the pack in energy RD&D relative to the size of its economy. Over the last decade, the Department of Energy (DOE) spent $4 billion annually, on average. Meanwhile, the cumulative amount of government funding for DAC RD&D to date is $11 million. The landmark study of negative emissions technologies by the National Academies of Sciences, Engineering, and Medicine (NASEM) recommends funding DAC research over the next ten years at an average annual level of $240 million. Compared to DOE spending on every other applied energy RD&D program, this sum would be small (ES.3). Congress should authorize comprehensive DAC and sequestration research programs that reflect the recommendations from the NASEM, enact them into law, and fully fund them through appropriations.

FIGURE ES.3.
NASEM average annual recommended federal funding for DAC and current DOE programs
$Millions per year



Source: NASEM, Congressional Research Service and Rhodium Group analysis.

Pursue Policy Pathways to Increase Demand for DAC

While RD&D is essential, a comprehensive industrial strategy should also stimulate demand for DAC technology. We assess three pathways for the federal government to do this based on existing policy frameworks and then quantify the level of support required to get at least nine million tons of DAC capacity built in the US through 2030. Fully implementing any one of these pathways should get DAC on track towards likely long-term deployment needs. These pathways include:

- Leverage Federal Procurement. The Department of Defense can ramp up competitive procurement of DAC based fuels from zero to roughly 23% of 2017 operational fuel consumption in 2030. The General Services Administration can launch a competitive procurement program for carbon removal from DAC with sequestration in addition to procuring low-carbon products made with DAC CO_2.

- Improve the Section 45Q Tax Credit for DAC. Congress can make several improvements to this program all focused on DAC: extending the commence-construction deadline for DAC eligibility to the end of 2030; extending the credit payout period to 30 years; increasing the value of the credit for geologic storage to $180 per ton; and lowering the minimum capture and use thresholds to 10,000 tons per year. These changes will allow the first wave of commercial DAC plants to break even if they also incorporate revenue from California's LCFS. The total annual cost to the government in 2031 would be just $1.5 billion, roughly half the current annual cost of solar photovoltaic (PV) tax credits.

- Establish a Federal Mandate for DAC Based Fuels. Congress can expand eligibility for the Renewable Fuels Standard or establish a standalone mandate for very low-carbon, drop-in fuels to increase consumption of DAC-derived fuels. By 2030, DAC-derived fuels need to equal roughly 0.4% of 2017 US on-road fuel consumption to achieve the goal of nine million tons of DAC capacity. Credit prices would need to be $2.50 per gallon to support the first one million tons of DAC capacity and $1.05 per gallon to support nine million tons of DAC capacity.

Overcome Non-Cost Barriers to DAC Deployment

The federal government should act to address long-term geologic storage monitoring and liability to provide certainty to project developers pursuing DAC with sequestration. Streamlined pipeline and CO_2 storage permitting can reduce costs and investment risks. The government should also facilitate sequestration projects by mapping geologic formations and assessing their suitability. Independent standard-setting organizations should proactively establish standards for CO_2-based products such as concrete and aggregate, removing a key market barrier.

Lower the Cost of Investment

We assessed several existing federal policies that reduce the amount of investment required to finance DAC plants including Loan Guarantees, Master Limited Partnerships, Private Activity Bonds, and Investment Tax Credits. None of these policies alone would be sufficient to support the construction of nine million tons of DAC capacity through 2030, but they could complement deployment policies. Congress should pursue an Investment Tax Credit of 30% for the most effective strategy among the options considered. This approach is well-proven, having been used to drive the rapid rise of solar PV deployment.

Leverage Opportunities for DAC in Infrastructure, Climate, or Energy Policy Frameworks

Many policy frameworks focused on other goals could be designed to provide support to DAC. An infrastructure bill could be used to increase demand for DAC-based products like concrete. Clean Energy Standards on electric utilities can incorporate offset mechanisms to support DAC, similar to provisions currently in place in California's Low Carbon Fuel Standard. Finally, if support arises for the federal government's direct involvement in carbon removal, an existing or new agency could be tasked with constructing and operating DAC plants with geologic sequestration.

Shaping the Policy Environment to Support DAC With Sequestration at Scale

While discrete deployment policies outlined above can help get DAC off the ground and heading in the right direction through 2030, a broad policy framework will be necessary to support the long-term US need for DAC with sequestration. We identify two capable options for the federal government to pursue: carbon pricing and a public carbon removal agency.

Integrate DAC With Sequestration in Carbon Pricing

While politically challenging at the moment, a cap-and-trade program or carbon tax similar in ambition to the scenarios considered in this analysis should be sufficient to support long-term deployment of DAC with sequestration. Carbon pricing deploys DAC as part of an integrated, economy-wide decarbonization policy framework, an upside to this approach To fully support DAC with sequestration, carbon pricing proposals should include a mechanism to credit carbon that is removed from the air and permanently stored underground.

Establish a Federal Carbon Removal Administration

As an alternative to carbon pricing, the US could choose direct public funding for carbon removal. Mechanisms for supporting DAC with sequestration include mandating public procurement, codifying a permanent version of the Section 45Q tax credit, or authorizing a new public agency with sole responsibility for achieving negative-emissions goals. Similar to DOE's Office of Environmental Management—which oversees the largest environmental cleanup operation in the world—Congress could charter an agency that would receive dedicated funding to remove a specified amount of CO_2 each year. Pursuing this option means separate policies to accelerate energy efficiency, end-use electrification, decarbonization of the electric power sector, and other mitigation and carbon removal actions would still be necessary to meet the ambitious GHG reduction targets examined in this report.

Create a Roadmap for Deep Decarbonization

Meeting long-term US GHG reduction targets requires a fundamental transformation of the energy system. To enable this decarbonized future, the US should improve the siting of renewable energy plants and long-distance transmission lines. Electricity generation expands by up to triple current levels with decarbonization and becomes dominated by zero-carbon sources like wind, solar, nuclear, and natural gas with carbon capture and storage. Meanwhile, demand for coal and gasoline would be pushed to near zero by midcentury demand for diesel and natural gas would decline dramatically. Our results highlight the need for further research on how incumbent industries should transition in a deeply decarbonized future.

The Opportunity for Global Leadership

The US has a long track record of leading the world in technological innovation. DAC is part of a suite of carbon capture utilization and storage breakthrough technologies recently identified by former Secretary of Energy Ernest Moniz and energy scholar Daniel Yergin as worth prioritizing for investment and policy support. With assets such as vast CO_2 pipeline infrastructure, proven enhanced oil recovery capacity and more than 2 trillion tons of geologic storage capacity, the US is well-positioned to foster development of DAC with sequestration. Fortunately, thanks to recent breakthroughs, the pathways to doing so are increasing in number and falling in cost. But just as is the case for other critical low-carbon technologies, like nuclear and carbon capture and sequestration, significant federal policy action is required to ensure DAC technology is available in time and at the scale to contribute to avoiding the worst impacts of climate change.

CHAPTER 1

Why Direct Air Capture and Why Now?

The problem of climate change is long-term, global and multifaceted. Its impacts are already felt across the US. Evidence suggests that these impacts will grow in breadth and severity in the years ahead if global emissions continue to increase.[i] In the 2015 Paris Agreement, countries from around the world pledged to work together to "hold the increase in global average temperatures to well below 2° Celsius above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels."[ii] Recent research suggests that meeting these targets would avoid trillions of dollars in future damages in the US and around the world, and prevent harder-to-quantify losses, like species extinction and ecosystem destruction.[iii]

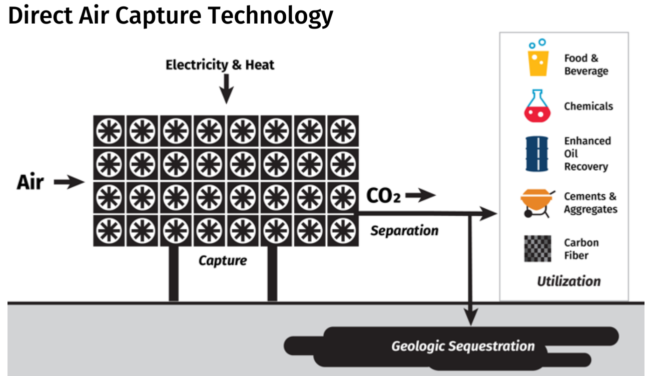
Scientists estimate that to limit global temperature increases to 2°C, global greenhouse gas (GHG) emissions will by 2030 need to decline 10% to 30% below 2010 levels and between 2065 and 2080 fall to net negative.[iv] To limit global temperature increases to 1.5°C, emissions need to by 2030 decline 40% to 60% below 2010 levels and between 2045 and 2055 fall to net negative. Achieving these reductions will require an unprecedented level of change in the global energy system and a wide array of solutions, incorporating technologies and practices that remove carbon dioxide (CO_2) from the atmosphere.

This report focuses on a specific carbon removal technology: Direct Air Capture (DAC). DAC technology has been in use since the 1950s primarily in the fields of spaceflight and submarines. Where breathable air is finite, DAC CO_2 scrubbers capture the CO_2 in the air from human respiration to keep ambient CO_2 concentrations at safe levels. Beyond these vital niche applications, DAC is one of many carbon capture and utilization technologies that contribute to the development of new low carbon products and fuels. If deployed at gigaton scale by mid-century, DAC has the potential to make a major contribution to the global response to climate change.

What Is Direct Air Capture?

DAC works by accomplishing two basic processes. First, ambient air is sent through an air contactor where CO_2 from the air is chemically bound using a solid or liquid sorbent. Second, energy—in the form of a vacuum, heat, or some combination—is used to separate the CO_2 from the binding chemical and isolate it into a stream of concentrated CO_2. In most examples of current DAC technologies, the CO_2 stream is pure enough for direct utilization or as a product feedstock (Figure 1.1). In some cases, additional energy may be required to concentrate or pressurize the CO_2 for truck or pipeline transport so it can be stored in permanent underground reservoirs or used in Enhanced Oil Recovery (EOR). There are currently eleven DAC plants installed around the world with one US-based plant located in Alabama.[v]

FIGURE 1.1.
Direct Air Capture Technology



Source: Adapted by Rhodium Group from World Resources Institute

A recent report by the Intergovernmental Panel on Climate Change (IPCC) indicates that carbon dioxide removal (CDR) is essential to achieving a 2°C or 1.5°C temperature target.[vi] An array of CDR options exist including bioenergy with carbon capture and storage (BECCS) and natural sequestration of CO2 in forests and soils. DAC is unique among CDR options in that the technology is limited only by costs.[vii] Abundant geologic reservoir capacity is available around the world to accommodate trillions of tons of CDR from DAC with sequestration (DACS). For these and other reasons, DACS may have the highest potential to reach the global scale of all leading CDR options.[viii] Aggressive action to decarbonize the US economy combined with CDR from a variety of approaches, including DACS, makes a net zero or even a negative emissions economy achievable.

Why the US?

The global nature of the climate challenge means that CDR technologies like DACS can be deployed anywhere in the world and achieve the same atmospheric impact. In this report, we focus on policy actions the US can take to get DAC to scale and drive deep GHG emission reductions. We do this for several reasons. First and foremost, DAC has the potential to be a huge global business, possibly as large as today's oil and gas industry by mid-century. With an effective and timely strategy, the US can position itself to lead this new sector and export the technology around the world. Second, the US has a long track record of steering global technological innovation. DAC is part of a suite of Carbon Capture Utilization and Storage (CCUS) breakthrough technologies recently identified by Former US Energy Secretary Ernest Moniz and energy scholar Daniel Yergin as worth prioritizing for investment and policy support.[ix] The US has a unique opportunity to bolster its leadership in related activities such as EOR and CCUS, as it hosts most of the EOR projects globally and maintains the largest network of CO_2 pipelines in the world.[x] The latter has the potential to be a bridge to a broad CO2 market that can drive DACS to scale.

Third, the US is home to world-class universities and national labs and spends over $4 billion a year on federal applied energy research.[xi] All of this experience and leadership provides a solid foundation for DAC technology development and deployment in the US. Fourth, its status as the world's largest economy means policies implemented in the US can influence global markets and technology deployment. Fifth, the US has world-class CO_2 geologic storage resources capable of permanently sequestering at least 2.4 trillion metric tons of CO_2.[xii] That's enough space to store nearly 500 years' worth of current annual US CO_2 emissions and presents an opportunity for America to lead the world in carbon removal. Finally, as the largest historical emitter of GHGs, the US has a responsibility to seize this opportunity and collaborate with other nations to meet global climate goals.

The Goal of This Report

This report seeks to inform federal policymakers and key stakeholders of the role DAC technology can play as part of a robust response to the threat of climate change and the actions required in the near, medium and long-term to get DACS to scale. Carbon180 asked Rhodium Group to conduct this independent analysis with financial support from the Linden Trust for Conservation and the ClimateWorks Foundation to advance understanding of this cutting-edge technology and identify pathways for the US to lead in its development. Informed by the latest peer-reviewed literature and dozens of expert interviews, this report presents first-of-a-kind analysis of the role of DAC in a decarbonized future and identifies policies that can put the US on a path to be a global leader in DAC technology development and deployment.

Following this introduction, we quantify the amount of DACS deployment required to achieve deep decarbonization in the US consistent with global emissions targets (Chapter 2). From there we review the current DAC technology and market landscape and assess the impact of existing policies on DAC deployment (Chapter 3). In Chapter 4, we identify new federal policy actions that can be taken to accelerate DAC deployment and catalyze the construction of millions of tons of DAC capacity over the next decade. In Chapter 5, we identify multiple options for longer-term policy frameworks that can support DACS deployment at scale. We then summarize key findings and recommendations in Chapter 6. At the end of this report, we include a technical appendix that describes our analytical methods and sources in detail.

CHAPTER 2:

The Scale of the Challenge

Any robust US response to climate change will require a diverse portfolio of solutions and innovations across all sectors of the economy. Government, academic, and independent research have identified several technologies, economic shifts, and market transformations that will play a role in achieving deep decarbonization.[1] These include aggressive energy efficiency, electrification of transportation and buildings, eliminating emissions in the electric power sector, capturing CO_2 from industrial sources, and improving the sequestration capabilities of America's forests, farmlands, and rangelands.[xiii] To date, almost no analyses have estimated the role DAC needs to play to help deliver deep decarbonization in the US. In this chapter, we fill this research gap using state-of-the-art modeling tools. With an estimate of the likely range of DACS required by mid-century, we establish pathways for scaling up DAC in the near- and medium-term to achieve deployment.

Current Global Estimates of DAC Requirements

An 'All-In' Approach

Countless global assessments completed over the past several decades identify the level of emission reductions required to achieve climate stabilization targets.[xiv] These same assessments have identified the type of energy and economic system changes needed and the magnitude necessary to achieve these goals. Recently, major energy companies have also published their outlooks for system transformation in a carbon-constrained world.[xv] While these studies differ in the relative roles of critical technologies in meeting the climate change challenge, nearly all identify the following six components as key to a low carbon future:

- Energy Efficiency: Improving the energy performance of buildings, industrial processes, vehicles, and equipment to provide the same services using less energy.
- Electrification: Converting fossil fuel-consuming vehicles, equipment, and appliances to electricity.
- Clean electricity: Shifting away from conventional fossil fuel-fired electric power generation to zero-emitting technologies like renewables, nuclear, and fossil generation with carbon capture and storage.
- Clean fuels: Switching from fossil fuels to alternatives with lower lifecycle GHG emissions, such as biofuels.
- Carbon capture utilization and storage (CCUS): Capturing CO_2 from industrial sources and electric power generators and using it as a feedstock in long-lived products or permanently storing it underground.
- Carbon dioxide removal (CDR): Enhancing natural carbon sequestration in soils and forests, ramping up BECCS, launching and scaling DACS, and developing other new technologies.[2]

Carbon Dioxide Removal Is Essential for Meeting Global Temperature Targets

As discussed in Chapter 1, recent research summarized in the October 2018 IPCC special report finds that net global GHG emissions must fall to zero between 2045 and 2055 to achieve a target of limiting global temperature increase to 1.5°C above pre-industrial levels with limited or no interim overshoot in temperature.[3][xvi] To limit temperature rise to 2°C, global net emissions must fall to zero between 2065 and 2080. After reaching zero, net GHG emissions need to then be negative for the remainder of the century. If the world takes immediate measures to dramatically cut CO_2 emissions nearly 60% by 2030 and over 90% by 2050, then natural CDR approaches may be sufficient on their own to achieve negative net emissions by 2055. That said, such dramatic cuts may be politically infeasible. The IPCC found that technological CDR including BECCS and DACS will be

[1] While deep decarbonization is a general term of art, we use it here to mean at least an 80% reduction in energy CO2 emissions relative to 2005 levels.
[2] Beyond these three options there are several early stage CDR options that could also play a role in meeting global temperature targets. The NASEM report explores several of these technologies. While they all hold promise, this report focuses on the three CDR categories that are furthest along in development: natural sequestration, BECCS and DACS.
[3] Overshooting a temperature target means global mean temperatures increase above a specific temperature target for an interim amount of time before GHG concentrations are reduced to a level that ultimately achieves the target.

required if the energy transition is slower, possibly at multi-gigaton scale by mid-century.[xvii]

Most models used to inform the IPCC assessments did not explicitly include DACS, though the technology could be pursued in place of BECCS should sustainable biomass prove limited. A comprehensive review of the negative-emissions literature found that global CDR from a portfolio of approaches will need to be between 0.5 and 8 gigatons per year in 2050 to achieve a 2°C target and between 5 and 15 gigatons per year to achieve a 1.5°C target. Of those amounts, DAC has the potential to provide 0.5 to 5 gigatons per year of CDR by 2050 and as much as 40 gigatons per year by the end of the century.[xviii]

The Role of DAC in the US

With that context in mind, what amount of DACS deployment will be required within the US for America to do its part in delivering a 2°C or 1.5°C global future? The answer depends on the same dynamics discussed above: the level of overall emission reductions required, the portfolio of technologies used to deliver those reductions, and the availability of other negative-emissions options, as well as what actions other countries take to tackle climate change. To estimate potential US DACS deployment requirements in 2050, we conducted some of the first-ever published energy system modeling of US GHG emission reduction targets with DAC explicitly represented.[xix] We constructed four bounding scenarios and modeled them using the Regional Investment and Operations (RIO) Platform coupled with the open-source EnergyPATHWAYS model.[xx] Both tools are owned, maintained, and configured for the US energy system by Evolved Energy Research.[xxi] The models were operated using input scenario specifications developed by Rhodium Group. For more information see the technical appendix that accompanies this report.

EnergyPATHWAYS is a detailed energy equipment stock accounting model with highly granular representation of technologies in all end-use sectors of the economy. The energy demand scenarios we developed in EnergyPATHWAYS capture a range of potential market outcomes described in detail below. RIO is a linear program optimization model of US economy-wide energy supply that explicitly represents BECCS and DAC technologies. RIO solves for the optimal, least cost transformation of US energy supply to meet a given demand profile from EnergyPATHWAYS while achieving a specified energy CO_2 reduction target. The high technological resolution, broad energy system coverage and explicit representation of key CDR technologies make the combined modeling framework well-suited for this analysis. For more details on all aspects of this analysis, see the technical appendix at the end of this report.

Setting Emission-Reduction Targets

Matching any specific US emissions pathway to a particular global temperature outcome requires making assumptions about what the US's "fair share" of required global emission reductions should be. This is a subject of intense and ongoing debate in international climate negotiations. It also depends on the equilibrium climate sensitivity (the amount of warming that occurs from an increase in CO2 concentrations in the atmosphere), about which there is a meaningful amount of scientific uncertainty. For simplicity, we use the following two net GHG emission reduction targets as the starting point for our DAC modeling:

1. **83by50**: A straight line reduction pathway from 26% below 2005 levels in 2025 to 83% below 2005 levels in 2050.

2. **100by45:** A straight line reduction pathway from 28% below 2005 levels in 2025 to 100% below 2005 levels (net zero emissions) in 2045 and 105% below 2005 levels in 2050.

The 2025 starting points reflect the current US Nationally Determined Contribution to the Paris Agreement.[xxii] The 2050 83by50 target is derived from the Waxman-Markey legislation that passed the US House of Representatives in 2009.[xxiii] The 100by45 target is derived from California executive order B-55-18 signed by Governor Jerry Brown in 2018.[xxiv] California's goal represents the most ambitious emissions reduction target set by a state executive in the US. Adopted nationally, it would put US action on course for the ambitious end of the 2045 to 2055 net zero target date that IPCC identified in the 1.5°C special report.

Identifying DAC Deployment Sensitivities

For each US emissions target, we constructed a high and a low bounding scenario for DAC deployment. In all scenarios, actions are taken across the economy to decarbonize the energy system with differing degrees of transformation and supply of CDR. Table 2.1 provides a summary of the four bounding scenarios used in this analysis. For more information see the technical appendix that accompanies this report.

TABLE 2.1.
DAC bounding scenarios used in this analysis

Scenario	Mid-century net GHG Target(s)	Electrification	Biomass Supply	Natural CDR
83by50 – High DAC	83% below 2005 by 2050	Slow	Constrained	Low
83by50 – Low DAC	83% below 2005 by 2050	Moderate	Upper bound	High
100by45 – High DAC	100% below 2005 by 2045, 105% below 2005 by 2050	Moderate	Constrained	Low
100by45 – Low DAC	100% below 2005 by 2045, 105% below 2005 by 2050	Accelerated	Upper bound	High

Both the EnergyPATHWAYS and RIO models simulate US energy CO_2 emissions, which in 2016 represented roughly 80% of gross GHG emissions in the US.[xxv] We set energy CO_2 targets for each scenario that achieve the net-GHG targets, accounting for assumptions around both non-energy CO_2 GHG emissions and natural sequestration.

For each bounding scenario, we assume all other GHGs except energy CO2 emissions follow trajectories in line with current federal policies with minimal regulatory rollbacks, as projected in Rhodium's Taking Stock 2018 report.[xxvi] This is reasonable for several reasons. First, 60% of non-energy CO2 GHG emissions come from sources that are difficult to mitigate such as agriculture and industrial processes due to a lack of cost-effective substitutes. Second, most non-energy CO2 GHG emissions come from economic activities that have traditionally avoided air pollution regulation such as agriculture, making it unrealistic to assume aggressive future action. Finally, increased demand for food to feed a growing population is likely to put upward pressure on agricultural emissions in the coming decades. We do assume Hydrofluorocarbon (HFC) emissions decline in accordance with US commitments under the Kigali amendment to the Montreal Protocol.[xxvii] We also assume that methane and N_2O emissions associated with fossil fuel production and consumption decline in rough proportion to demand in EnergyPATHWAYS. The combination of all of these factors leads to non-energy CO2 GHG emissions of 947 to 1,042 million metric tons CO2e in 2050. This is a 28% to 21% reduction in non-CO_2 GHG emissions respectively relative to 2016 levels. In all of our scenarios, non-energy CO2 GHG emissions in 2050 are lower than in any of the scenarios considered in recent US government mid-century analyses.[xxviii]

One CDR approach not explicitly represented in our modeling platform is natural sequestration of carbon in forests and soils. Every year CO2 is removed from the atmosphere by plants and other organisms through photosynthesis and other biological processes. The carbon can stay in soil, trees and roots resulting in net removal of CO2. In 2016, these processes removed 716 million tons of CO2 from the air. Projecting future CDR from natural sequestration is challenging given the complex dynamics of terrestrial ecosystems, related market interactions with demand for forest products, and the potential extent of land-use change between sectors. In addition, the impact of climate change on ecosystem CDR capacity is highly uncertain. A complete assessment of CDR from natural sequestration is outside the scope of this analysis. For our scenarios, we rely on upper and lower bound US Mid-century Strategy report.[xxix] In 2050 we assume high CDR from natural sequestration of 613 million metric tons of CO2 and low CDR of 381 million metric tons of CO2.

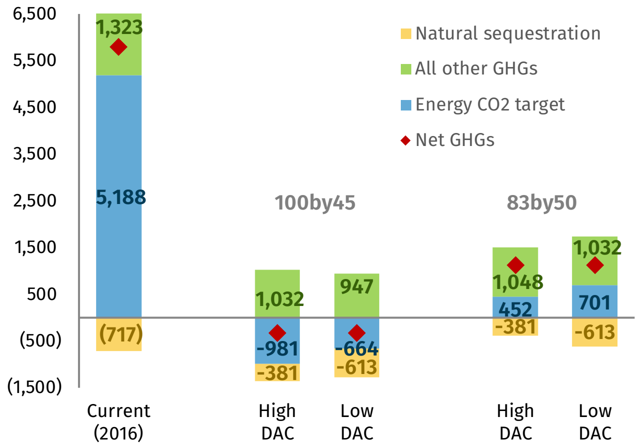
Sustainable biomass is another important factor in deep decarbonization. Sustainable biomass, assumed in this report to have lifecycle GHG emissions equal to zero over a 100-year timeframe, can be used to produce biofuels, heat, and electricity. Biomass can provide CDR if the emissions from combustion are captured and safely stored in geologic reservoirs. In the Low DAC scenarios, we assume nearly a billion dry tons per year of sustainable biomass would be available in 2050 (Figure 2.9). This is close to the upper bound estimated in several recent studies and roughly triple current total US biomass supply.[xxx] In our High DAC scenarios, we reduce the biomass supply in 2050 by 70%, consistent with levels requiring no change in current land uses.[xxxi] This assumption reflects concerns about the potential for bioenergy crops to interfere with food production.

The combination of a reduction in CDR from natural sequestration in 2050 relative to today and slower declines in non-energy CO2 GHGs relative to the emission reduction targets in our scenarios means the energy system has to take on a larger share of the burden (Figure 2.1). For example, to meet the 83by50 target energy CO2 must meet a target of 88% to 93% below 2005 levels in the Low DAC and High DAC scenarios respectively. To meet the 100by45 target in 2050, energy CO2 must meet a target of 111% to 116% below 2005 levels in 2050 in the Low DAC and High DAC bounding scenarios, respectively. The 100by45 energy CO_2 targets are fairly ambitious compared to other studies and proposals.[xxxii]

FIGURE 2.1.

US current emissions and 2050 targets by bounding scenario

Net million metric tons CO_2e



Source: US Environmental Protection Agency (EPA), US Mid-century Strategy, Rhodium Group analysis

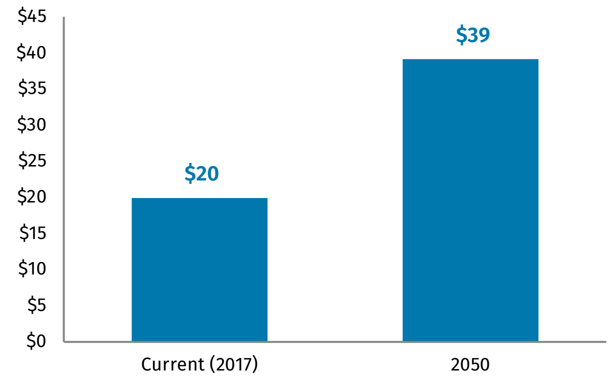
Unprecedented Mitigation Action on All Fronts

In our bounding scenarios, the pace of electrification and energy efficiency in buildings, vehicles and other end-uses is assumed to scale with the ambition of GHG reductions as part of a broad portfolio of climate policy action. Across all four scenarios, we assume the US economy continues to grow while aggressive action is taken to transform the energy system. We assume that US GDP grows at a 2.1% annual rate resulting in a doubling of output in real terms by 2050 compared to 2017 (Figure 2.2).[xxxiii] We assume aggressive energy efficiency improvements are pursued across the economy in all scenarios. Starting in 2025, we assume the most efficient appliances, equipment, and devices available for a given energy service are used regardless of costs. Industrial energy efficiency performance improves at a rate of 1% per year. These efficiency improvements overall result in the decoupling of final energy consumption from economic growth, leading total energy demand to decline from today's levels by up to one-third (Figure 2.3), even while the nation's population grows by 22% to nearly 400 million people by mid-century. We discuss the energy demand associated with DACS and other mitigation actions taken on the supply side of the energy system in Chapter 5.

FIGURE 2.2.

US Gross Domestic Product, current and 2050

Trillion 2018 dollars

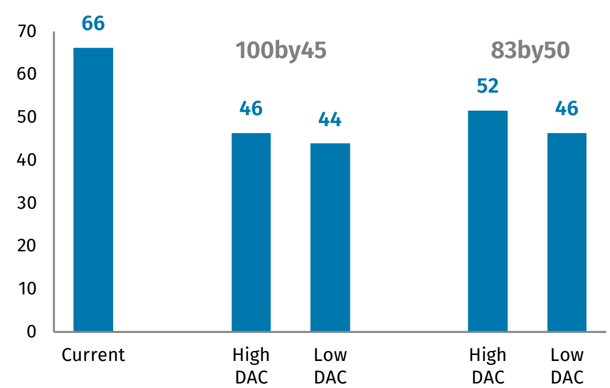


Source: EIA and Rhodium Group analysis.

FIGURE 2.3.

Initial US final energy demand, current and 2050

Quads



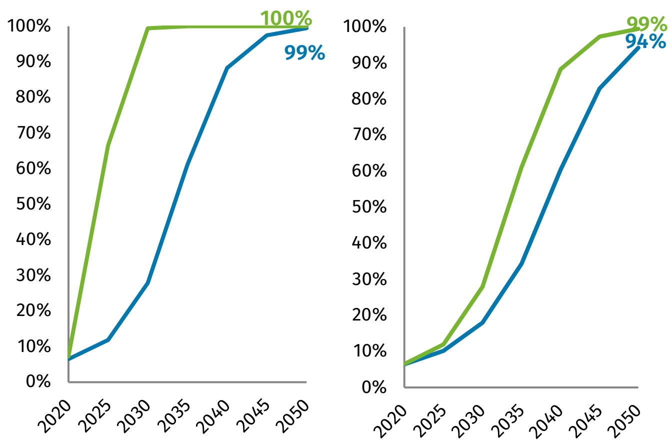
Source: EIA, Rhodium Group and Evolved Energy Research analysis. Note: While efficiency assumptions are consistent across scenarios, final energy demand is not, due to different electrification assumptions.

Four factors determine the economy-wide pace of electrification: which end-uses electrify, when do electric technology options become available, how quickly electric technologies secure large shares of annual equipment sales and, most importantly, how much of a given stock of equipment gets replaced each year. For example, in meeting an 83by50 target we assume light-duty electric vehicles (EVs) achieve 18% and 28% of sales in 2030 in our High DAC and Low DAC scenarios respectively, up from 1.2% in 2017 (Figure 2.4).[xxxiv] Sales shares climb to 94% and 99% for the same scenarios in 2050. In meeting the 100by45 target, electrification ramps up much faster with EVs achieving 28% of sales in our High DAC scenario and 99% in our Low DAC scenario by 2030. All but the 83by50 High DAC EV sales share pathway are more aggressive than the most optimistic deployment pathways recently published by the National Renewable Energy Laboratory; therefore, policy action will be required to achieve them.[xxxv]

FIGURE 2.4.

Electric vehicle share of light-duty vehicle sales

% of sales



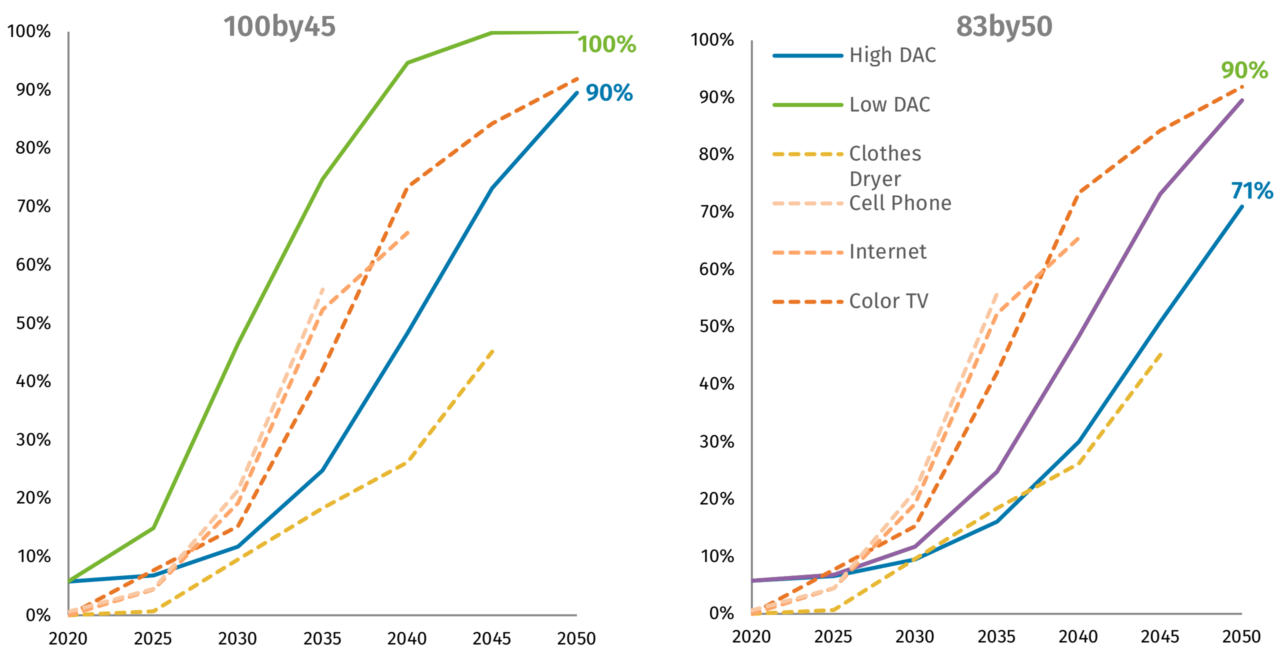
Source: Rhodium Group and Evolved Energy Research analysis.

The CO_2 emissions reduction benefits of EVs are not immediate even when achieving high sales shares, partly because it takes time for new EVs to replace existing conventional cars on the road. For example, achieving 99% EV sales in 2030 in the 100by45 Low DAC scenario results in 46% of all cars on the road being electric in 2030 and 95% being electric by 2040 (Figure 2.5). The entire light-duty vehicle fleet would not be fully electric until 2050, illustrating the urgency of ramping up electrification now to make it easier to achieve long-term climate targets later. However, there is no way the US will reach 99% EV sales in 11 years without unprecedented policy action. Figure 2.5 also shows deployment rates for popular technologies introduced in the 20th century. The rate of EV adoption in the 100by45 Low DAC scenario is unprecedented and exceeds even cell phone adoption rates. For comparison, the slowest deployment rate for EVs in our analysis, associated with the 83by50 High DAC scenario, is comparable to the rate of clothes dryer adoption in the US. The pace of EV market penetration in our 100by45Low DAC scenario is considerably faster than cell phones, color TVs, or the internet.

FIGURE 2.5.

Electric vehicle share of light-duty vehicle stock and penetration of other technologies

% of stock

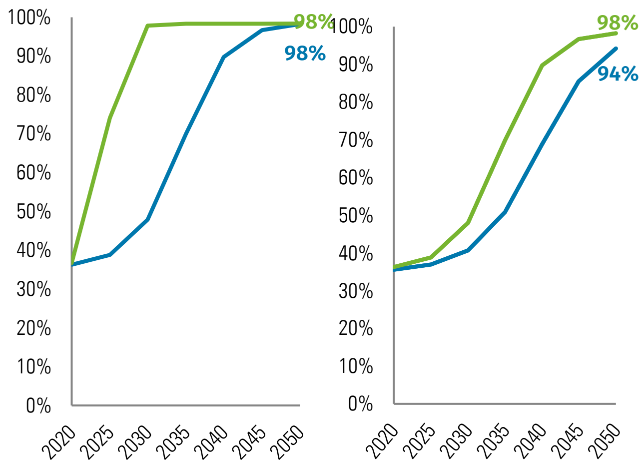


Source: Rhodium Group and Evolved Energy Research analysis.

The pace of electrification in buildings in our scenarios is exemplified in Figure 2.6 by the electric share of new residential heaters. Electric heaters must achieve a similar portion of total sales to electric light-duty vehicle sales. Currently, the electric sales of residential heaters is around 35% (Figure 2.6).

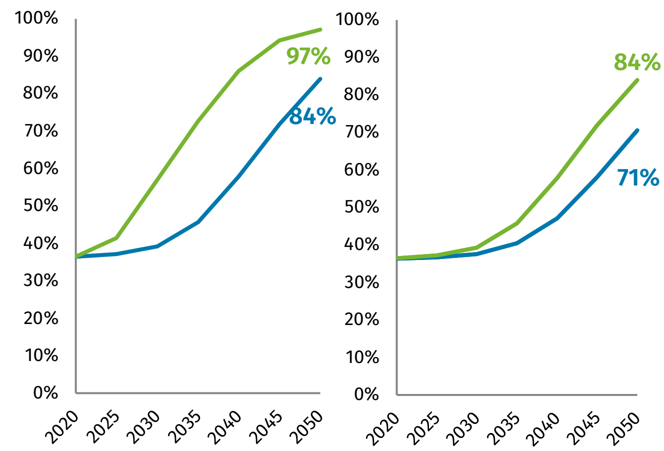
Sales shares for electric residential heating are quite high in all scenarios by 2050, though the rate of electrification of the total residential heating stock is much slower due to the increased difficulty of turning over building heating stock. By 2050, in our 83by50 High DAC scenario, 71% of residential heating is electric. In both the 83by50 Low DAC and 100by45 High DAC scenarios, 84% of total residential heating is electric and in our most ambitious electrification scenario, 97% of all residential heating is electric (Figure 2.7).

FIGURE 2.6.
Electric share of new residential heaters
% of sales



Source: Rhodium Group and Evolved Energy Research analysis.

FIGURE 2.7.
Electric share of all residential heating and penetration of other technologies
% of stock

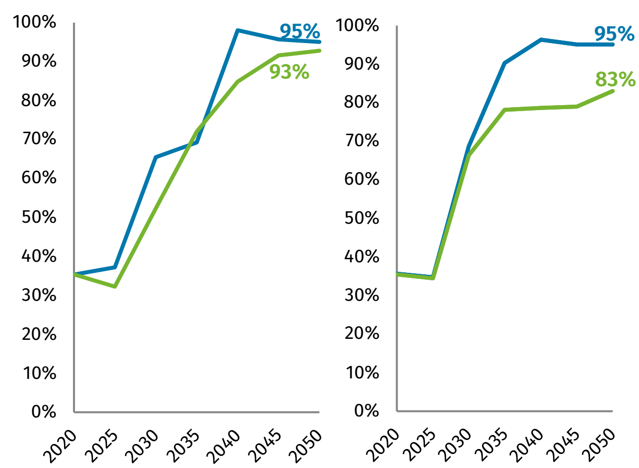


Source: Rhodium Group and Evolved Energy Research analysis.

The Future of Energy Supply

In all of our scenarios, an array of electric power generation technologies compete to serve conventional and newly-electrified loads, as well as any additional demand from the operation of DACS facilities, hydrogen, and other fuel production. Available options to decarbonize the electric system in the model include wind, solar photovoltaics (PV), hydro, small modular nuclear reactors, natural gas with CCS, biomass generation with CCS, and other technologies. Fossil fuels remain available to supply electric power generation and conventional fuel demand across the energy system but they become increasingly uncompetitive as emission-reduction targets grow tighter. In three of our four scenarios, more than 90% of electricity comes from zero-carbon sources by 2040, up from 35% today (Figure 2.8).

FIGURE 2.8.
Zero emissions share of electricity generation
Percent



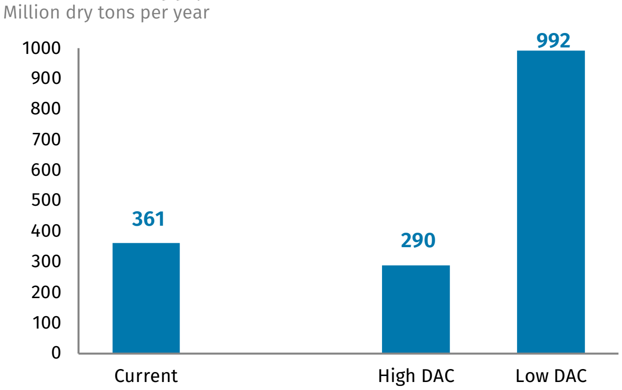
Source: Rhodium Group and Evolved Energy Research analysis.

Electrification of end-use sectors substantially reduces demand for liquid and gaseous fuels. Still, even the highest levels of electrification can't decarbonize industrial activities with high-temperature heat requirements or long-haul aviation and shipping. To address emissions from these and other tough-to-decarbonize sectors our modeling allows industrial CCS, biofuels, hydrogen, and synthetic drop-in fuels (made from hydrogen combined with captured CO_2 from industrial sources or DAC) to be produced and used to meet remaining non-electric energy demand while achieving emission reduction targets. In addition, sustainable biomass is available to meet energy system demand subject to supply constraints that vary across our scenarios (Figure 2.9).

FIGURE 2.9.

US biomass supply, current and 2050

Million dry tons per year



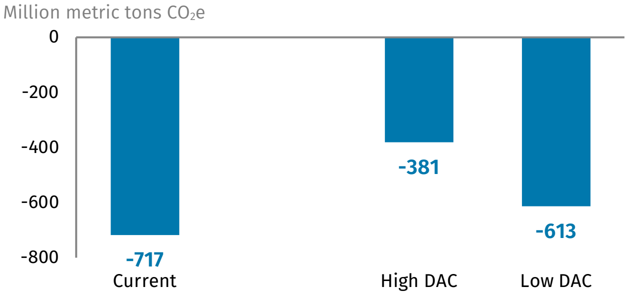
Source: DOE, US Department of State and Rhodium Group analysis.

Remaining energy CO_2 emissions not addressed through efficiency, electrification, CCS or clean fuels must be offset by CDR to meet energy CO_2 targets in our model. We set bounding cases for CDR from natural sequestration that represent the starting point offsetting energy CO2 emissions. If more CDR is required to meet a given target, the model can choose to build BECCS either as biorefineries equipped with CCS or biomass-fired power plants with CCS. Finally, DACS is available to offset energy CO_2 emissions if the model finds that it is the most economic option available.

FIGURE 2.10.

CDR from natural carbon sequestration, current and 2050

Million metric tons CO_2e



Source: EPA, US Department of State and Rhodium Group analysis.

2050 DAC Requirements

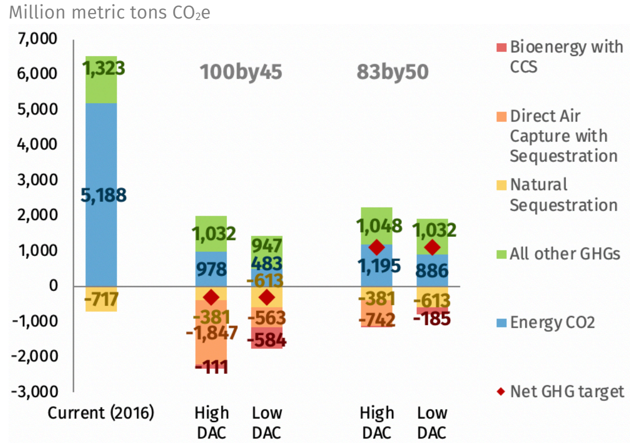
The exact quantity of DACS required is an output of our modeling and reflects the aggregate, interactive impacts of all of our scenario assumptions and the least cost pathway to achieving a given GHG reduction target. We find that DACS is essential for the US to achieve a 100by45 emissions target in 2050. In our Low DAC scenario, 563 million metric tons per year of CDR is needed by 2050, similar in scale to all CO_2 emissions from buildings in the US in 2016. In our High DAC scenario, that rises to 1.85 billion metric tons of CDR per year (Figure 2.11). That's roughly the same size as CO_2 emissions from the US electric power sector in 2016. Faster progress in reducing non-CO_2 emissions like methane and N_2O from farming and livestock would reduce the amount of DAC required, but abatement in these areas faces considerable political and technical challenges. Betting the future on the ability to do so is a high-stakes proposition when it comes to meeting 100by45 targets, even if successful, large quantities of CDR would still be required. We discuss this later in this chapter.

Even under a less ambitious but still very challenging 83by50 target, between zero and 724 million metric tons per year of DACS are required by 2050 in our modeling. If the pace of electrification is very rapid and both biomass supply and natural sequestration are high, then DACS may not be necessary. But this would require changes of unprecedented speed in the energy and land-use sectors. If these other decarbonization options do not deliver, then a significant amount of DACS will be needed. Therefore, to meet the 83by50 target, DACS represents an important insurance policy if other decarbonization strategies fall short.

FIGURE 2.11.

US GHG emissions under DAC bounding scenarios, current and 2050

Million metric tons CO_2e



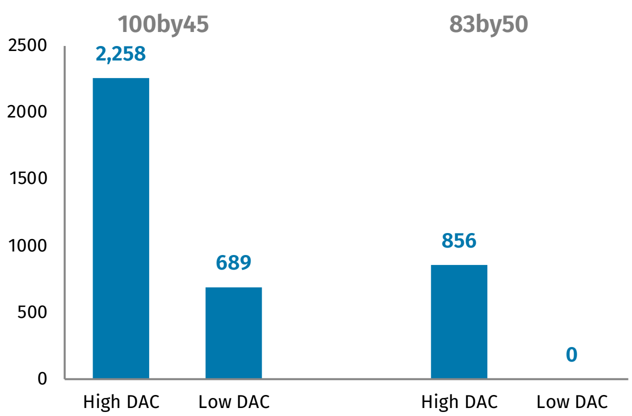
Source: Rhodium Group and Evolved Energy Research analysis.

How many DACS plants will need to be operating in 2050 to achieve the CDR shown in Figure 2.11? A typical industrial scale DAC plant is expected to have a capture capacity of at least 1 million tons of CO_2 per year.[xxxvi] These plants won't operate 100% of the time due to maintenance and the variable costs of energy. That means that the number of plants will be higher than a given amount of carbon removal associated with them. We find that in order to achieve the upper bound DACS required to meet an 83by50 target, the US will need 856 DACS plants in 2050. To achieve the 100by45 target the US will need 689 to 2,258 DACS plants in the same year. If DACS plant capacities end up being greater than 1 million tons per year, then fewer plants will be required to achieve the same total CDR capacity.

FIGURE 2.12.

US DACS installed capacity, 2050

Number of megaton scale plants



Source: Rhodium Group and Evolved Energy Research analysis.

Based on these results, and keeping in mind that the future is uncertain, we recommend using the approximate upper bound of each emission reduction target range to establish a low and high deployment goal for DAC in the US of 850 to 2,250 million tons of DACS capacity in 2050. To put these goals in context, today there are 613 facilities in the industrial, waste, and electric power sectors in the US emitting one million metric tons CO_2 equivalent or more of GHGs annually. Collectively, these facilities are responsible for over 2 billion metric tons CO_2 equivalent of emissions.[xxxvii]

What if other CDR and non-energy system mitigation options deliver?

Our scenarios include the rapid and unprecedented transformation of the US energy system as part of concerted policy action to meet GHG reduction targets. We assume less ambitious action in tough-to-decarbonize sectors such as agriculture. We also assume CDR from natural sequestration plays a role in line with government projections. What if these assumptions turn out to be too conservative? A massive consumer shift away from meat consumption and towards plant-based substitutes coupled with near universal adoption of organic farming practices could lead to substantial cuts in methane and N_2O. Widespread adoption of no-till farming, cultivation of new crops that increase underground biomass and soil carbon, plus a revolution in forest management to prioritize carbon sequestration could also increase natural CDR in the US.[xxxviii]

Achieving such outcomes on either front would undoubtedly increase the chances that the US will meet either GHG reduction target considered in this analysis. The need for technological CDR (BECCS or DACS) would be smaller. To understand the maximum potential impact on CDR deployment of transformations in US agriculture, consumer behavior, and land management we consider three alternative cases:

- All GHG emissions associated with agriculture are eliminated resulting in GHG emissions that are 588 million metric tons CO2e lower in 2050 than we report above ("zero ag GHG" in Table 2.2.);
- Net CDR from natural sequestration in 2050 is double the amount in our Low DAC scenarios or 1,226 million metric tons, a 63% increase from 2016 levels ("2x natural CDR" in Table 2.2.); and
- Both 1) and 2) are achieved ("both" in Table 2.2.).

Table 2.2 presents the results of these alternative cases. If agriculture emissions fall to zero, we find that our initial results are directionally the same. Technological CDR is required to meet GHG reduction targets in three out of four of our bounding scenarios. If natural sequestration is double our initial upper bound projection, then technological CDR is needed only in the two 100by45 scenarios. If both agriculture emissions are eliminated and 1,226 million tons of natural sequestration is secured in 2050 then over half a billion tons of technological CDR would still be needed to meet the 100by45 target using High DAC bounding assumptions for all other variables. These alternative scenarios illustrate the need to pursue emission reduction and CDR opportunities in every corner of the US economy. They demonstrate multiple additional unprecedented transformations that need to succeed to achieve deep decarbonization without DACS.

TABLE 2.2.

Technological CDR required to meet 2050 GHG reduction targets under alternative scenarios

Million metric tons CO2

Scenario	Initial Findings	Zero Ag GHG	2x Natural CDR	Both
83by50, High DAC	742	154	0	0
83by50, Low DAC	185	0	0	0
100by45, High DAC	1,958	1,370	1,113	525
100by45, Low DAC	1,147	559	534	0

Note: Technological CDR values assume either DACS, BECCS or a combination of both could be used to meet requirements.

If any one component of a multipronged approach to meeting GHG reductions targets fails, technological CDR, especially DACS will be required as backup. Electrification could be slower than projected, for instance, or energy efficiency improvements could continue at current rates rather than the step change we assume. A limited supply of sustainable biomass, a lack of agricultural breakthroughs, and no vast enhancements in US natural CDR capacity would also necessitate DACS. At a minimum, DACS should be seen as a hedge on any bet that the US will meet an ambitious GHG reduction target. It can serve as insurance if other decarbonization efforts don't deliver as planned. That said, DACS is an essential component of meeting the most ambitious GHG reduction targets. With all this in mind, DACS and other technological CDR options do not offer a "get-out-of-jail-free card" on the hard work of decarbonization. There is no moral hazard to pursuing DAC when all the tools in the toolbox, including technological CDR, are needed to get from here to a low carbon future.

Gigaton Scale DAC Deployment is Achievable

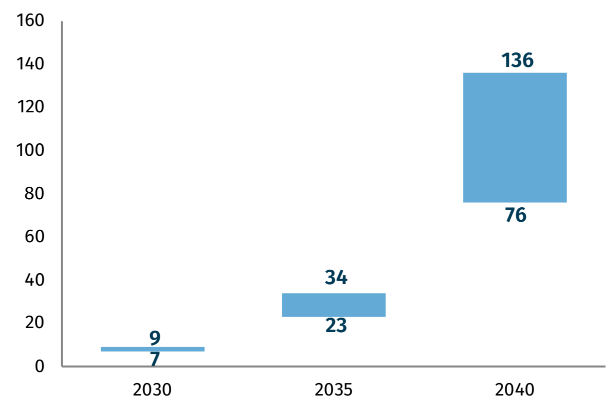
If the US gets started now, it has 30 years to innovate, demonstrate and improve DAC technology while building it out at gigaton scale in line with our findings. Developing a new industry from scratch doesn't happen overnight. What's critical is to build several demonstration plants as soon as possible to kick start innovation.[xxxix] In this current early stage, the actual applications of DAC technology matter little so long as multiple plants get built and commence operation. This means this first wave of DAC capacity can be used for clean fuel production and other uses of CO2, DACS or as a feedstock into products. The primary goal is to get experience building and operating DAC plants and reducing costs as opposed to large scale CDR from DACS. After 2030 however, deployment needs to increasingly focus on DACS to get on track for mid-century deployment goals and associated CDR to meet GHG reduction targets.

To establish interim deployment goals, we assume that several demonstration plants get built in the US quickly and are followed by the construction of one or two million tons of DAC capacity by 2025. Then we assume exponential growth paths to meet the 2050 goals. Based on this approach, the US needs seven to nine million tons of capacity in place by 2030 to stay on track. From there, 23 to 34 million tons of cumulative DACS capacity will be needed by 2035 and 76 to 136 million tons of cumulative DACS capacity by 2040, 20 years from now (Figure 2.13). After 2040, DACS deployment will need to accelerate rapidly to hit the 2050 goals. Over the roughly 30-year period between now and 2050, DACS deployment will need to follow a compound annual rate of growth of 26% to 31%.

FIGURE 2.13.

US DAC installed capacity ranges, 2030, 2035, 2040

Million metric tons of DAC capacity



Source: Rhodium Group and Evolved Energy Research analysis.

The US has scaled up industrial technologies like DAC before. The expansion of the nation's electric power system and associated generating technologies shows that the goal of building 850 to 2,250 DAC plants over 30 years is achievable. We tallied the cumulative amount of capacity deployed over time for four key utility-scale generating technologies: coal steam, natural gas combined cycle (NGCC), onshore wind, and solar PV, then normalized each by typical unit size (Figure 2.14).[xl] Making comparisons across technologies is difficult given different minimum capital requirements, construction profiles, unit sizes, and infrastructure needs. Still, it can be useful for providing directional insights into what's possible for DAC scale up.

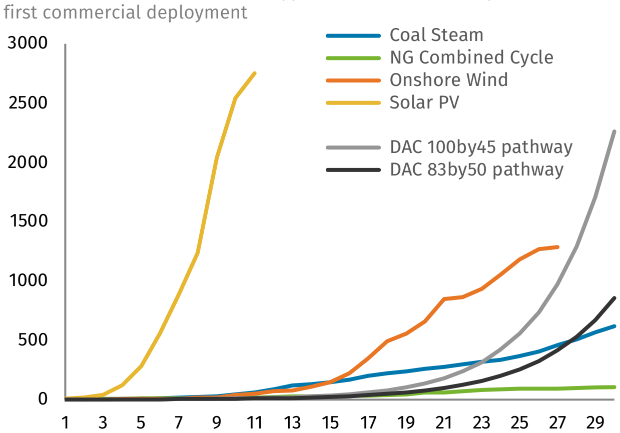
We find that the US deployed the equivalent of 258 typical coal steam units in that technology's first 20 years. That's nearly double the high end of the range for DAC deployment required in the same amount of time. What's more, onshore wind has achieved in its entire 27-year commercial existence the equivalent of over 1,200 typical units—far more than the lower bound 30-year DAC deployment goal of 856 plants. While the level of investment required per unit of utility-scale solar PV is lower than other electric generating technologies and may not provide an apples-to-apples comparison, that technology has achieved deployment of over 2,700 typical units in just 11 years. Both wind and solar have benefited from substantial federal R&D support as well as state and federal deployment incentives. The success of these technologies demonstrates the potential role policy can play to propel DAC to gigaton scale over the next three decades.

Another lesson from the electric power sector comes from the historical deployment of NGCC units. Over the first 30 years, NGCC units experienced much slower deployment compared to other technologies (Figure 2.14). In part to blame was the complicated nature of the technology as compared to a steam boiler. The technology also faced a lack of infrastructure and affordable supplies relative to coal. Still, enough NGCC capacity was deployed to allow improvement and learning. When fuel cost and infrastructure constraints lifted, the technology took off, nearly quadrupling installed capacity in just five years (Figure 2.15). After the surge, NGCC deployment continued at a much faster rate than in the past. This illustrates the importance of deploying DAC quickly and building enough plants to master the technology in preparation for the rapid take-off that will be necessary when the US chooses to address the threat of climate change comprehensively. It also illustrates that if a technology lacks the relevant infrastructure, then deployment will be constrained. For DACS, high-quality geologic sequestration sites and CO2 pipelines are both relevant infrastructure that will need to be built out if the technology is going to achieve mid-century deployment goals

FIGURE 2.14.

US DAC deployment goals and electric power generating technology deployment pathways, 30-year timeframe

Cumulative number of installed typical size units in each year after the first commercial deployment

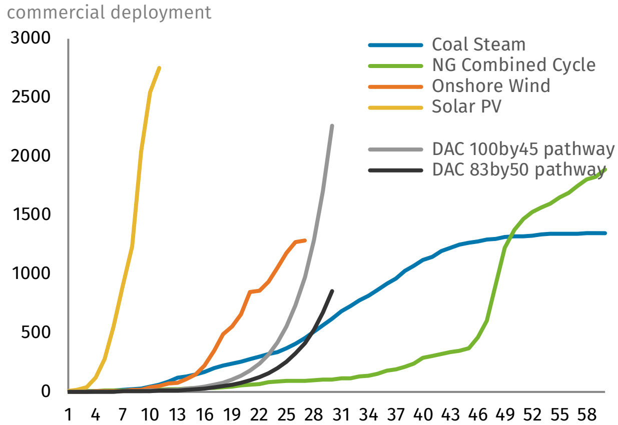


Source: Rhodium Group analysis.

FIGURE 2.15.

US DAC deployment goals and electric power generating technology deployment pathways, 60-year timeframe

Cumulative number of installed typical size units in each year after first commercial deployment



Source: Rhodium Group analysis.

While the challenge ahead is significant, this analysis demonstrates that scaling DACS to meet deployment goals is essential to ensuring the US achieves mid-century climate targets. Moreover, the DACS goals identified here are achievable when compared to technology deployment in the electric power sector. In the next chapter, we consider what the DAC industry and policy landscape looks like today and what federal policy can do to get the US on a path towards achieving DACS at the necessary scale.

CHAPTER 3

The Current Landscape

For several decades, DAC technology deployment was limited to niche applications such as scrubbing CO2 out of the air on spacecraft and submarines. At the turn of the century, concerns about climate change drove new research into the prospect of using DAC at scale to remove CO_2 from the atmosphere and store it underground. Researchers developed and tested several lab-scale technologies.[xli] A few small commercial ventures arose during the late 2000s. Simultaneously, the US House of Representatives passed the American Clean Energy and Security Act of 2009, a comprehensive climate change bill from Reps. Henry Waxman (D-Calif.) and Ed Markey (D-Mass.), that would have established a nationwide price on carbon. While the bill never became law, the notion of a US economy-wide carbon constraint provided the first glimpse of a potential commercial market for DACS.

Since then, progress toward improving DAC technologies has advanced slowly and steadily, but no large-scale facilities have been built. Currently, three private companies across the globe operate DAC plants. Two of these three companies, Climeworks and Carbon Engineering, are based outside the US. Global Thermostat, based in New York, operates the sole US plant located in Huntsville, Alabama. Backed by private investors, major energy and mining interests, and government funding, these companies are all focused on getting DAC to scale with their proprietary technologies.[xlii]

DAC has now arrived at the "valley of death," where new technologies often fail to commercialize due to lack of investment.[xliii] A handful of companies exist with proven technologies, but in general, they are not cost-competitive enough to pursue market opportunities and attract private capital without government support. Wind and solar photovoltaic (PV) electric generation technologies existed in this same limbo in the 1970s. After the energy crises of that decade, the federal government invested heavily in wind and solar PV research, development and demonstration (RD&D) and followed up with tax incentives to drive deployment. These policy actions helped both technologies cross the valley of death. State-of-the-art DAC technology is ready for a similar take-off. With thoughtful and focused policy action, the US can get started now on a path to meeting the long-term deployment needs outlined in Chapter 2. Without such support, however, DAC runs the risk of joining many other technologies that failed to attract the critical mass of investment necessary to achieve deployment at scale.

DAC Cost Estimates Have Declined, but More Innovation Is Needed

Informed by a recent assessment of DAC technology by the National Academies of Sciences, Engineering, and Medicine (NASEM), we estimate that the first state-of-the-art, megaton scale DAC plant will have a levelized cost in the range of $124 to $325 per metric ton of carbon dioxide removed from the atmosphere.[xliv] [xlv] The range reflects different DAC technologies and the cost of energy.[4] For a full description of the methods used to construct these estimates, please see the technical appendix that accompanies this report. This estimate only reflects the cost of carbon capture and does not include the cost of pressurization and injection in geologic storage. While these costs can vary, we use $18 per metric ton of CO_2 stored throughout this analysis.

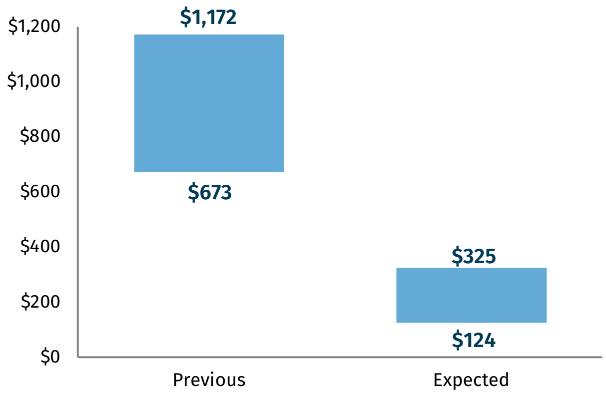
The exact cost of DAC is still uncertain given the early stage of the technology. It is likely that projects already deployed and near-term projects are higher in cost than our estimated range because such projects are small and have yet to benefit from economies of scale. Meanwhile, one DAC company claims that they can reach a levelized cost of $50/ton in the near future.[xlvi] Still, as the understanding of DAC technology has improved cost estimates have declined. Less than ten years ago, estimates of megaton scale DAC costs were over $1,000 per ton (Figure 3.1).[xlvii] Substantial cost reductions can be achieved when more and larger DAC plants are built in the US, thus driving down technology costs through competition, economies of scale, mass production, and learning-by-doing.

[4] What matters most is not the size of the plant but how much total DAC capacity can get built cost-effectively. For the purpose of analysis we use a million ton capacity plant as a benchmark size for all cost estimates used through this report.

FIGURE 3.1.

Previous and expected DAC cost estimates

Levelized \$2018/metric ton of CO_2 removed from the atmosphere



Source: House, et al. APS, NASEM and Rhodium Group analysis. Note: Values do not include the cost of transportation, injection, and storage of CO_2. All values are adjusted for inflation. Expected costs reflected estimates for the first megaton scale plan.

While the latest cost estimates of DAC are promising, no megaton-scale plants are operating anywhere in the world. At this stage in development, two dynamics determine whether a technology will cross the valley of death: federal RD&D push efforts and market demand pull measures.

First, technology can be pushed into full-scale deployment through government RD&D. Government RD&D programs have played an essential role in driving technologies to market in the past and can do so again in the case of DAC. Private capital investments in DAC companies, such as Chevron and Occidental Petroleum's recent investments in Carbon Engineering, could also play a role.[xlviii] However, slim revenue prospects mean private capital for DAC is likely to remain scarce. This puts RD&D investment largely in the hands of the federal government. Therefore, a major federal RD&D program is needed to support work at national labs, universities, and companies. The US has spent over \$4 billion per year on applied energy RD&D over the past decade in areas like advanced nuclear reactors, next-generation biofuels, coal electric generation with CCS and renewable technologies.

Alternatively, technologies can be pulled into the market through demand for their services, thus attracting private capital. Policies that stimulate demand for new technologies have played a critical role in driving new technology deployment in the past. For example, federal vehicle air pollution standards were instrumental in fostering widespread deployment of the catalytic converter in the 1970s.[xlix] In the absence of policy, niche markets that are underserved by incumbent technologies can provide opportunities to pull new technologies into the economy. If these technologies can provide better service at lower costs, they may be able to gain a foothold. Many technologies that are commonplace today benefited from both an RD&D push and a policy pull. The recent success of wind and solar in electric power markets offers two key examples.[l]

Current Market and Policy Opportunities for DAC

Before examining what policies are required to get DAC to megaton scale and on a path to meeting 2050 deployment goals, it is worth reviewing the current policy landscape and market opportunities. In the push category, DAC technology has advanced through academic research efforts. Leading DAC companies have to-date attracted less than \$100 million in total capital from private and government investors.[li] Meanwhile, the US government has spent an average of nearly a billion dollars per year on applied fossil energy programs over the past decade, including geologic sequestration efforts, which could benefit DACS.[lii] Only \$11 million of federal funding has focused explicitly on DAC technology.[liii] This amounts to less than 1% of the over \$4 billion DOE has spent annually on applied RD&D over the past decade.[liv]

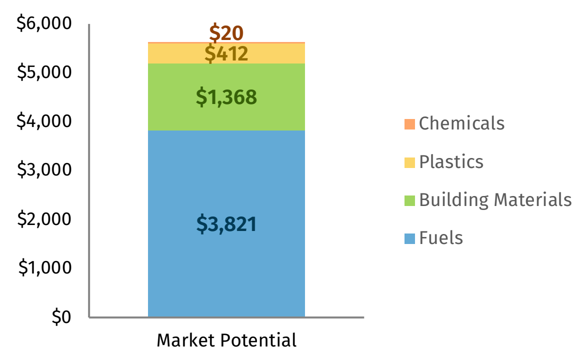
Market Opportunities

CO_2 utilization continues to receive increasing attention in the US and abroad.[lv] While the utilization field includes recycling of CO_2 from industrial sources, it also provides potential market opportunities for DAC. Globally, an estimated \$5 trillion worth of products that could be produced using CO_2 (Figure 3.2).[lvi]

FIGURE 3.2.

Global market value of potential CO_2 utilization products

\$2017 trillions



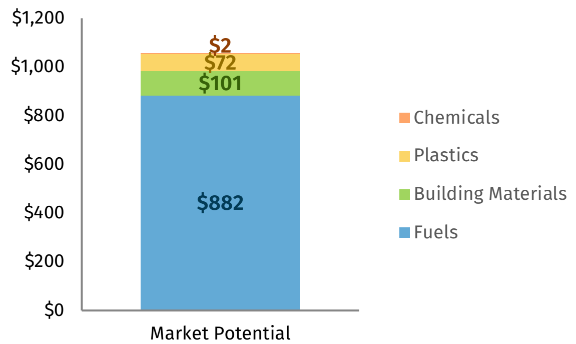
Source: Carbon180

Fuels and building materials, such as concrete and aggregate, represent the two largest markets by value. DAC CO_2 can be used as a feedstock for either, offering a climate benefit compared to current options, as long as the electricity and heat used in the production process are from low- or zero-emitting sources. Several companies are developing methods to compete in these markets using DAC or recycled CO_2.[lvii] The potential US market for these products is over $1 trillion per year (Figure 3.3).[lviii] Beyond the markets for products that contain CO_2, CO_2 itself is a commodity with global demand that today exceeds 350 million metric tons per year (Figure 3.4).[lix] Current primary uses of CO_2 include EOR, food processing, and beverage carbonation.

FIGURE 3.3.

US market value of potential CO_2 utilization products

$2017 trillions

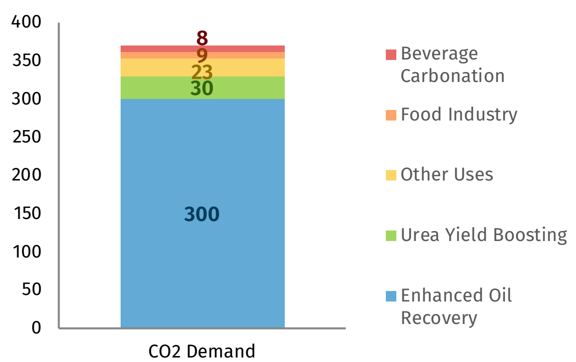


Source: Carbon180

FIGURE 3.4.

Global CO_2 demand

Million metric tons



Source: Global CCS Institute. Note: Values reflect upper bound estimates for all categories. Other Uses includes fire suppression, electronics, steel manufacturing, water treatment, non-EOR oil and gas and additional applications.

While all these opportunities are available to DAC, they are also available to all-natural sources, and point-source emitters of CO_2, including fossil-fuel-fired power plants, ethanol producers, oil refineries and factories. The sources that can capture and deliver CO_2 at the pressure, volume, and purity required for a given application at the lowest cost will likely secure the bulk of these opportunities. Currently, DAC is at a disadvantage to pursue most market opportunities because the price point for CO_2 is far lower than the current costs for DAC and other cheaper sources of CO_2 are readily available. However, two attributes may allow DAC technology to play in niche markets and get a foothold. First, some DAC technologies are scalable to demand at a given location, so a DAC plant can be built to provide the exact amount of CO_2 required by a customer and provide it on demand. Second, DAC can be built anywhere there is access to affordable electricity, heat, and CO_2 transportation and sequestration infrastructure—a crucial competitive advantage over point sources of CO_2 such as power plants. If point sources are far from demand and CO_2 pipelines aren't available, large volumes must be shipped via truck or train. CO_2 prices in regions with no local supply and little competition can reach as high as $200 to $300 per metric ton.[lx] DAC plants built and operated by Climeworks are taking advantage of such niche opportunities by supplying CO_2 to a greenhouse and for beverage carbonation in Switzerland.[lxi] Global Thermostat will produce CO_2 for beverage carbonation in Huntsville, Alabama (4,000 metric tons per year capacity).[lxii]

While these niche applications provide deployment opportunities for DAC technology, they don't offer incentives for CDR from DACS. This highlights the need for policy frameworks that will drive investment into DACS deployment to make sure the technology is ready and available to be used to meet deep decarbonization goals.

Layers of Current Policy Support

Policies designed to pull DAC and other carbon capture and utilization technologies into the market by making current opportunities more attractive have been adopted in the US at both the state and federal levels. In 2018, two longstanding policies were revised to include provisions that explicitly support DAC: California's Low Carbon Fuel Standard (LCFS) and the federal Section 45Q tax credit. The recently-passed Buy Clean California Act also has the potential to support DAC, depending on how it is implemented. These programs are not mutually exclusive. A DAC company can receive credit under multiple programs for the same project as long as all eligibility requirements are met, potentially increasing the total deployment support available.

At the federal level, modifications to a tax credit for CCS under Section 45Q of the tax code improved the incentives for DAC. The provisions, included in broader budget legislation, enjoyed strong bipartisan approval in Congress as well as support from a broad and diverse set of stakeholders.[lxiii] [lxiv] The program offers support for CO_2 utilization, EOR, and storage from most sources of CO_2, including DAC, so long as the source captures at least 100,000 tons of CO_2 per year. Projects receive a tax credit of up to $35 for every ton of CO_2 used for feedstock or EOR, and up to $50 for every ton of CO_2 permanently sequestered in geologic formations. Eligible projects can claim the tax credit for every ton used or sequestered over 12 years. Importantly, the program requires rigorous accounting of lifecycle GHG emissions. This requirement ensures DAC projects can be credited for net CO_2 removed from the atmosphere. All qualifying projects must commence construction before 2024. While this deadline is nearly five years away, few projects are likely to move forward before the Internal Revenue Service completes its implementation guidance for the credit. These include establishing a definition of permanent geologic storage, safe harbor provisions for tax equity investors, and lifecycle accounting requirements.

In California, the state's Air Resources Board (CARB) has operated its LCFS since 2011. The program applies a lifecycle CO_2 emissions intensity (CI) standard for transportation fuels and requires all fuel providers in the state to meet a steadily increasing target for reduction.[lxv] By 2020, the directive calls for a 10% reduction in the CI of the state's transportation fuels. Fuel providers can meet the target by procuring fuels with a lower carbon intensity or by purchasing credits from others that exceed the target. Low-carbon fuel producers can supply transportation fuel retailers as long as the fuel is produced under a CARB-approved pathway that confirms the fuel's lower carbon intensity. LCFS credits are denominated in metric tons of CO_2 with historical credit prices fluctuating between $100 and $185 per ton through 2018. CARB projects that credit prices will decline closer to $100 per ton in the 2020s.[lxvi] To date, most of the low-carbon fuel supplied under the LCFS has come from biofuels.[lxvii]

CARB recently revised the LCFS to extend the program to 2030 and require a 20% reduction in carbon intensity by that year. CARB also approved new rules that expand the range of eligible technologies that can be used in fuel pathways including two explicit pathways to allow DAC to participate in the program beginning in 2021. The LCFS will allow fuels produced using CO_2 from DAC to qualify and receive credit based on their carbon intensity so long as the fuels are sold in California. DAC-based fuels have two competitive advantages over the biofuels being used to meet the standard today. First, if zero-emitting energy is used to power the DAC and fuel production processes, then the CI of the fuel can be as much as 90% lower than gasoline.[lxviii] Second, DAC-derived fuels can serve as direct substitutes for the fossil fuel products they replace so they can be used without limit in existing vehicles and pipelines. Unlike E10 gasoline and B20 biodiesel, there is no blend wall for DAC derived fuels. The LCFS also provides credit for DACS CDR occurring anywhere in the world, allowing such activities to serve as an offset for transportation fuels with high carbon intensity. For every net ton of CO_2 removed from the atmosphere and permanently stored, DAC facilities receive LCFS credits. Companies are responsible for stored CO_2 for 100 years.

The Buy Clean California Act may also provide new opportunities for CCUS and DAC. The act requires all state agencies to comply with procurement standards for key construction materials. By 2021, standards will be in place that set maximum acceptable lifecycle emissions for key construction materials including structural steel and carbon steel rebar.[lxix] State agencies will be prohibited from procuring products with lifecycle emissions higher than the standards. Notably, cement, concrete, and aggregate are not currently subject to the law. The Hawaii legislature is also currently considering a requirement that all state building construction uses CO_2-enhanced concrete.[lxx]

Assessing Current Opportunities for DAC

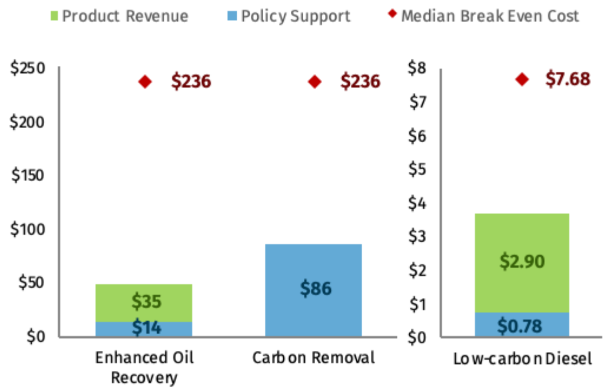
To assess how existing and potential policies could accelerate DAC deployment in the US, we constructed a comprehensive model that is calibrated to the latest DAC cost and performance estimates from the NASEM.[lxxi] The model considers only existing and proven DAC technologies developed by leading companies, and incremental improvements that could arise through deployment. It also considers the full breadth of current DAC technological approaches to carbon removal and incorporates costs for transportation and storage of CO_2 or conversion to products as appropriate. It does not consider potential new laboratory breakthroughs. The model allows us to determine two things. First, we can assess whether the revenue streams available under a given set of market opportunities and policies is enough to make DAC economic in a given application. Second, it allows us to estimate potential DAC cost reductions associated with technology learning as DAC deployment accelerates with policy support. In our assessment, we assume all plants are megaton scale though, in reality, DAC plants can be any size. We also consider qualitative factors such as construction timelines and storage requirements that may be important. For a full discussion of our analytical approach and methodology, see the technical appendix to this report.

Current Policy and Market Opportunities Can't Get DAC on Track to Scale

We consider the value of the current policy and market opportunities over the 30-year life of the first megaton scale plant for three DAC applications: EOR, carbon removal, and low-carbon diesel production. Section 45Q provides support for all three applications but only for 12 years, equating to a lower levelized value over 30 years compared to the nominal amounts in the tax code. LCFS credits also support all three applications, but values are market-driven and uncertain. We assume that the LCFS program is in place for the next 30 years and rely on CARB's credit price projections, which show prices declining out to 2030. We assume that trend continues in later years. We also consider the revenue from product sales when applicable such as CO_2 for EOR and diesel fuel. Since standards are still being drafted, we do not consider the implications of California's Buy Clean program. We use a 30-year time horizon for consistency with the NASEM report.[lxxii]

We find that current market pull opportunities for DAC are not enough to support the deployment of the first megaton scale DAC plant. Costs have not yet declined enough to get DAC off the ground at scale. Using the 30-year levelized median cost estimate for the first plant as a target, we find that DAC needs to achieve $236 per ton to break even (Figure 3.5). Current policy support and product revenue combined provide $49 per ton for enhanced oil recovery and $86 per ton for CDR from DACS. Looking at diesel fuel production, we estimate the 30-year levelized breakeven cost for the first DAC to diesel plant to be $7.68 per gallon. Meanwhile policy support and product revenues come in at $3.68 per gallon—slightly less than half of what is required. Even if LCFS credit prices remained at the program's price ceiling of $200 per metric ton for 30 years, a highly unlikely assumption, the total support available from current policies would not be enough to get the first megaton scale DAC plant off the ground.

FIGURE 3.5.
Policy support and median DAC costs
30 year levelized values



Source: Rhodium Group analysis. Note: Costs are for the first megaton scale plant.

Some niche opportunities may be available to close the gap under special circumstances. For example, if oil prices rise, CO_2 for use in EOR may have a higher price per ton in operations far from CO_2 point sources and/or pipelines. That said, from the national vantage point, more support is required to get DAC to scale in the US. Urgency is heightened by the January 1, 2024, commence-construction deadline to qualify for Section 45Q tax credits. In the next chapter, we consider what new federal R&D push efforts and demand-pull measures will be required to get up to nine million tons of DAC capacity in place by 2030 and put the technology on a path to achieving long-term deployment goals.

CHAPTER 4

Achieving Take-off

While market opportunities and current policies have some potential to support DAC, they alone are not enough to get DAC to market. In this chapter, we consider new policy actions to push and pull DAC across the valley of death and get at least nine million tons of capacity operating in the US in 2030. First, drawing on recent work by the NASEM and others, we provide an overview of a recommended federal RD&D program for DAC and carbon sequestration. We then consider new federal policies and quantify the associated level of support needed to pull DAC into the marketplace. We also quantify how finance policies can help lower costs. From there, we identify policy actions that can reduce or eliminate non-cost barriers to DAC deployment. Finally, we consider how other potential climate and energy policies can be designed to support DAC deployment.

Research, Development, and Demonstration for DAC

Without investment in research, development, and demonstration, DAC costs will remain higher than our estimated cost range because the DAC industry has yet to build large scale plants. The tried-and-true way to get the DAC industry to scale and costs down to our starting range is to launch a comprehensive DAC RD&D program coupled with demand pull incentives. This will drive technology innovation and early stage DAC projects at larger scales than we have seen to date. As we noted in the previous chapter, only $11 million has been dedicated to DAC to RD&D over the past decade in the US.[lxxiii] Proposals to increase DAC RD&D funding have been put forward in Congress. Before discussing what such a program could look like, it's worth considering US RD&D spending in context.

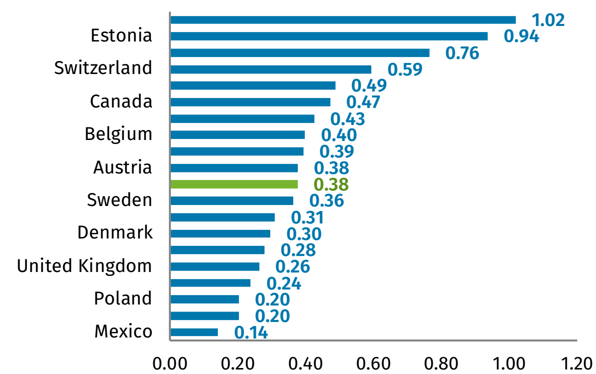
US RD&D Spending Lags Other Countries

The US spends more on energy RD&D in absolute terms than any other developed country on earth.[lxxiv] Over $4.8 billion has been spent each year, on average, over the past ten years.[lxxv] However, that translates into less than 0.3% of total federal spending in 2017, placing the US in 11th place in terms of developed country energy RD&D spending per unit of GDP, behind countries like France, Canada, Japan, and Norway (Figure 4.1).[lxxvi] The US is part of the Mission Innovation Coalition, a diverse group of countries all committed to doubling their clean-energy RD&D spending from 2016 to 2021.[lxxvii] The US is off to a strong start in meeting this goal with low-carbon energy RD&D spending up by 11% from 2016 to 2017.[lxxviii] Still, the US has a long way to go. DAC technology presents a crucial opportunity for US leadership in technology innovation.[lxxix]

FIGURE 4.1.

Developed country energy RD&D spending, 2017 or latest year available

Per thousand units of GDP



Source: IEA

A Federal RD&D Program for DAC

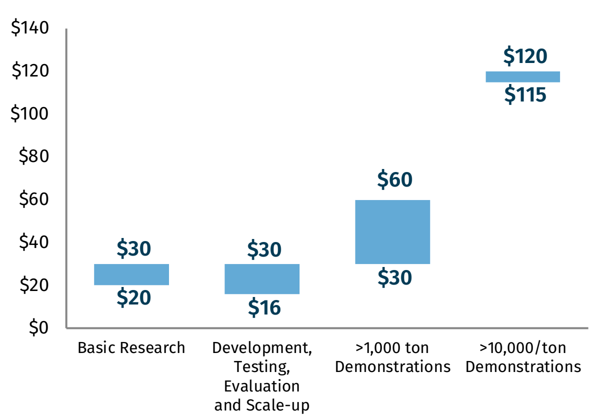
While the exact design of such a DAC RD&D program is outside the scope of this paper, the NASEM provides comprehensive recommendations on key activities and funding levels for a 10-year program supporting basic and applied RD&D.[lxxx] Each component plays an important role in fostering breakthroughs and getting DAC to scale. The NASEM recommends basic research to develop new materials and process designs that could lead to dramatic improvements in cost and performance over the long-term. It also recommends development and scale-up programs to improve the efficiency of key DAC components and systems, and public funding for demonstration projects to generate field data and knowledge that can accelerate innovation and cost reductions. Finally, and critically important for scaling up DAC, NASEM recommends that deployment incentives should be set up to support the construction of commercial-scale DAC plants.

The NASEM's recommended DAC federal funding range is \$181-\$240 million annually for ten years with the majority focused on supporting demonstration plants (Figure 4.2). DOE should direct these activities with national labs, the National Institute of Standards and Technology, US Geological Survey (USGS), and DAC companies participating where appropriate. The Department of Defense could also play a role in DAC research given the potential the technology holds for scalable, distributed fuel production. Work underway by other independent researchers will provide a roadmap for how to structure the federal bureaucracy to best support DAC.[lxxxi] Lastly, the NASEM also recommends new investments in geologic sequestration science and technology. The goal is to better understand storage reservoirs, reduce uncertainty around storage permanence and improve public acceptance of safe, long-term CO_2 storage.

Congressional Action Is Needed to Catalyze Innovation

Congress should authorize and fully fund a DAC and sequestration program as envisioned by the NASEM as quickly as possible. It is an essential first step in making the country a leader in carbon removal technology. Bipartisan proposals such as the USE IT Act and Fossil Energy Research and Development Act have been put forward in recent years to create a DAC RD&D program, though not yet enacted.[lxxxii] The funding levels authorized by these proposals are in the range of tens of millions of dollars per year. While these proposals represent a step change in funding for DAC, the NASEM makes the case that far more funding is necessary over a sustained period to adequately support DAC innovation.

FIGURE 4.2.
NASEM recommended annual federal funding allocations for DAC RD&D by activity
\$Millions per year



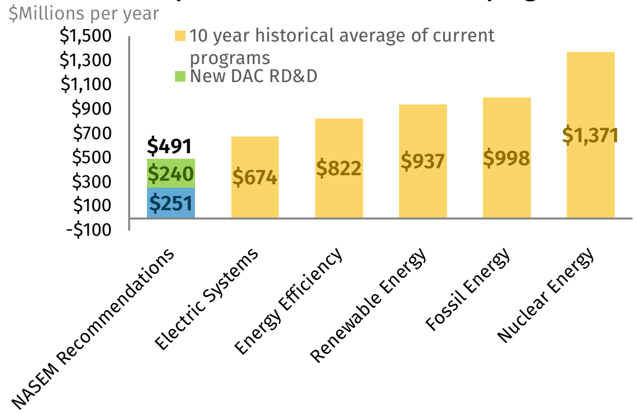
Source: NASEM

A fully-funded comprehensive RD&D DAC and sequestration program will support early-stage deployment and has the potential to scale up DAC plants quickly. That said, historical RD&D experience suggests that the road ahead may be bumpy with plenty of successes and failures. Each will provide opportunities for learning and technology improvement. Specific DAC technologies will follow different pathways to cost reduction and scale. It will be essential to explore a broad portfolio of DAC options to avoid picking winners and to maximize the federal government's return on investment.

DACS RD&D Represents Small Growth in Total Spending

The NASEM recommended RD&D program for DAC and sequestration, if implemented, would increase federal clean energy spending, contribute to meeting the nation's Mission Innovation commitment and put the US on a path towards global leadership in energy innovation. The NASEM-recommended \$491 million funding for DACS is smaller, on an annual average basis, than any single applied RD&D program currently in place at DOE. It would be equivalent to 73% of the \$674 million in average annual spending on DOE's smallest program: electricity systems research (Figure 4.3).[lxxxiii] The recommended sum also represents less than 36% of DOE's spending on nuclear energy research.[lxxxiv] Expanding the federal budget to support DACS is not a trivial political exercise and will require concerted efforts by a range of stakeholders to make that case that such investments are essential for US technological leadership.

FIGURE 4.3.
NASEM average annual recommended federal funding for DAC and sequestration and current DOE programs
\$Millions per year



Source: NASEM, Congressional Research Service, and Rhodium Group analysis.

Federal Policies to Accelerate Deployment

Numerous policies could drive demand for DAC to reach megaton scale and advance towards long-term deployment goals once an RD&D program is in place. The challenge DAC faces is similar to that of other technologies that have crossed the valley of death. Consider the experience of wind and solar, the two fastest-growing clean technologies today in the US. As we demonstrated in Chapter 2, both these technologies offer critical examples of how the federal government can use policy to both push and pull new technologies into the marketplace.

Wind and solar were deployed far faster on a unit normalized basis than the rate we estimate DAC will need to deliver gigaton-scale carbon removal by mid-century. However, these historical examples are a useful guide for DAC. State policies, as well as policy actions in other countries, helped to commercialize both technologies. By the early 2000s, wind and solar had already benefited from substantial research and development investment. They had also received early-stage deployment support but had not yet reached full commercial-scale deployment, where technologies can readily attract private capital to finance deployment.

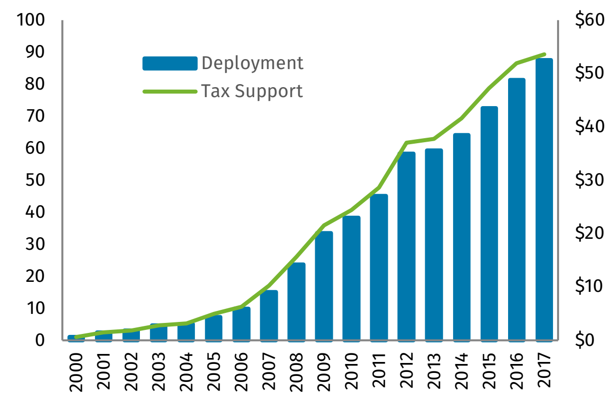
Accelerating Wind and Solar Deployment and Driving Down Costs

Congress passed a Production Tax Credit (PTC) for wind in 1992 and an Investment Tax Credit (ITC) for solar in 2006. With the tax credits, plus other more modest federal tax advantages and state policies in place, wind and solar deployment began to take off and attract large amounts of private investment (Figures 4.4 and 4.5). Through 2017, we estimate that the federal government provided $54 billion in deployment support for wind and $24 billion for solar. Over the past decade, on average, solar has received $2.4 billion per year while wind has received $4.3 billion per year. These efforts launched utility-scale installed capacity from near zero at the turn of the century to 116 GW of combined solar and wind at the end of 2017—roughly 11% of total US electric generation capacity.

FIGURE 4.4.

Federal policy support and wind deployment

Cumulative wind capacity, GW (LHS); Cumulative tax support, $2017 billions (RHS)

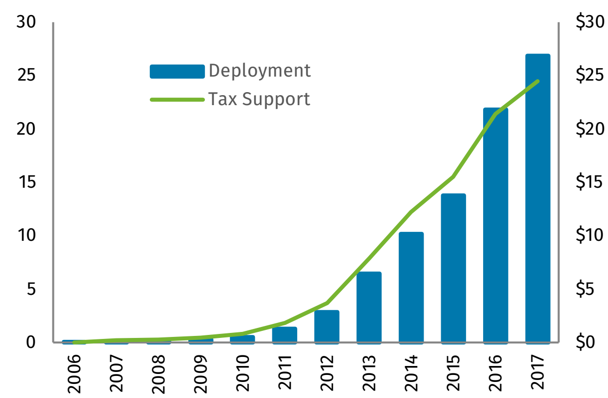


Source: EIA, Rhodium Group analysis.

FIGURE 4.5.

Federal policy support and solar deployment

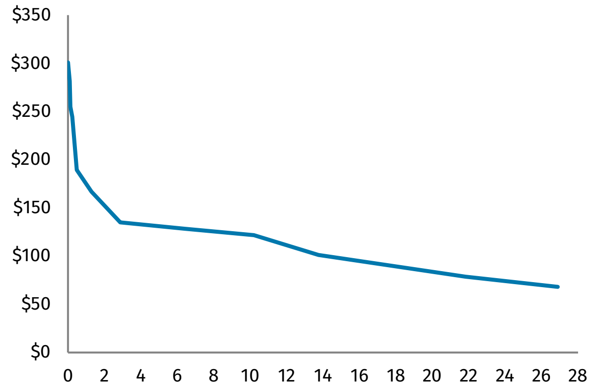
Cumulative solar capacity, GW (LHS); Cumulative tax support, $2017 billions (RHS)



Source: Lawrence Berkeley National Lab, EIA, Rhodium Group analysis

Federal deployment support accelerated the clean energy transition in the US electric power sector and, most importantly, drove down the cost of both technologies. We estimate that the national average levelized cost of energy of utility-scale solar since 2006 has dropped by 77%, falling from $300/MWh in that year to $70/MWh in 2017 (Figure 4.6). Costs declined mainly due to technology learning, especially the development of efficient and mature supply chains. As capacity installations increased, the solar industry developed innovations to cut costs. Meanwhile, the same dynamics drove the national average levelized cost of wind energy down by 50% from 2009 to 2017.[lxxxv]

FIGURE 4.6.
Solar levelized cost of energy and deployment
Cumulative deployment, GW (x-axis); Levelized cost of energy, $/MWh (y-axis)

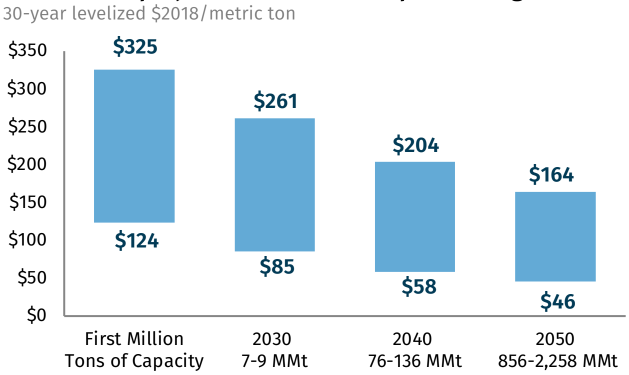


Source: Lawrence Berkeley National Lab, EIA, Rhodium analysis.

DAC Can Follow the Same Path as Wind and Solar

With ambitious federal action, DAC can follow in the footsteps of wind and solar. If the US succeeds in getting DAC on track to meeting the long-term deployment goals identified in Chapter 2, we estimate that the costs of current DAC technologies will drop substantially through scaling and learning by doing. To get DAC on track for long-term goals, policies need to provide enough support to get nine million tons of DAC capacity in operation by 2030. We estimate that levelized costs of capture may drop by 20% to 30% below our expected estimates of first plant costs once that goal is achieved (Figure 4.7). If the US stays on track toward 850 to 2,250 plants by 2050, we estimate that costs could drop to a range of $46 to $164 per metric ton over that timeframe. Given the early stage of DAC technology cost estimates and cost reduction pathways, both are subject to considerable uncertainty. The ranges shown here reflect different technologies, levels of deployment, energy cost, and learning rate assumptions.[lxxxvi]

FIGURE 4.7.
Current and projected cost of CO_2 capture using DAC
30-year levelized $2018/metric ton



Source: Rhodium Group analysis.

Identifying and Assessing Federal Priorities for DAC Deployment

In this section, we examine a subset of the wide range of options that exist to accelerate DAC deployment, each of which is grounded in existing policy frameworks or draws from existing policy experience. We start from the premise that any policy option must be able to deploy nine million tons of cumulative DAC capacity in 2030 in order to gain the technology experience, foster learning-by-doing, and drive down costs. With this in mind, policies do not have to specifically focus on DACS deployment. Many DAC applications are in play. Passage and implementation of the deployment policies considered here should be pursued as quickly as possible, including concurrent to the pursuit of an RD&D program. The 2030 deployment goal should be within reach if an RD&D program is established no later than the early 2020s and at least one deployment policy is in place before 2025.

We group policies into three pathways: 1) a federal procurement pathway; 2) a pathway focused on the tax code; 3) a pathway focused on fuels. Fully implementing any one of these pathways should get DAC on track towards long-term deployment needs. All of these policy pathways are assumed to benefit from the RD&D program described above to get DAC to commercial scale.[lxxxvii] Any of these policies could be expanded to include other CDR or CCUS technologies and activities. However, we focus our assessments and recommendations solely on DAC.

In assessing each policy pathway, we employ the same DAC cost model used in Chapter 3 to quantify current policy support for DAC. We assume there are interactions with current policies on the books today, such as California's LCFS and Section 45Q tax credits.[lxxxviii] We leave the assessment of the political viability of each pathway to the reader. For a full description of our methodology and analytical approach see the Technical Appendix that accompanies this report. Except for interactions with existing policies, we examine each policy pathway in isolation. We quantify the level of policy support necessary to achieve nine million tons of DAC capacity and break even. Where appropriate, we also consider the costs of converting CO_2 into products such as transportation fuels, utilization for EOR, and the costs of geologic sequestration. Because the economics and potential revenue streams for these three DAC use cases vary, the level of necessary policy support also depends on the usage of DAC CO_2. When assessing each pathway, we consider what parameters are necessary to support DAC, assuming median costs. Importantly, if RD&D efforts yield technology breakthroughs quickly, then the level of policy support needed to achieve 2030 deployment goals could be lower than what we consider here.

Pathway 1: Federal Procurement to Drive DAC Deployment

The federal government can leverage its massive procurement activities to drive DAC deployment. Some actions may be possible through executive orders, though a congressional mandate through authorizations or appropriations would likely be necessary to provide sufficient support to meet the 2030 capacity deployment goal. For example, federal agencies can leverage their purchasing to follow the lead of California's AB262 (the Buy Clean California Act) with a focus on DAC deployment. The General Services Administration (GSA), the Postal Service, the Department of Defense (DOD) or other agencies can set procurement targets and requirements for products that meet specific lifecycle carbon intensity targets. Alternatively, such a program could specifically call out DAC-derived products for procurement. Either way, it will be important to include some lifecycle carbon intensity requirements to make sure there is a climate benefit and to foster learning-by-doing on all aspects of low-carbon DAC CO_2 utilization. Finally, there should be data collected on performance and disseminated to encourage broader learning.

We consider three possible products that the executive branch could procure: military fuels, building materials (concrete and aggregate), and CDR. We assess each option in isolation though, they do not have to be mutually exclusive in practice. It is important to note that a congressional procurement mandate will provide more certainty and potentially a greater level of support than if the executive branch pursues procurement alone. Executive orders are not permanent and can turn over from one administration to the next. Alterations in procurement policies provide less certainty for DAC project developers. Also, without explicit congressional directives, the executive branch must procure products at least cost making it challenging to pay a premium to support DAC.

Federal Procurement of Low Carbon Fuels for the Military

In fiscal year (FY) 2017, DOD operations across all services consumed nearly 3.7 billion gallons of fuel, at a cost of $8.2 billion, making DOD the largest single petroleum buyer in the world.[lxxxix] The Air Force consumed more than half of that, and the Navy one-third, with the remainder consumed by the Army and Marine Corps. The DOD has a decade of experience in testing, evaluating, and competitively procuring alternative fuels, mostly biofuel blends as part of its Great Green Fleet initiative.[xc] It also maintains an Operational Energy Strategy that in part seeks to identify and reduce logistics and operational risks from energy supply vulnerabilities.[xci] Since DAC fuels can be made anywhere that there is ample low carbon generation and don't rely on complex supply chains, they may be well suited to enhancing security at large military bases that have the space and infrastructure to accommodate large scale production.

A DOD DAC fuels procurement program will require near-term efforts for testing and evaluation of DAC fuels to meet military-use specifications, as well as steadily increasing procurement targets to support a ramp-up in DAC deployment. If military fuel procurement is the only new policy pursued to support DAC deployment, the procurement targets will need to follow the below schedule to support enough DAC to meet the 2030 deployment goal:

- 2023: 95 million gallons (3% of 2017 consumption)
- 2025: 190 million gallons (5% of 2017 consumption)
- 2030: 850 million gallons (23% of 2017 consumption)

In the absence of any additional DAC policies in place before 2030, procurement targets may need to be maintained for several decades to give DAC fuel producers certainty in their investments. The first few DAC plants may also be able to take advantage of the Section 45Q utilization tax credit. Currently, California's LCFS does not apply to military fuels, so we do not include any credit value from that program in our assessment. Assuming these targets are met, and at least 9 million tons of DAC-to-fuel capacity is deployed by 2030, then procured fuels will cost the military roughly $3.00 more per gallon or 75% more on average. Fuels from the first few plants will cost more than the average values presented here for all cost assumptions. Eventually, however, prices will fall as more plants are deployed and DAC technology costs are reduced.

Federal Procurement of DACS

The GSA or another agency could be directed to procure CDR from DACS through a competitive bidding process. Assuming median DAC costs, a 90% utilization rate and pressurization and permanent storage costs we estimate that the annual cost to the US government for these services would be approximately $161 million to support the first million tons of capacity on top of support from current policies. If government procurement ramped up to support nine million tons of capacity in 2030, then the average annual cost to the government in that year would be $1.2 billion.

Federal Procurement of Concrete and Aggregate

The GSA could require that all federal building projects use DAC CO_2 infused cement, concrete, and aggregate instead of conventional materials. Doing so would provide a small boost for DAC deployment and it may not add costs to government projects. Multiple companies offer CO_2 infused concrete in the US.[xcii] If all US concrete demand were met with these new CO_2 infused products and if DAC is used to supply CO_2 then there would be enough demand to support up to three million tons of DAC capacity. The federal government share of concrete demand is a fraction of total demand and alone would not be sufficient to support nine million tons of DAC capacity in 2030. Still, procurement requirements can help prime the market for these new concrete technologies and expand the market for DAC CO_2.

Renewable Fuels Standard as a Pathway for DAC

An alternative existing authority opportunity involves establishing an approved pathway for DAC fuels under the federal RFS. The US Environmental Protection Agency (EPA) has the authority to approve new fuel production pathways for eligibility with the RFS so long as they meet statutory requirements. A key statutory requirement is that eligible fuels must be produced using biomass feedstocks. The RFS mandates that a minimum amount of renewable fuel must be sold in the US each year. The statutory target for 2019 is 28 billion gallons. Due to the lack of eligible fuel supply and fuel blending limitations, EPA has ruled to reduce the target to 19.88 billion gallons. For compliance, producers of eligible fuels are awarded Renewable Identification Numbers (RINs) for each gallon produced. Fuel blenders obtain RINs, which are valued in dollars per gallon, to demonstrate compliance with the RFS.

For DAC to receive support under the current RFS, DAC fuel providers would need to petition EPA to approve a fuel pathway. While it is not out of the question, it is unclear whether EPA can approve a DAC fuel pathway under existing law. An in-depth legal analysis of this option is outside the scope of this paper. In addition to legal uncertainty, there are two other aspects of the current RFS that make it less suitable for DAC support as currently constructed. First, RFS targets are revised each year, making it challenging to project RIN values. Second, congressional authorization of the RFS expires after 2022. After that, EPA may have the authority to set targets for future years and keep the program in place though EPA's role in such a situation is not completely clear. We highlight this possible pathway as an area of future research but given the uncertainty of how DAC fuels could qualify, we don't assess the potential impact of this option. Instead, we consider legislative action to revise the RFS in the third pathway we analyze.

Pathway 2: Revisions to the Tax Code

The experience of renewable energy shows the federal government can catalyze large-scale deployment of new technologies by leveraging the tax code. In this pathway, we assess improvements to the existing Section 45Q tax credit that could further support DAC for utilization or sequestration. Section 45Q could be modified in several ways, and a combination of these modifications could provide the support needed for DAC to achieve the 2030 objective. Specifically, Congress should extend the commence-construction deadline beyond 2023 for DAC projects; extend the number of years the tax credit is paid out beyond the current 12 years; lower the minimum threshold for capture and utilization from their current respective levels of 100,000 ton and 25,000 ton levels; and increase in the value of the credit beyond the current $35 per ton for utilization and $50 per ton for sequestration.

Improving Section 45Q to Expand DAC Support

For Section 45Q to drive the deployment of nine million tons of DAC capacity in 2030, the commence-construction deadline for DAC plants must be extended beyond 2024 at a minimum. Given current requirements, we estimate that at most one plant will be operational in time to take advantage of the current credit—and this is assuming the RD&D program is in place and successful. For this analysis of a potentially expanded Section 45Q, we assume the deadline is extended to the end of 2030 for DAC plants.

Extending the tax credit payout from 12 years to 30 years is also necessary. DAC plants are likely to have a useful lifetime of 30 years and they are unlikely to be built or operate without revenue certainty over that timeframe.[5] This is three times longer than the PTC payout for wind and represents an unusually long payout compared to most tax incentives. Given the number of activities, including many fossil-fuel production related processes that receive permanent support under the tax code, extended payouts are not a complete outlier. If 30-year payouts are not politically feasible, a shorter period could be sufficient so long as the US puts in place ambitious climate policies before the end of the 2020s. Future policies could fill the gap in support. See Chapter 5 for further discussion.

[5] We assume the same plant lifetimes used by the NASEM

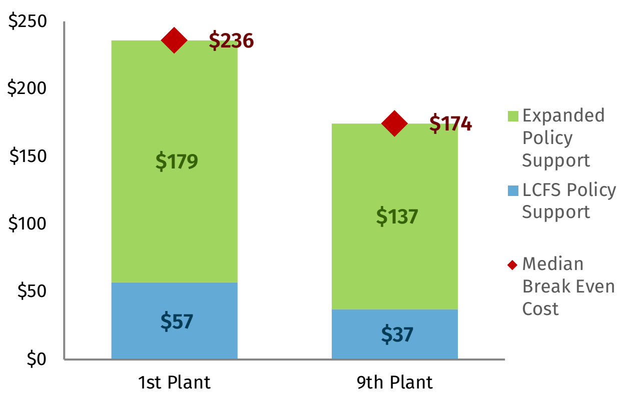
Finally, given the modular nature of some DAC technologies, it is prudent to lower the minimum capture threshold from 100,000 tons per year down to 10,000 tons per year. The minimum utilization threshold should also be lowered from 25,000 tons to 10,000 tons per year. Doing so will allow a wider range of DAC projects to harness the tax credit. Furthermore, it will require an order of magnitude less scale up for current DAC technologies to take advantage of the credit compared to current law. This all can help to build early momentum towards the 2030 deployment goal.

Assuming both a 30-year payout, lower minimum threshold and an eligibility in-service deadline of the end of 2030, we find that EOR and DACS are likely to require a lower level of federal support than other DAC applications. The credit value for the first megaton DACS plant will need to be $179 per ton (Figure 4.8). The credit value required would come down to $137 per ton for the ninth plant. These values incorporate LCFS credit revenue, which is lower for the ninth plant because our assumed LCFS credit prices decrease 10% annually after 2030. If LCFS credit prices are lower, we assume that the credit will need to be higher and vice-versa.[6] These results suggest that the current Section 45Q value needs to be enhanced to support DAC deployment.

FIGURE 4.8.

Expanded Section 45Q policy support for DACS cost estimates

30-year levelized $2018/metric ton



Source: Rhodium Group analysis.

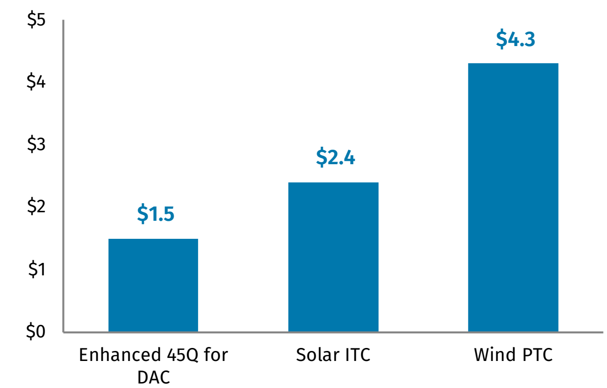
Lower Costs Than Renewable Energy Tax Credits

While these credit values appear high at face value, it is worth putting them in context. If Section 45Q for DAC sequestration is modified as described above with a credit value of $179 per ton, and that catalyzes the construction and operation of nine million tons of DACS capacity through 2030, then the estimated total annual cost to the federal government in 2031 would be $1.5 billion dollars (Figure 4.9). That's nearly one billion and three billion dollars less than the annual cost of solar and wind tax credits respectively. With more deployment, the per-ton cost of DAC will come down as will the credit value required to support DAC. This suggests that a gradual reduction in the credit value over a reasonable timeframe could provide ample support to keep DAC deployment on track for long-term goals.

FIGURE 4.9.

Current ITC/PTC and estimated 2031 enhanced Section 45Q annual costs

$2018 billion



Source: Rhodium Group analysis.

Pathway 3: Legislative Fuels Policy

Congress could pursue the construction of a fuel policy that supports DAC deployment. This could be part of a broader effort to reauthorize or reform the current RFS, or it could be a standalone fuel mandate. We assess what a federal fuel mandate for DAC fuels needs to look like under these pathways to achieve the 2030 nine million ton capacity deployment goal. Given the uncertainty of the existing RFS, especially whether DAC can qualify, a congressional pathway could offer clarity to DAC producers so long as it can be enacted into law.

A federal fuels mandate that supports multi-million ton DAC deployment could either set a target specifically for DAC-derived fuels or set a carbon intensity requirement low enough that DAC fuels would be competitive. If the latter path is pursued, a 90% reduction in carbon intensity relative to gasoline on a lifecycle basis should be effective. For consistency, current RFS lifecycle analysis guidelines should apply for determining fuel carbon intensity. For this analysis, we assume DAC-to-fuels plants would be used to create

[6] We do not consider the potential interactive effects of an expanded 45Q credit on LCFS credit prices. That said, if all 9 million tons of DAC capacity end up supply credits into the LCFS market then it is likely that LCFS credit prices would face downward pressure.

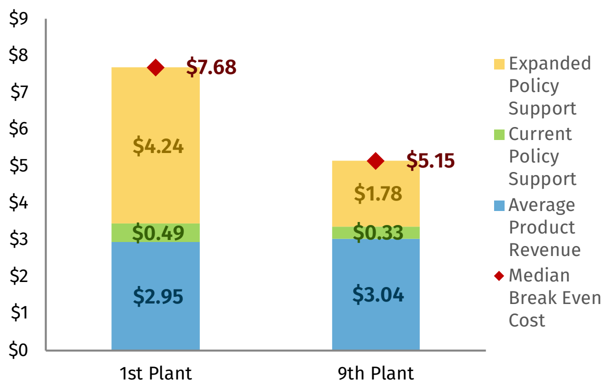
diesel fuel. However, any ground transportation fuel producing using DAC CO_2 could be eligible.

We find that a relatively small and technically feasible mandate of 850 million gallons in 2030 would support the deployment of nine million tons of DAC capacity. This represents roughly 0.4% of 2017 US transportation fuel consumption. Beyond the target, we estimate that the incentive needed to support the first DAC-to-fuels plant eligible to supply the mandate is $4.24 per gallon which equates to a $2.49 Renewable Identification Number (RIN) price assuming that diesel would still receive 1.7 RINs per gallon. For the ninth DAC-to-fuels plant, the required incentive is $1.78 per gallon which equates to a $1.05 RIN price (Figure 4.10). This assumes that the plants can also qualify for credit under the LCFS.

FIGURE 4.10.

Expanded RFS policy support and cost of DAC-to-fuels estimates

30-year levelized $2018/gallon



Source: Rhodium Group analysis.

Finance Policy Options

There are several federal finance policies in place to support other technologies that could be expanded by an act of Congress to include DAC. They are not sufficient on their own to achieve the operation of nine million tons of DAC capacity in the US by 2030. However, they can help lower the cost of deployment and enhance the effectiveness of the other policies assessed above.

Policies to Reduce the Cost of Capital

We assess three finance policies that can reduce the cost of capital for DAC plants, assuming eligibility rules were expanded to include DAC. These are Loan Guarantees, Master Limited Partnerships (MPLs) and Private Activity Bonds (PABs).

Loan Guarantees: Under a loan guarantee, the government is contractually obligated to cover a borrower's debt in case the borrower defaults on its loan from private creditors, such as banks or other commercial loan institutions. This can benefit DAC projects by reducing interest rates associated with any debt financing. Based on loan guarantee cost of capital impacts for renewables and biofuels under the American Recovery and Reinvestment Act (ARRA), we assume a 2% decrease in the weighted average cost of capital.[xciii]

Master Limited Partnerships: An MLP is a partnership business structure with publicly traded units, hence it combines the benefits of being exempt from corporate taxes (like any other partnership), while still being able to access public investment by listing its units on stock exchanges (like any other publicly traded company). By current law, MLPs are only allowed if they earn 90% or more of their income from qualified business activities. Typically these activities include the exploration, production or transportation of natural resources or real estate. If DAC projects were considered qualified business activities, then the cost of equity could be lower, all-else-equal. We estimate that reforming MLP definitions to allow DAC as qualified assets for MLP treatment would decrease the weighted average cost of capital of DAC by approximately 1%.[xciv]

Private Activity Bonds: A Private Activity Bond (PAB) is a tax-exempt bond issued by or on behalf of state or local government to finance the project of a private entity. Such projects, often airports and stadiums, are usually deemed to broaden economic activity. While they qualify for tax-exempt status, such bonds typically are not backed or guaranteed by government credit. If DAC projects were eligible for PAB financing then developers would have access to cheaper, tax-exempt debt. For this analysis, we assume that 50% of the capital financing for a DAC plant will come from private activity bonds and the total impact will be a 0.5% decrease in the weighted average cost of capital.[xcv]

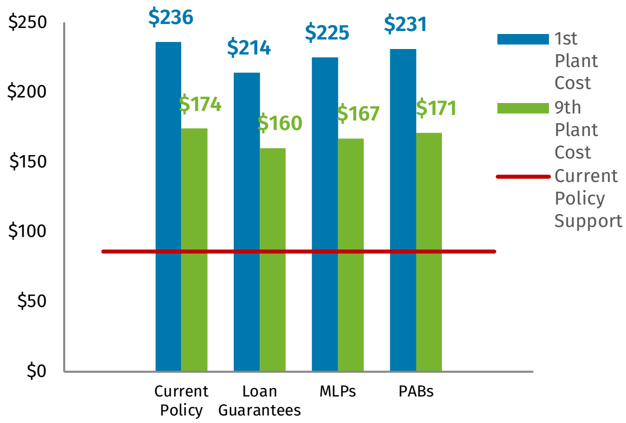
Comparing Finance Policy Options

Loan guarantees yield the largest decrease in the cost of capital among these options, resulting in a 9% reduction in the levelized cost for the first DAC plant (Figure 4.11). PABs provide the least support at a 2% reduction in cost. None of these policies on their own are sufficient in reducing levelized costs to make DAC plants economic within existing policy frameworks.

FIGURE 4.11.

Cost of DACS with finance policies

30-year levelized $2018/metric ton



Source: Rhodium Group analysis.

Accelerated Depreciation

Clean technology deployment has also been aided by allowing accelerated depreciation of capital in the tax code. Congress could allow DAC project developers to fully depreciate the capital costs of DAC in tax year one, deferring income tax liability to future years. We do not quantify the potential impact of this option because all of our estimates focus on the economics of a given DAC plant, not the profitability of that plant for investors. That said, accelerated depreciation should make DAC more attractive from an investor standpoint, all else unchanged. This option alone is not sufficient to catalyze millions of tons of DAC capacity, but it could be helpful and warrants further research.

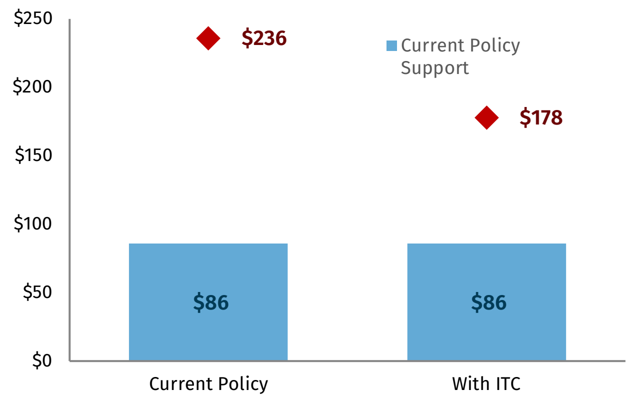
An Investment Tax Credit for DAC to Reduce Capital Costs

Another finance policy option is to create an Investment Tax Credit (ITC) for DAC. DAC plants, especially the first few large-scale plants, will have high capital costs. An ITC could be an effective way to relieve developers of some of these costs and reduce breakeven prices for DAC overall. For example, solar PV is currently eligible for an ITC equal to 30% of the capital costs of a project. We estimate that applying the same 30% ITC to the capital cost of the first DACS plant could cut the median breakeven cost by 25%, a significantly larger cost reduction than those provided by the finance policy options described above (Figure 4.12).

FIGURE 4.12.

Current policy and 30% ITC revenue and breakeven costs for DACS

30-year levelized $2018/metric ton



Source: Rhodium Group analysis.

Finance Policies Can Complement Deployment Policies

Although finance policies alone will not drive the deployment of the nine million tons of DAC capacity needed by 2030, they can be used in combination with deployment policy pathways described above (Table 4.1). For example, a 30% ITC coupled with expanded Section 45Q could bring down the necessary 45Q credit value down to $125 per ton sequestered, which accounts for a 30% reduction in levelized cost per ton. Finance policy levers that lower the cost of capital have more modest impacts but can reduce the amount of deployment policy support required by up to 11%.

TABLE 4.1

First plant deployment policy requirement comparison

Deployment Policy	Without Finance Policy	Loan Guarantees	Master Limited Partnerships (MLPs)	Private Activity Bonds (PABs)	Investment Tax Credit (ITC)
Procurement (per gallon premium)	$4.24	$4.00	$4.10	$4.17	$3.57
Expanded Section 45Q (per ton sequestered)	$179	$160	$168	$174	$125
Revised RFS (RIN price)	$2.49	$2.35	$2.41	$2.45	$2.10

The Most Impactful Finance Policy Is the ITC

Establishing an ITC for DAC is the most effective finance policy option considered in this analysis. It is substantial enough to reduce the level of ambition and policy support required if the US were to establish a federal procurement policy, revise Section 45Q credit values, or revise the RFS. If an ITC for DAC is implemented, it could make the politics of pursuing any of these deployment policies incrementally easier since associated costs would be lower.

Enabling Policies

Alongside a federal RD&D program and policies to accelerate deployment, there are non-cost barriers that will need to be overcome to allow DAC to fulfill its potential for both CDR and CO_2 utilization over the medium and long term. These barriers include liability issues, permitting, reservoir assessments, and product certification/standards. All of these barriers need to be addressed for DACS to meet mid-century deployment goals. Faster action on these issues means a faster launch for DAC, so long as RD&D and deployment policies are also adopted.

Liability

When CO_2 is sequestered underground in geologic reservoirs, the intention is that it will stay there permanently. Meanwhile, the entity that injected the CO_2 into the ground may stay in operation for the foreseeable future but is not in a position to commit to maintaining responsibility for a site over geologic timescales. Legal liability for stored CO_2 in the long-term is still an unsettled issue and likely barrier to widespread deployment if left unresolved. Currently, California's CCS protocol requires the operator of a CO_2 sequestration site to maintain responsibility and monitoring for 100 years, with the potential for financial penalties for the first 50 years.[96] The federal government should set a national floor for minimum site responsibility and liability while setting up a public risk-sharing initiative or facilitating a voluntary industry-led effort.[97] While the risks associated with stored CO_2 are low, a comprehensive framework will provide certainty to investors and operators as well as assure the public of the safety of long-term geologic sequestration.

Permitting

An EPA regime is currently in place to set permitting rules for CO_2 injection and sequestration, but the process to secure permits is lengthy and leads to increased investment risk.[98] The permitting of CO_2 pipelines also involves a lengthy process. The USE IT Act, as proposed, contains provisions to streamline infrastructure and injection permitting. If passed, this measure could effectively shorten the permitting process, allowing for faster adoption of DAC technology.

Storage Reservoir Assessments

While DOE and other agencies such as USGS have done much work to identify possible storage reservoirs across the US, individual potential CO_2 storage sites are not well characterized. If geologic CO_2 sequestration and DACS are going to play a substantial role in deep decarbonization, geologic assessments and mapping of vast underground formations will be required. The federal government can do a lot of the legwork and put reservoir data in the public domain to enable developers to identify the most suitable sites. This is similar to what the National Renewable Energy Laboratory does in mapping renewable resources around the country. DOE's Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative is already doing some of this important work and could be expanded to accelerate progress.[99]

Expanding Product Standards and Certifications

As discussed above, there are many markets where CO_2 from DAC or other sources could be used as a feedstock to produce useful products like cement, concrete, and aggregate, as well as transportation fuels. The problem is that, in some cases, these new products need to be certified for use by government, intergovernmental, or industrial standard setting organizations. For example, ASTM International, founded as the American Society for Testing and Materials, sets structural standards for concrete but has yet to certify CO_2 infused products as compliant. Separately, the recently announced Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) program under the International Civil Aviation Organization (ICAO) establishes a CO_2 reduction program for commercial air travel that allows low-carbon fuels yet to be certified by ASTM to count towards required emission reductions.[100]

When DAC to fuel companies reach scale and produce commercial quantities of fuel, they will need to secure certification to receive credit under the program. Until that happens, DAC will miss out on a roughly 5 billion gallons per year market in international aviation fuel consumption for US carriers alone.[101] As a member of ICAO, the US can advocate for prioritizing DAC to fuels certifications. Lastly, the US government can conduct lifecycle analysis research to help DAC fuel producers demonstrate the carbon benefits of their products.

Incorporating DAC Into Other Policy Goals

There are a number of other policy ideas that may be considered by Congress in the coming years that do not directly focus on DAC technology but could be designed to help meet the 2030 goal of nine million tons of DAC capacity. These include carbon pricing, infrastructure investment, clean energy standards, and comprehensive climate legislation such as a Green New Deal. We review each option and identify design elements in each that can be used to support DAC. We stop short of assessing the exact levels of support each policy option would need to provide to support to meet the 2030 goal given the complexity and uncertainty around how each of these policies could ultimately be designed.

Carbon Pricing

Carbon pricing via a carbon tax or cap-and-trade program may prove an essential component in achieving the long-term emissions reduction targets analyzed in Chapter 2. Several bills have recently been proposed by both parties in both houses of Congress that would establish a tax on CO_2 emissions.[102] Tax rates contained in these proposals range from a starting level of roughly $15 to $50 per ton in the early 2020s, rising to $30 to $115 per ton by 2030. The higher the carbon price, the more potential support for DAC. A price alone isn't sufficient however as a provision must be included that allows DACS project operators to receive compensation for each ton of CDR they undertake. For a carbon tax, this means the policy needs to include a tax credit for DACS for every ton of CO_2 removed from the atmosphere and permanently stored underground. In a cap-and-trade program, DACS project operators must be eligible to generate offset credits that are fully fungible with allowances otherwise, there is no incentive for CDR. Currently, cap-and-trade programs in California and the Northeast do not contain such provisions and represent a missed opportunity to provide support to DAC. Lifecycle assessments of DACS projects aren't required so long as GHG emissions associated with the energy used by DACS are priced.

Aside from the essential crediting mechanism described above, carbon pricing programs can support for DAC in two other ways. First, if carbon prices aren't high enough to drive DAC deployment, projects could be awarded double or triple the credit for a limited time, until shorter-term deployment goals are met and/or until DAC costs drop below the carbon price. Extra credit mechanisms represent a simple but powerful way to support DAC technology development. Second, revenue from allowance auctions or taxes can be used to fund DAC RD&D, deployment and/or finance policies. For example, a portion of the revenue from a carbon pricing program could be directed to pay for an ITC for DAC or to fund a comprehensive RD&D program.

Infrastructure

Many elected officials have called for a massive investment in the nation's infrastructure, and some have called for infrastructure spending that also provides climate benefits. There are a number of ways an infrastructure bill could support DAC. First, the bill could authorize public spending on procurement for CDR. Second, the bill could require that all carbon-intensive building materials such as steel, concrete, and cement purchased with federal money meet ambitious low-carbon performance standards that catalyze investment in DAC to products. Finally, the federal government can directly invest or incentivize private investment in CO_2 pipelines as well as streamline pipeline permitting.

Clean Energy Standards

In 2011, President Obama proposed a new legislative program under which America would get 85% of its electricity from clean energy by 2035.[103] This Clean Energy Standard (CES) would have required all utilities to procure a steadily rising amount of electricity from low-emitting sources until the goal was met. Over the past few years, a number of states have established 100% clean energy targets. Congress could take a lead from the states and consider a federal CES. If it did so, a CES could provide incentives for DACS in the same way that California's LCFS does. CES credits could be awarded to eligible DACS projects based on the net CO_2 removed from the atmosphere. Those credits could then be sold to utilities as part of their compliance with the standard. CES credits are typically denominated in megawatt hours but could easily be converted into metric tons using national emission rates. The exact level of support for DACS from a CES and the total amount of net emission reductions achieved by the policy will depend on the ambition of the standard and which electric generation technologies qualify.

Comprehensive Climate Legislation

A comprehensive climate policy, such as one crafted in the spirit of the "Green New Deal" resolution proposed in February 2019 by US Representative Alexandria Ocasio-Cortez (D-N.Y.) and Senator Edward Markey (D-Mass.), may seek to leverage public expenditures and programs to tackle the problem of climate change.[104] Among other provisions, the Green New Deal resolution specifically calls on the US to remove pollution from the atmosphere as well as from manufacturing and industry. One way to achieve this would be to fund the RD&D program discussed above and create a public agency tasked with removing carbon from the atmosphere at scale using

DACS. This agency is discussed in further detail in Chapter 5. Using public funds, the new agency could construct and operate DACS plants to meet the 2030 deployment goal. Alternatively, this agency could solicit competitive bids for CDR from private DAC companies.

Opportunities for States

Our results show that the California LCFS provides material support to DAC, though it is not enough on its own to get DAC to nine million tons of capacity in 2030. Other states could pursue policies that deliver additional opportunities for DAC. This could include broader adoption of an LCFS or carbon pricing at levels that come close to the LCFS's triple-digit credit prices. Alternatively, states could develop new, creative approaches. For example, a number of existing nuclear plants in the US are available to supply low-carbon electricity and heat to power DAC facilities. Many states are subsidizing these same power plants to prevent their premature retirement, in part to fight climate change. States could put in place policies that facilitate DACS while providing guaranteed demand for energy from nuclear plants. Many of the federal policy options assessed above could also be adopted independently at the state level. States can provide tax credits to DACS, establish low-carbon procurement programs, or fuel mandates to support DAC. Any efforts taken by states will expand opportunities for DAC and complement federal action in whatever form it eventually takes.

CHAPTER 5

Supporting Long-Term Deployment

Assuming the 2030 goal of deploying nine million tons of DAC capacity is met thanks to robust and timely federal action, what else will be needed to keep DAC on track to meet 2050 goals? Through 2030 the purpose of policy action is kickstarting deployment, getting DAC to scale, and to reducing costs through any number of DAC applications. At some point, however, the focus of policy must shift to a more comprehensive framework that drives deep decarbonization of the US economy and accelerates CDR including DACS. The faster the US puts a comprehensive framework in place, the greater the chance of meeting long-term emission reduction targets. Furthermore, implementing this framework rapidly lends credibility and certainty to the notion that DAC will have a market. This is critical for establishing long-term investment expectations to support broad deployment. In this chapter, we explore long-term policy frameworks that could be sufficient to support DACS at scale and their interaction with near- and medium-term interventions identified in Chapter 4. We also evaluate the resources and infrastructure needed to support the deployment and operation of 850 to 2,250 million tons of DACS capacity in 2050.

Long-Term Policy Frameworks

To achieve deep decarbonization and catalyze the construction of hundreds of millions of tons of DACS capacity in US, a comprehensive policy must be implemented that values both the removal of CO_2 from the atmosphere and its permanent geologic storage. Broadly defined, there are two options: 1) put a price on carbon sufficiently high enough to incentivize DACS; or 2) directly fund DACS at scale.

Pricing Policies

Pricing CO_2 emissions is broadly believed to be the most economically efficient way to address climate change. In Chapter 4 we describe how carbon pricing can, among other policies, be designed to support DACS should a political window open in the near term. We also identified several other options to meet 2030 deployment goals. However, over the long term we find that a carbon price is a leading option for meeting mid-century emission reduction targets.

As noted previously, policymakers can establish a price by applying a tax on CO_2 emissions or through a cap-and-trade program that limits the quantity of emissions allowed in a given year and requires emitters to hold permits for every ton emitted. A carbon tax sets a known price for emissions into the future, which could provide necessary certainty to DACS developers and investors. The downside is that the total emissions under a tax are uncertain. In contrast, a cap-and-trade program potentially guarantees that emission targets are met, but the carbon price is uncertain and determined by allowance markets. Hybrid policies that blend aspects of both approaches are also possible. DACS can receive a revenue stream under a carbon tax by being awarded a transferable tax credit for every ton of CO_2 removed from the atmosphere and permanently stored underground. Under a cap-and-trade program, DAC can receive an offset credit fully fungible with emissions allowances to fund CDR. With its low risk of being reversed and clear contribution to carbon removal, DACS should be relatively easy to incorporate into an offset system relative to other options.

Economy-wide carbon pricing policy supports the long-term deployment of DACS, in addition to incentivizing decarbonization across the board. Depending on how consumers and producers respond to the price and the ambition of a pricing policy, other complementary policies may be required to meet a given emission reduction target.[cv]

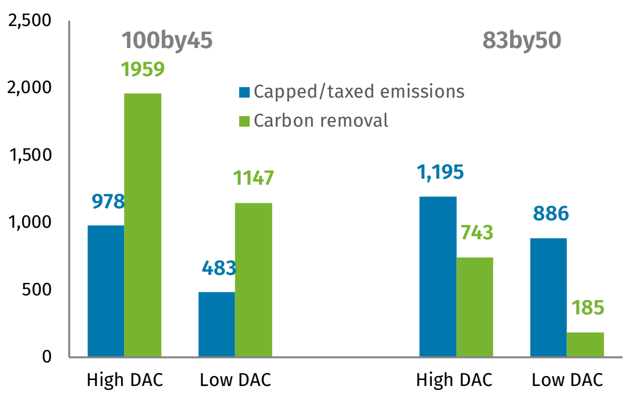
Our modeling of possible US climate targets, discussed in Chapter 2, shows that emissions caps are sufficiently ambitious to drive the deployment of DAC. Of course, projections of the future have their own uncertainties. The cost and performance of clean energy technologies, the pace of electrification, the supply of biomass, the amount of CDR achieved from natural sequestration, and even the cost of DAC itself will all influence the carbon price required to achieve long-term climate targets. For certain, the more investment, innovation, and deployment of DAC technology in the near and medium term, the cheaper and more readily available DAC will be in the long term. This, in turn, will drive down the carbon price required to deploy DAC and lower the overall cost of achieving deep decarbonization.

One potential long-term issue with carbon pricing and CDR is that the government may not collect sufficient funds from taxing carbon or auctioning allowances to pay for all of the CDR required to meet a given emission reduction target. For example, assuming a carbon tax is the pricing policy under our 100by45 target, energy CO_2 emissions subject to a carbon the tax in 2050 are between 483 and 978 million metric tons across our bounding scenarios (Figure 5.1). Meanwhile, the amount of CDR from DACS and BECCS combined in the same year is roughly 1.2 to 2 billion tons. All of this CDR would receive tax credits and in turn reduce the amount of net revenue the government received from the carbon tax. Since the total amount of CDR receiving credit is larger than taxed emissions, net revenue under the tax is negative. This means some amount of additional public funding for CDR may be required with a carbon tax in place. Under a cap-and-trade program, it could mean public funding of offsets. Over time, under an ambitious carbon pricing policy allowance or tax revenue may not be available for other policy goals.

FIGURE 5.1.

Capped or taxed energy emissions and carbon removal, 2050

Million metric tons CO_2



Source: Rhodium Group and Evolved Energy Research analysis. Note: Carbon removal includes DACS and BECCS.

Government Procurement or Management of Carbon Removal

An alternative option to support long-term DAC deployment is public funding or public management of CDR. Public funding could take several of forms, but here we describe three general approaches. One is to build on the current Section 45Q tax credit by making it permanent and awarding the tax credit for all DACS CDR accomplished each year. This would require removing the 12-year limit on awarding the credit and the commence-construction deadline. To manage costs to the government, the value of the credit would also need to decline on a predictable schedule to reflect expected cost reductions in DACS as technology improves and scales.

Another approach to public funding involves the government conducting a competitive solicitation for DACS CDR. This is similar to the competitive procurement of fuel and other goods and services used by the federal government. If this approach is pursued, DACS operators would need to meet certain performance and qualification criteria. All solicitations would need to be conducted transparently to maintain public support and to demonstrate that taxpayer funds are being spent prudently. To provide certainty to DACS operators, winning bidders would enter into long-term contracts with the federal government to establish steady, predictable revenue for verified CDR.

Finally, the government could undertake the task of CDR itself.[7] This approach is similar to the Department of Energy's Office of Environmental Management (DOE-EM), a federal agency tasked clean up and long-term management of waste and facilities associated with US nuclear weapons production.[cvi] DOE-EM was created by Congress in 1989 and is the largest and most complex environmental cleanup effort in the world with a multi-billion dollar annual budget operating on multi-decadal project timescales. Like DOE-EM, a Federal Carbon Dioxide Removal Administration (FCDRA) would need to be chartered by Congress and receive dedicated funding along with a clear mandate to meet specific environmental goals. An FCDRA would be directed by Congress to achieve a specified, increasing amount of CDR each year at a reasonable cost and to report publicly on its performance. The attraction of this option is that a guaranteed amount of carbon removal could be attained each year. Under this model, the risk arises that government ownership of all US CDR operations would wipe out competition, stagnate innovation, and lead to higher costs for taxpayers compared to a carbon price, competitive procurement, or targeted tax credits.

To be clear, any strategy that consists solely of DACS procurement falls short of driving decarbonization across the US economy. Any deployment and support policy narrowly targeting DAC may help achieve DAC deployment goals, but it will need to be coupled with other clean energy policies such as a clean energy standard, efficiency standards, and electrification incentives or mandates if the US is going to achieve mid-century emission reduction targets.

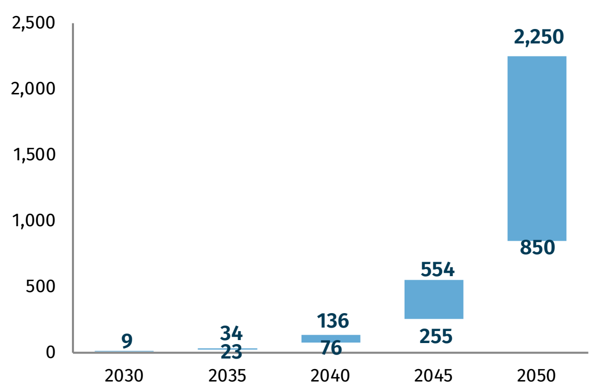
[7] Alternatively, the federal government could grant CDR monopoly power to a private utility with sufficient regulation and oversight.

The Transition From Near-Term Policy to Long-Term Support

All of the options discussed above allow for an orderly transition from the near- and medium-term deployment policies put forward in Chapter 4. Importantly, long-term policies can fill any gap if the federal government succeeds in enacting near- and medium-term deployment policies for DAC but is unable to set the time horizons of such policies to cover the full 30-year expected lifetime of DAC plants. Those long-term policies also need to be well established in the 2020s for them to become credible. Once a long-term policy is in place, Congress could phase out early deployment policies and allow the first wave of DAC capacity to participate.

Our long-term deployment pathways for DACS accelerate at an exponential rate to meet mid-century targets of 850-2,250 million tons of capacity (Figure 5.2). Whichever long-term policy framework is chosen it will need to be sufficiently ambitious enough to drive the accelerated deployment of DACS from 2030 through 2050 and beyond.

FIGURE 5.2.
US DACS installed capacity ranges, 2030- 2050
Million metric tons of DACS capacity



Source: Rhodium Group and Evolved Energy Research analysis. Note: 2030 values include all DAC deployment not just DACS.

The Cost of Achieving DACS Deployment Goals

All CDR including from DACS is a pure public benefit. No matter how it is supported, the public will pay for it one way or another. This could take the form of energy cost increases from a carbon price. Alternatively, other taxes could be raised to pay for DAC procurement or government-administered CDR. The ultimate cost incurred by the public will depend on how much the cost and performance of DAC and sequestration technologies improve over time. The minimum annual cost using our cost and deployment estimates is roughly $40 billion. While this sounds like a large amount of money, it represents well below 0.5% of the projected 2050 GDP. Still, this makes the near- and medium-term investments in RD&D and deployment all the more critical. The faster costs come down, the easier it will be to make a case for large-scale public support for DACS. Beyond costs, government leaders and advocates will need to lay out the benefits of large scale DAC deployment to solidify public and political support.

Energy System Transformation to Support DACS

DAC deployment on the scale outlined in this report will have significant implications for the energy system in the US. This section provides an overview of the potential impacts. Projecting a deeply decarbonized energy system 30 years from now is an inherently challenging and uncertain exercise. It's important to note at the outset that in our modeling we adopt relatively conservative estimates of future improvements in DAC energy performance from learning-by-doing. We do this to avoid understating the challenges ahead in meeting mid-century climate targets. Our results highlight the importance of RD&D investments and innovation to minimize both the cost and energy system impact of DACS at scale. Any technological breakthroughs that arise from RD&D will result in more modest impacts than we find in this analysis.

As discussed in Chapter 2, to meet the climate targets considered in this analysis will require a vast array of transformations at unprecedented rates of change across the entire US economy. Throughout this section, we focus on the intersection of DACS and the energy system.

DACS Energy Requirements

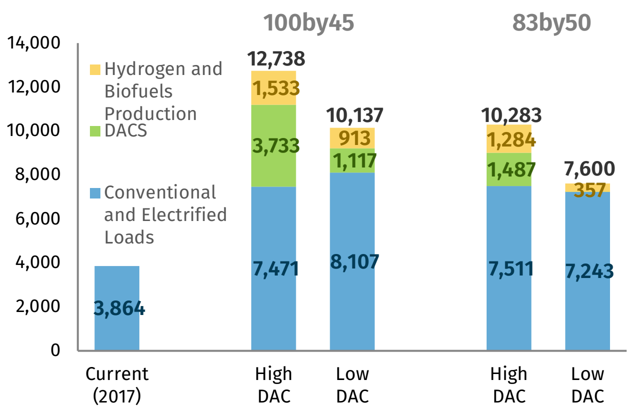
DAC requires electricity and heat to remove CO_2 from the atmosphere. In our 2050 modeling, we find that the least cost way to supply both energy requirements is through low- and zero-emissions utility-scale electric generation. Industrial scale electric resistance heaters provide heat for CO_2 sorbent/solvent regeneration after capture. When DACS is deployed at the levels identified in this report, it creates a substantial amount of new electric demand (Figure 5.3).

In 2050, electrification of end-uses alone drives an increase in electric demand equal to roughly 90% to 110% of current retail sales across our four scenarios despite aggressive, economy-wide energy efficiency improvements. The production of hydrogen and biofuels to fuel other parts of the economy adds electric demand equal to 9% to 33% of current retail sales under an 83by50 target and 24% to 40% of current retail sales under a 100by45 target. In the three scenarios where DACS is deployed, it represents the single largest source of additional electric demand after electrified loads. To supply 2,250 million tons of DACS capacity (the upper bound in a 100by45 scenario), up to 3,733 terawatt hours will be required, roughly the same amount of electricity consumed nationwide in 2017. All told, US electric demand under an 83by50 target is 97% to 166% higher in 2050 compared to today, and under a 100by45 target it is 162% to 229% higher.

FIGURE 5.3.

US electricity demand, current and 2050

Terawatt hours



Source: Rhodium Group and Evolved Energy Research analysis.

Electric Supply for DACS

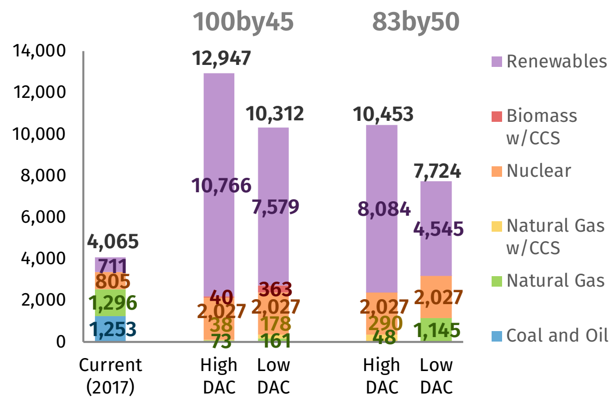
To meet mid-century emission reduction targets, we find that the electric power system almost entirely decarbonizes by 2050 in all but the 83by50 Low DAC scenario (Figure 5.4). Indeed, as described in Chapter 2, the power system becomes more than 90% emissions-free between 2035 and 2040. DAC isn't the only technology that needs to scale up rapidly over the next 30 years to meet this change. To supply the massive growth in electric load across the economy, non-hydro renewables as well as nuclear power and natural gas with CCS, all need to ramp up dramatically in our modeling. The exact balance of these zero-carbon generation sources will, of course, depend on their individual costs and levels of public acceptance, neither of which are the focus of this report.

With the cost and performance assumptions used in our modeling, renewable generation increases by a factor of 6 to 11 over today's levels to meet an 83by50 target in 2050, providing 59% to 77% of all electricity (Figure 5.5). To meet a 100by45 target, renewables need to scale by a factor of 11 to 15 compared to today and provide 73% to 83% of total generation in 2050. Meanwhile, nuclear generation, primarily from small modular reactors as well as the maintenance of most of the current fleet, increases to 2.5 times today's levels. All of this new generation fills in behind the complete elimination of coal and the decline of non-CCS-equipped natural gas generation. CCS-equipped electric generation fueled with natural gas or biomass play a role in some scenarios.

FIGURE 5.4.

US electricity supply, current and 2050

Terawatt hours

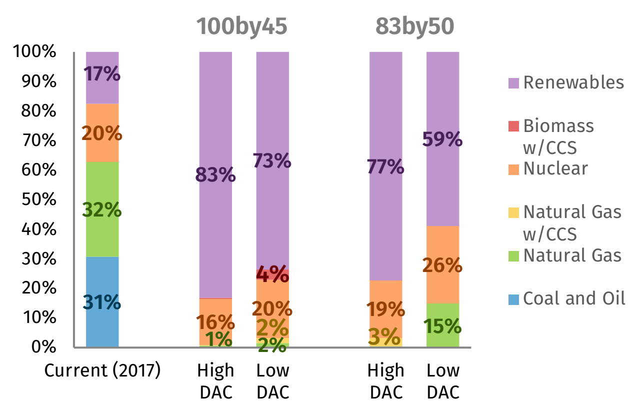


Source: Rhodium Group and Evolved Energy Research analysis.

FIGURE 5.5.

US technology shares of electric supply, current and 2050

% of total generation



Source: Rhodium Group and Evolved Energy Research analysis.

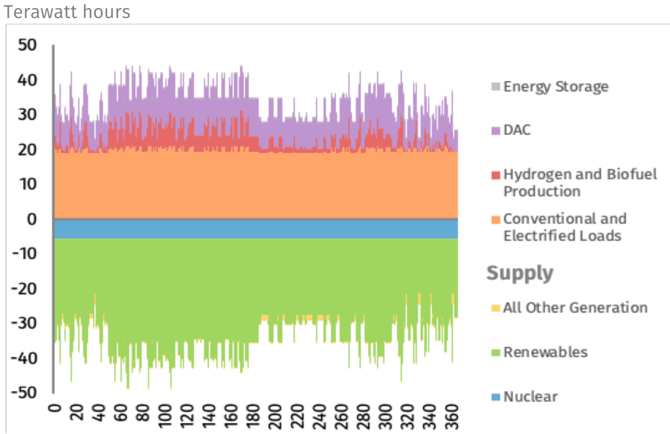
DACS as a Resource in Balancing Electric Supply and Demand

Nearly all new electric loads in our modeling, including DACS, are flexible to some degree. DACS can be located close to affordable low-emissions energy sources and can serve as one component of a portfolio of resources for balancing supply and demand. The other parts of this portfolio are hydrogen and biofuel production, energy storage and demand response from electrified and conventional end-uses. All of these resources together enable the bulk power would be deployed if it is economic to do so. Instead, there is enough excess generation to power DACS at utilization rates of over 80 percent. High enough to make DACS economically viable. Figure 5.6 illustrates the daily balance of supply and demand for the 100by45 High DAC scenario.

FIGURE 5.6.

Daily electric supply and demand balance in 2050, 100by45 High DAC scenario

Terawatt hours



Source: Rhodium Group and Evolved Energy Research analysis. Note: All other generation includes natural gas and biomass with CCS.

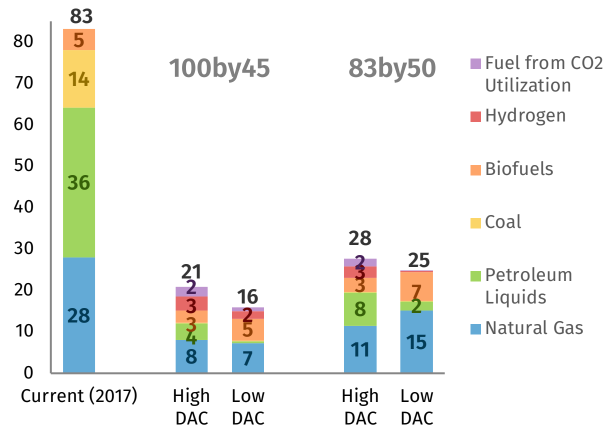
DAC and Fuels in 2050

In Chapter 4, we identified DAC-based fuels policies that have the potential to drive the implementation of the first wave of deployment. Over the long-term, we find that DAC to fuels will play a much smaller role than DACS in helping the US meet midcentury climate targets. If the US takes action to meet an 83by50 or a 100by45 emission reduction target the market for fuels will contract as buildings, industry, and transportation electrify. As electric demand increases, total non-electric energy demand will drop from 83 Quads in 2017 to 16-28 Quads in 2050 depending on the climate target and bounding scenario (Figure 5.7). This represents a 66% to 80% decline from current levels. Coal will be almost completely phased out. Natural gas and petroleum demand will decline by at least 46% and 78% respectively. Meanwhile, biofuel production ramps up to supply fuel to sectors that are difficult to electrify, such as aviation, and hydrogen serves high-temperature heat requirements in the industrial sector. These results highlight the need for more research on how best to facilitate an orderly transition for the fossil fuel industry as the US pursues deep decarbonization.

FIGURE 5.7.

US non-electric energy demand, 2050

Quads



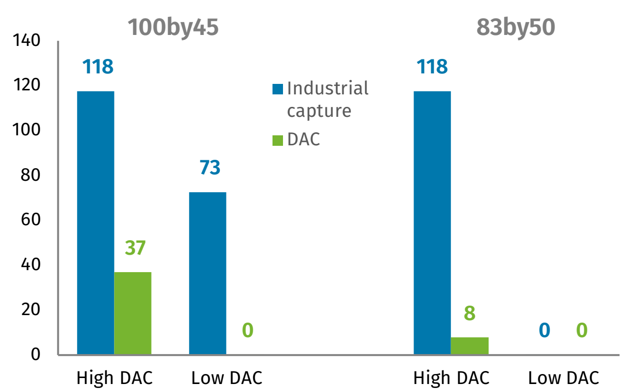
Source: Rhodium Group and Evolved Energy Research analysis.

We find that CO_2 utilization in fuel production plays a role in the US energy system in 2050 but represents no more than 2.2 Quads or 10% of non-electric energy demand. Further, we find that the majority of CO_2 used to produce these fuels is captured at industrial sources because it is cheaper than DAC CO_2 (Figure 5.8). The small role of DAC to fuels in the future does not run counter to promoting fuel production policies since their primary goal is to catalyze DAC deployment in the short and medium term. The results of our analysis reinforce the notion that industrial point-source CO_2 capture will mostly out-compete DAC CO_2 when the two are on an even playing field. It also reinforces the point that the primary long-term value of DAC is not in utilization but CDR. This means that the primary focus of long-term DAC policy support should be on DAC coupled with permanent geologic storage.

FIGURE 5.8.

CO_2 utilization by source, 2050

Million metric tons of CO_2 used



Source: Rhodium Group and Evolved Energy Research analysis. Note: In this analysis CO_2 is primarily used for fuel production.

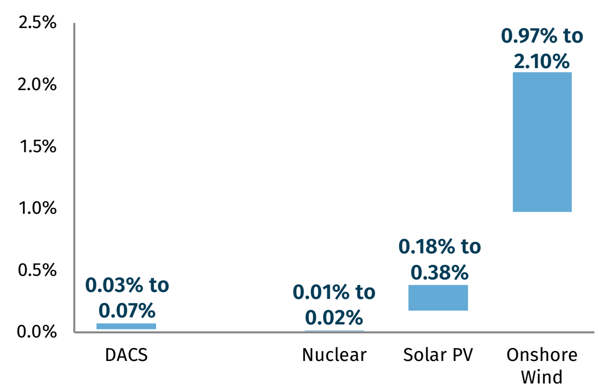
The Land Requirements for DAC and Associated Energy Supply

The energy transition associated with our 83by50 and 100by45 scenarios will require shifts in land uses to accommodate all of the new electric generation discussed above. Adapting to the space requirements of DACS poses fewer challenges for two reasons. First, given the current state of technology, the total land area required by a one-megaton DAC plant ranges from 0.3 to 2 square miles.[cvii] This is roughly the size of a conventional coal steam power plant. Second, DACS plants will be sited close to geologic storage reservoirs which tend to be in rural areas. Relying on the median value of the DACS footprint range, we estimate that 850 million tons of DACS capacity; built around the US in 2050 (the upper bound in an 83by50 scenario) will in aggregate take up 942 square miles. This is less than 0.05% of the land area of the continental US. 2,250 million tons of DACS capacity (the upper bound in a 100by45 scenario) will require 2,484 square miles or less than 0.1% of the continental US (Figure 5.9).

Electric generators needed to power DACS will also require land. The actual amount of land needed will depend on the mix of generation that ultimately gets built. While land requirements for DACS are non-trivial, they are small compared to the land required by electric generators powering DAC machines. Considering just DAC's share of total electric demand, supporting 850 million tons of DACS capacity will require all of the electricity generated by 219 GW of nuclear or 494 GW of wind or 658 GW of solar PV. The land required by nuclear plants is small, roughly 1 square mile per plant. However, the land required by solar is vast and wind more significant still.[cviii]

We estimate that the land required by nuclear to power 850 to 2,250 million tons of DACS capacity would be slightly smaller than that are used but DACS itself or 0.01% to 0.02% of total continental US land area (Figure 5.9). Solar PV to power DACS will require 0.18% to 0.38% of continental US land area, and onshore wind will require 0.97% to 2.1%. Importantly, onshore wind can be co-sited with other land uses such as farming and ranching. Its oversized land requirement does not mean up to 2% of the US will be off limits. While not quantified here, natural gas generation equipped with CCS would likely take up slightly more land area than nuclear without considering land required for gas production. Additionally, the gigawatts of nuclear needed to supply this amount of DAC is an upper bound using resistive heat generated by nuclear power. There are ways to optimize a DACS plant fueled by nuclear energy or other thermal generators that would likely require a smaller total capacity and thus smaller land area.

FIGURE 5.9.
Land requirements of DACS and associated electric generation for 2050 deployment range
% of continental US land area



Source: Rhodium Group and Evolved Energy Research analysis.

Innovation may improve the efficiency of DACS plants as well as the performance of wind and solar PV over time. If substantial improvements are achieved, then the land requirements would be smaller than reported here. Offshore wind and floating solar PV, two technologies not fully characterized in our analysis, could also alleviate land requirements. Innovation may be critical not just to reduce the cost of DAC, but also to avoid land-use conflicts that could arise from the massive build-out of renewables. Investments in basic research could lead to breakthroughs that dramatically improve DAC efficiency and may indirectly improve public acceptance of ambitious climate action by reducing the need for transformation of a large share of the national landscape.

CHAPTER 6

Conclusions and Key Findings

A growing body of research, both in the US and around the world, makes it clear that carbon removal solutions including DACS will be critical to solving climate change. We've conducted first-of-its-kind modeling to identify the amount of DAC required for the US to take a leadership role in meeting global climate targets. The quantities required are substantial, but the industry is well-positioned for takeoff. DAC technology now must to cross the valley of death, the point where many breakthrough technologies fail due to lack of investment. To accomplish this, the federal government needs to pursue policy action on multiple fronts such as research, development, demonstration and large-scale deployment. Our report lays out a federal policy roadmap for doing so.

Based on our analysis we make the following key findings:

Meeting Ambitious GHG Reduction Targets by Midcentury Requires Large-Scale Carbon Removal with Direct Air Capture Technology

We find that even with break-neck electrification of vehicles, buildings, and industry, unprecedented improvements in energy efficiency, completely decarbonized power generation, and CDR from enhanced natural sequestration, DAC technology will be essential for the US to completely decarbonize by midcentury. Our analysis indicates that for the US to reach net-zero emissions by 2045 (our "100by45" scenarios) between 560 and 1,850 million metric tons of CO_2 will need to be removed using DACS, depending on the pace of electrification in the transportation, buildings, and industrial sectors, on the availability of other CDR options, such as BECCS and natural sequestration. Even under a less ambitious US target of 83% below 2005 levels in 2050 (our "83by50" scenarios), CDR technology remains necessary to offset stubborn sources of CO_2 such as long-haul aviation and shipping, and energy-intensive industrial activities.

DAC Deployment Is Achievable, but Current Market Opportunities Are Not Sufficient for Scale Up

If the US gets started now, it has 30 years to innovate and improve DAC technology. Dedicated academic researchers and three commercial DAC companies have worked diligently over the last decade to improve the performance of the technology. Collectively, these companies have built 11 DAC plants around the world, the largest of which is located in Alabama and is designed to capture 4,000 tons per year.

For the US to become a leader in DAC technology the most important thing is to quickly get plants built, increase scale, and reduce costs through learning and experience. This means the precise application of DAC—whether for fuels, products, EOR, or sequestration—matters little at this stage compared to the need to meet the 2030 deployment goal of nine million tons of DAC capacity. While some niche opportunities may exist now where DAC is economic, current market opportunities and policy incentives do not provide enough support for the first large scale DAC plant to break even. This is the case across multiple DAC technology applications, even after accounting for existing policy incentives like California's LCFS and the federal Section 45Q tax credit.

A Comprehensive RD&D Program Is an Essential First Step

A comprehensive RD&D program modeled on the recent recommendations of the NASEM is required to get DAC from pilot scale to megaton scale in the near future. Without such a program, additional federal incentives for DAC will not be sufficient to make sure DAC is available and affordable for widespread deployment by mid-century. RD&D investments now catalyze breakthroughs that can lead to dramatic reductions in long-term costs.

Without Removing Non-Cost Barriers, DAC Will Be Constrained

The federal government should act to address long-term geologic storage monitoring and liability. Doing so will provide certainty to DACS project developers. Streamlined pipeline and CO_2 storage permitting can reduce costs and mitigate investment risks. The government can also facilitate DACS CDR by mapping geologic formations and assessing their suitability. Independent standard-setting organizations can proactively establish standards for CO_2-based products such as concrete and aggregate. Removing these barriers will make carbon utilization and removal opportunities far more accessible for DAC developers.

There Are Multiple Policy Pathways to Get DAC Across the Valley of Death

The success of any new policy support for DAC deployment hinges on implementing a robust RD&D program and addressing non-cost barriers to deployment. Assuming both occur, we have identified three pathways for the federal government to support the deployment of at least nine million tons of DAC capacity built in the US through 2030. Fully implementing any one of these pathways should get DAC on track towards likely long-term deployment needs. These pathways include:

Leverage Federal Procurement. The Department of Defense can ramp up competitive procurement of DAC based fuels from zero to roughly 23% of 2017 operational fuel consumption in 2030. The General Services Administration can launch a competitive procurement program for carbon removal from DAC with sequestration in addition to procuring low-carbon products made with DAC CO_2.

Improve the Section 45Q Tax Credit for DAC. Congress can make several improvements to this program all focused on DAC. It should extend the commence-construction deadline for DAC eligibility to the end of 2030, extend the credit payout period to 30 years, increase the value of the credit for geologic storage to $180 per ton, and lower the minimum capture and use thresholds to 10,000 tons per year. These changes will allow the first wave of commercial DAC plants to break even if they also incorporate revenue from California's LCFS. The total annual cost to the government in 2031 would be just $1.5 billion to support nine million tons of DAC capacity, roughly half the current annual cost of solar photovoltaic (PV) tax credits.

Establish a Federal Mandate for DAC Based Fuels. Congress can expand eligibility for the Renewable Fuels Standard or establish a standalone mandate for very low carbon, drop-in fuels to increase consumption of DAC-derived fuels. By 2030, DAC-derived fuels need to equal roughly 0.4% of 2017 US on-road fuel consumption to achieve the goal of nine million tons of DAC capacity. Credit prices would need to be $2.50 per gallon to support the first DAC plant and $1.05 per gallon to support the ninth DAC plant.

Lowering Capital Costs Can Complement Deployment Policies

Policies to lower the cost of capital for DAC developers can augment each of the three policy pathways identified above and help accelerate deployment. These include Loan Guarantees, Master Limited Partnerships, Private Activity Bonds, and Investment Tax Credits. None of these policies alone is sufficient to support the construction of nine million tons of DAC capacity through 2030, but they can complement deployment policies. We find that of the options considered, an Investment Tax Credit of 30% is the most effective. It is also well-proven, having helped drive the rapid rise of solar PV deployment.

Comprehensive Policy Is Needed for the Long Term, and Needs to be Set in Place in the Next Decade

While there are a range of policies that can help DAC cross the valley of death over the next decade, supporting deployment at scale will require a more comprehensive framework, in the form of either carbon pricing or large-scale public investment.

Carbon Pricing: A cap-and-trade program or carbon tax that credits CDR and is sufficiently ambitious to meet emission reduction targets in 100by45 or 83by50 scenarios and should be sufficient to support long-term DAC deployment. The upside to this approach is that it deploys DAC as part of an integrated, economy-wide decarbonization policy framework. Depending on the level of ambition, additional public funding of CDR credits may be required near mid-century as the amount of revenue brought in by the sale of allowances or tax collection may be lower than what the government owes DAC operators for CDR.

A Federal Carbon Removal Administration: As an alternative to carbon pricing, the US could choose to publicly fund DACS and other CDR options directly through a permanent version of the Section 45Q tax credit, public procurement, or through a new public agency with sole responsibility for achieving negative-emissions goals. Similar to DOE's Office of Environmental Management, the largest environmental cleanup operation in the world, this new agency would be chartered by Congress, receive dedicated funding, and be given a mandate to achieve a specified amount of CDR each year. If this option is pursued, policies to accelerate energy efficiency, end-use electrification, decarbonization of the electric power sector, and other mitigation and CDR actions will be necessary to meet ambitious GHG reduction targets examined in this report.

The US has an Opportunity to be a Global Leader

The US has a long track record of leading the world in technological innovation. DAC offers a unique opportunity for the US to build on its extensive CO2 pipeline infrastructure and EOR investment and capitalize on more than 2 trillion tons of geologic storage capacity. These assets can serve as a stepping stone to CDR from DACS at scale. This report demonstrates that DACS needs to be an integral part of a comprehensive US response to climate change. Sustained policy support for DAC will not only help the US achieve the net negative emissions required to address climate change but drive the development and deployment of technology in a way that helps other countries do so as well. Ultimately these actions will increase the odds that the world will avoid the worst potential impacts of climate change.

Technical Appendix

This document provides additional detail on the methods and data sources used in the report.

Setting Boundaries to Establish a Range for DAC in the US

To quantify the role direct air capture (DAC) will have in achieving deep decarbonization, Rhodium Group partnered with Evolved Energy Research (EER)[cix] to run a series of bounding scenarios using their modeling framework which is a pairing of two energy system models—EnergyPATHWAYS (EP) and the Regional Investment and Operations model (RIO). Specifically, EP which is a bottom-up energy system tool that tracks energy infrastructure including stocks for buildings, industry, and transportation, was used to model the demand-side of the energy system. RIO is a cost-optimization, supply-side model that blends capacity expansion and detailed sequential hourly system operations to effectively capture the value each resource type can offer the system as part of an optimally dispatched portfolio.

Rather than a snapshot of resource valuation during a single year in time, RIO captures the full set of dynamics across the energy system over the study horizon. It is a powerful tool for both planning and asset evaluation that supports understanding which optimal investments can achieve future policy goals reliably, and what role specific technologies can play in a least-cost future energy system.

We chose to use the paring of EP and RIO for this analysis because this state-of-the-art modeling framework can capture traditional supply-side technologies as well as those that will potentially play a role in a decarbonized energy system, including BECCS, DAC, hydrogen production and synthetic low-carbon fuel creation. Additionally, EP can assess future energy systems with high penetrations of electrification in end-use sectors and coordinate the intricate impacts on the supply-side with RIO.

For this analysis we looked at four scenarios with the goal of bounding the amount of DAC that may be deployed in two different decarbonization scenarios. Table A.1 shows a summary of the input assumptions in each scenario.

TABLE A.1.

DAC bounding scenarios

Scenario	2050 net GHG Emissions Target	Electrification	2050 Biomass Supply (Million Dry Tons)	2050 Natural Sequestration (Million metric tons CO_2)
83by50 – High DAC	83% below 2005	Slow	270	381
83by50 – Low DAC	83% below 2005	Moderate	992	613
100by45 – High DAC	100% below 2005 by 2045, 105% below 2005 by 2050	Moderate	270	381
100by45 – Low DAC	100% below 2005 by 2045, 105% below 2005 by 2050	Accelerated	992	613

We found that the four main factors that influenced the amount of DAC deployment in decarbonization scenarios are 1) the level of decarbonization necessary, 2) the amount of electrification in the demand-side sectors, 3) The amount of available sustainable biomass supply and 4) the level of natural sequestration. Therefore, we designed our bounding scenarios to vary these four assumptions.

Below is a detailed description of the assumptions made in each case:

2050 Net Greenhouse Gas (GHG) Emissions Target

1. 83by50 target: A straight line reduction pathway from 26% below 2005 levels in 2025 to 83% below 2005 levels in 2050.

2. 100by45 target: A straight line reduction pathway from 28% below 2005 levels in 2025 to net zero emissions in 2045 and 105% below 2005 levels in 2050.

Non-energy CO_2 Greenhouse Gases

EPA and RIO only model CO_2 emissions from energy consumptions. Projections for all GHG emissions other than CO_2 directly associated with fossil fuel consumption are derived from Rhodium Group's Taking Stock 2018 Low Energy Cost scenario.[cx] We chose this scenario because it leads to the lowest non-CO2 GHG emissions. One key exception to this is that methane, CO_2, and N_2O emissions from the production, transport, and combustion of fossil fuels are assumed to decline based on the level of electrification of end-uses and decarbonization of electric generation in each of our bounding cases. The more decarbonization of end-uses and electrification, the lower the emissions from these sources.

Electrification

The accelerated electrification assumptions have sales shares of electrification measures reaching their estimated upper bound by 2030 (including low sales penetration technologies like electric boilers) and remain at that level through 2050. Most measures achieve their estimated upper bound of stock saturation (same as upper bound of sales share) by 2040 and some slower adopting sectors with long-lived equipment (e.g., medium duty trucks, commercial space heating) achieving the remaining 10-15% saturation by 2050.

The moderate assumptions have the same estimated upper bounds as the accelerated scenario, but adoption is delayed essentially by a decade. With sales shares very near their limit in 2040, and at their limit by 2050. Electrified stock shares are within 80% to 97% of their estimated upper bounds by 2050.

The slow assumptions apply similar logic to the moderate assumptions but delay adoption by roughly an additional decade.

Biomass Supply

In the upper bound, nearly a billion dry tons per year of sustainable biomass is available in 2050. We rely on the benchmark scenario from the US Mid-century Strategy for this estimate.[cxi] In our Low DAC scenarios, we reduce the High DAC supply by 70% by taking the upper-bound estimate and removing any biomass supply whose production would require a change in current land uses. This approach is consistent with the National Academies method for constructing their lower-bound estimate. What remains is biomass supply that requires no change in current land uses.[cxii] It is assumed that the lifecycle GHG emissions associated with biomass in all scenarios are equal to zero. For biomass supply values from 2020 through 2049 we assume a straight-line increase from current biomass supply levels from DOE to our upper bound value and a straight-line decrease to our lower bound value.

Natural Sequestration

For natural sequestration, we assume that negative emissions from US forest and soil sinks decline by 14% to 47% in 2050 compared to 2016 levels as forest stocks continue to mature and land-use conversion trends continue. The upper and lower bound are sourced from the US Mid-Century Strategy Benchmark and Limited Sink scenarios respectively.[cxiii] The MCS values have been adjusted downward by 2.5% to align with the EPA's 2018 GHG Inventory. In the low case, we assume there is 381 million metric tons CO_2e of negative emissions from natural sequestration in 2050. In the high assumptions, we assume 613 of million metric tons CO_2 of negative emissions. The variation represents climate change impacts and the effectiveness of policies to enhance carbon sinks. For sequestration values from 2020 through 2049 we draw straight lines from 2016 levels to our upper and lower bound 2050 values.

Below are additional assumptions made in our scenarios:

Energy Efficiency

Buildings energy efficiency is the best available technology (BAT) deployed in all buildings by 2025 and moving forward. Industrial efficiency is assumed to be a 1% per year improvement over the baseline energy demand.

DAC Costs

To be consistent with the other technologies in RIO that are competitors with direct air capture, we assume "nth-of-a-plant" DAC costs, which we define as the cost of a DAC plant with a million metric ton capacity per year after three capacity doublings. This is equivalent to the costs of the 9^{th} plant. The costs of the 9^{th} plant are derived from our detailed DAC costing, the methodology of which is outlined in the next section. A summary of first-plant costs is on page 5 of this appendix, detailing DAC cost projections. Table A.2 below summarizes our cost inputs into RIO for the 9^{th} plant.

Energy costs for DAC are determined endogenously. We use our median cost estimates for the 9th plant for all scenarios because preliminary test scenarios revealed that within our determined low-to-high DAC costs range for the 9th plant, there is not a substantial impact on DAC deployment when we varied costs within our range. It should also be noted that these inputs are meant to be representative of a DAC technology that is agnostic to a liquid solvent or solid sorbent system; inputs are a median of costs for both technologies.

TABLE A.2.

DAC for sequestration cost inputs and parameters for RIO

Inputs	900 million metric tons CO_2 capacity parameters
Capital Costs ($M)	739
Annual FOM ($M)	41
Variable OM ($/ton)	8
Electrical Efficiency (MWh/ton)	0.3
Heating Efficiency (MMBtu/ton)	5.6
Lifetime (years)	30
Interest rate (%)	7.7

Source: Rhodium Group Analysis

Macroeconomic Assumptions

Population, Gross Domestic Product and other drivers of energy service demands in EP and RIO are tuned to EIA's Annual Energy Outlook 2017 reference case.[cxiv]

Key Electric Power Sector Assumptions

For this study, RIO was configured to optimize the electric power system within the three US Interconnects. Electric power generating technology costs and performance are primarily sourced from the National Renewable Energy Laboratory's Annual Technology Baseline 2018.[cxv]

Estimated DAC Costs

To assess the potential policy pathways for direct air capture technology (DAC), current and projected costs for DAC are required as inputs for our policy models. It is important to note that our estimated direct air capture costs represent the anticipated costs for the first megaton scale direct air capture plant. Therefore, the costs are not meant to be a representation of the cost at currently operating DAC facilities. We calculate the costs of DAC as follows:

Cost of capture = levelized capital costs + non-energy operating costs + energy costs

To determine these costs, we refer to the 2018 study by the National Academy of Science (NASEM) on negative emissions technologies to guide our cost model.[cxvi] The NASEM covers the emissions impact and costs of direct air capture in Chapter 5 of its report, specifically the emissions and costs associated with two key DAC technologies – solid-sorbent technology and liquid-solvent technology. For liquid-solvent DAC technology, we take the high- and low-range estimates of the capital costs presented in the NASEM report. Using these estimates, we calculate a mid-range estimate for capital costs by averaging the high-cost and low-cost estimates. For solid-sorbent technology, mid-range capital costs are already presented in the report, and so we take all three cost estimates for this technology. Using the three capital cost estimates for each technology, we then calculate a range for the levelized capital cost for each technology, using an interest rate of 11.55%, a payback period of 30 years, and a utilization rate of 90%.[8],[9] For non-energy operating costs, consistent with the methodology in the NASEM report, we calculate maintenance costs as 3% of the total capital requirement and we calculate labor costs as 30% of maintenance cost. For the liquid-solvent technology, we then add makeup and removal costs, which were estimated in the NASEM report to be $5-$7 million per year. Table A.3 shows a summary of these values for each technology.

TABLE A.3.

Range of capital and operating costs for DAC for two key technologies – solid sorbent and liquid solvent

Technology	Liquid-solvent technology			Solid-sorbent technology		
Cost scenario	Low	Mid	High	Low	Mid	High
Capital cost ($ millions)	634	675	1106	965	1255	1711
Non-energy operation and maintenance costs ($/ton)	27	35	48	47	60	74

Source: NASEM and Rhodium Group Analysis

To calculate energy-related operating costs, we use the energy requirements for each technology cited in the NASEM report. From the maximum and minimum energy requirements of each technology, we calculate the mid-range energy requirement. For each technology, we model three energy scenarios captured in Table A.4. This gives us a total

[8] This gives us a capital recovery factor (CRF) of 12.00%

[9] NAS assumes 100% utilization rate. Hence, we do not use their levelized costs as presented in their report.

of 18 cost scenarios to input into our policy models and fuel production model.

TABLE A.4.
DAC cost scenarios

Energy cost scenario	Liquid-solvent technology: Low	Liquid-solvent technology: Mid	Liquid-solvent technology: High	Solid-sorbent technology: Low	Solid-sorbent technology: Mid	Solid-sorbent technology: High
1	$40/MWh electricity (PPA) $3.72/GJ natural gas	$40/MWh electricity (PPA) $3.72/GJ natural gas	$40/MWh electricity (PPA) $3.72/GJ natural gas	$40/MWh electricity (PPA) $0.60/GJ steam	$40/MWh electricity (PPA) $0.60/GJ steam	$40/MWh electricity (PPA) $0.60/GJ steam
2	on-site generation $3.72/GJ natural gas	on-site generation $3.72/GJ natural gas	on-site generation $3.72/GJ natural gas	$66.34/MWh electricity $0.60/GJ steam	$66.34/MWh electricity $0.60/GJ steam	$66.34/MWh electricity $0.60/GJ steam
3	$66/MWh electricity $3.72/GJ natural gas	$66/MWh electricity $3.72/GJ natural gas	$66/MWh electricity $3.72/GJ natural gas	$66/MWh electricity $1.80/GJ steam	$66/MWh electricity $1.80/GJ steam	$66/MWh electricity $1.80/GJ steam

For the low-, mid-, and high-range estimates of DAC liquid-based solvent technology, we calculate the cost of capture for:

1. if using power-purchase agreements (PPAs) at $40/MWh
2. if electricity were generated on site – capital costs increase in this scenario by $5.67/ton due to added on-site power generation.[cxvii]
3. if electricity were purchased from the grid (where electricity is priced at $66/MWh)

For the low-, mid-, and high-range estimates of DAC solid-based sorbent technology, we calculate the cost of capture for:

1. low-cost steam ($0.60/GJ) and zero-emissions electricity purchased using PPAs ($40/MWh)
2. low-cost steam ($0.60/GJ) and electricity purchased from the grid ($66/MWh)
3. high-cost steam ($1.80/GJ) and electricity purchased from the grid ($66/MWh)

For electricity purchased from the grid and natural-gas prices, we use industry-sector electricity and natural-gas rates from RHG-NEMS, a modified version of the detailed National Energy Modeling System used by the Energy Information Administration (EIA) maintained by Rhodium Group. We take electricity rates and natural-gas prices from the central scenario of our Taking Stock analysis, which incorporates moderate energy market and technology input assumptions.[cxviii] We average the 2023-2030 electricity and natural-gas prices from RHG-NEMS, calculating $66.34/MWh for electricity from the grid and $3.72/GJ for natural gas to be used as inputs in our model.[cxix] In our model, both technologies use electricity for certain aspects of the DAC process, whereas only liquid-solvent technology uses natural gas for its heating requirements. For the solid-sorbent technology, we assume that steam is used to satisfy its heating requirements because a lower temperature is required. The steam cost assumptions are based on the NASEM study at $1.80/GJ or $0.60/GJ, depending on the cost scenario; we assume $0.60/GJ is a representation of low-cost waste heat.

Given the estimates from our 18 cost scenarios, we calculate the range of capture-costs to be $173-290/ton for liquid-sorbent technology and $124-$325/ton for solid-sorbent technology. These are CO_2-capture costs for a DAC plant with the capacity to capture a megaton of CO_2 annually. These costs are also for the first-such plant built, before any learning-by-doing effects occur over time.

TABLE A.5

Range of DAC costs for two key technologies – solid sorbent and liquid solvent

	Liquid Solvent ($/ton)			Solid Sorbent ($/ton)		
Energy scenario	Low	Mid	High	Low	Mid	High
1	173	236	275	124	207	314
2	221	233	273	130	214	320
3	187	250	290	135	218	325

It is important to note that the cost of capture – as defined and used in this paper – differs from the terms "cost of net capture" and the "cost of capture and sequestration." The cost of capture only accounts for the cost to capture CO_2 from the atmosphere and remove it from the binding material used at a purity of about 90-95%. The cost of net capture penalizes for the emissions produced during the DAC process (i.e. emissions released from electricity use and burning natural gas for heating purposes) and does so by multiplying the cost of capture by a cost factor based on tons of CO_2 emitted per ton of CO_2 captured. In our cost model, we assume zero-emissions electricity is used. We also assume co-capture of any CO_2 released in natural gas combustion for the liquid-solvent technology scenarios. These assumptions are made in order to maximize the net capture of CO_2 from the air (and thus minimize net capture costs). However, it should be noted that the cost of net capture increases significantly if carbon-intensive electricity or natural gas is used to power the DAC process. In our cost model, when we ran the scenario with grid-supplied electricity at grid emissions rates (i.e. 743 g-CO_2/kWh), we found net capture costs to be impractically high given the context of our policy analysis. The cost of capture for DAC could be cheaper using more carbon-intensive electricity or heat but we consider the net capture costs to determine which DAC infrastructure is practical.

The cost of capture and sequestration accounts for the cost of capturing both CO_2 from flue gas (if there is any) and ambient air, as well as the cost to compress, transport, and sequester this CO_2. For the liquid-solvent DAC technology, we incorporate the use of an oxy-fired kiln, which allows for the easy capture of CO_2 generated from burning natural gas. Thus, we assume the cost of capture of flue-gas CO_2 to be zero, as oxy-fired kilns produce a pure CO_2 stream upon condensation of the vapor created during combustion. As a result, in our model, capture plus sequestration costs only incorporate the cost of capture of ambient CO_2, in addition to the costs of compression, transport, and sequestration of both ambient and exhaust CO_2. For the solid-sorbent DAC technology, there is no natural gas combustion (because we assume heating requirements are satisfied by low-temperature heat in the form of zero-carbon steam). As a result, capture plus sequestration costs incorporate the cost of capture, compression, transport, and sequestration of only ambient CO_2. Incorporating compression and sequestration costs, we estimate capture-sequestration costs to be $191 - $308/ton for liquid-solvent technology and $142-$343/ton for solid-sorbent technology. We assume that it costs $18/ton to compress and sequester CO_2 captured in the DAC process, consistent with figures found in the NASEM study.

The cost of sequestration is only relevant to our policy analysis when the ambient CO_2 captured is ultimately sequestered instead of being used in end-products such as in cement and transportation fuel. As such, the cost of sequestration is relevant to policy scenarios that address enhanced oil recovery (EOR), geologic sequestration, and the application of a carbon tax (which helps generate a market for CO_2 that is ultimately placed underground).

Projected DAC Costs

For our policy analysis, knowing how DAC costs may change over time with increased deployment is important to consider when we calculate how DAC should be supported monetarily to drive down costs. This is because, as each new DAC plant is built, learning-by-doing and economies of scale allow for lower DAC costs, which in turn allows for DAC technology to be less dependent on policy support in the long term.

We determine how costs will decline over time by applying a learning rate to current estimated costs, where final DAC costs are a function of the number of megaton-scale DAC plants that are deployed. We calculate DAC costs for the "nth" plant as follows:

Cost of capture for "nth" DAC plant = Initial cost * [(1 – learning rate) ^ (ln(n)/ln (2))]

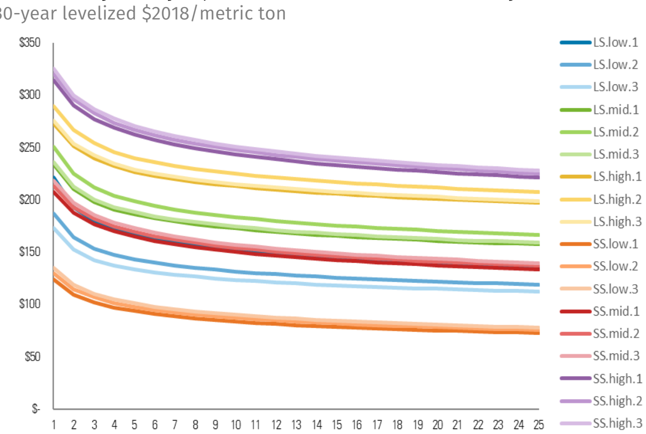
Where n is the number of plants constructed, including the initial megaton-scale DAC plant deployed. We do not account for the cost-reduction impact that research and development (R&D) will have in our model because we assume that a megaton-scale commercially ready DAC plant will be at a stage where R&D will no longer be a significant driver of cost reductions. Thus, we only consider learning due to total prior capacity-built in our model.

In our cost model, we assume all capital costs and energy requirement improves at the learning rate. We assume the energy requirement learns until the point of a lower bound constraint which is set by the low scenarios in the NASEM report; once the energy requirement reaches this lower bound, no further learning occurs in the model for energy demand. Energy costs themselves remain static. The non-energy operating costs also remain static, consistent with modeling assumptions from the Energy Information Administration (EIA).[cxx]

We determine that a range of 10-15% for the learning rate is applicable to DAC technology, as literature review and expert interviews confirmed that other technologies with characteristics similar to DAC have similar historical learning rates (e.g. Sulphur dioxide removal and solar PV).[cxxi] That said, we apply this range of learning rates across our cost scenarios, assuming a 10%, 12.5%, and 15% for the high, mid and low scenarios respectively. Thus, the low scenarios with a 15% learning rate represent our most optimistic cost projections, whereas the high-cost scenarios with only a 10% learning rate represent our most pessimistic cost projections.

The projections for the first 25 DAC plants of MMT/year capacity amongst our 18 scenarios is shown in Figure A.1. Using these 18 scenarios we calculate the median value as an input to our DAC deployment modeling and policy analysis. We use the median capital and O&M costs for the 9th plant from these projections as inputs for the RIO model.

FIGURE A.1.
Cost of capture projections for the first 25 DAC plants
30-year levelized $2018/metric ton



Expected Fuel Production Costs

For the purpose of our policy analysis, which includes analysis on DAC-to-fuels policy incentives, we calculate fuel production costs using DAC CO_2 as a feedstock. We use the maximum (high), median (mid), and minimum (low) estimates of DAC capture costs as inputs for our fuel production model. Our expected fuel production costs are for the first DAC-to-fuels plant of megaton-scale size. This equates to a fuel production plant capacity of 210 thousand gallons per day. The expected costs of fuel production are for a plant that would be built and begin operation in the early 2020s. Therefore, these costs do not represent near-term, small-scale production of fuels from direct air capture. Costs of fuel production are calculated as follows where the fuel in question is synthetic, diesel approximated to dodecane($C_{12}H_{26}$):

Cost of fuel production = DAC costs + Hydrogen production costs + CO_2 reduction costs + Fischer-Tropsch costs + compression/sequestration costs

The process used to create synthetic fuel from CO_2 is the Fischer-Tropsch process. The Fischer-Tropsch process is a collection of chemical reactions that converts carbon monoxide and hydrogen into liquid hydrocarbons. The CO_2 captured from ambient air is first reduced to CO and is reacted with H_2 in an approximate 2:1 ratio according to the following equation:

$$25\ H_2 + 12\ CO \rightarrow C_{12}H_{26} + 12\ H_2O$$

Thus, we need to account for the costs of hydrogen and CO production, which are the reactants needed to carry out the Fischer-Tropsch process.

Determining that 0.22 tons of fuel is produced for every ton of CO_2 used in the fuel production process (we assume a CO_2-to-CO conversion efficiency of 80%), we calculate that the DAC costs for fuel production is in the range of $1.64-$4.21 per gallon of fuel produced for the first plant.

Hydrogen Production

The purpose of our DAC-to-fuels production numbers is to examine policy support necessary under a revised RFS or federal procurement pathway. We don't expect that these policies will be viable until the early 2020s and therefore we use Department of Energy (DOE) 2020 hydrogen production via electrolysis cost targets based on the cost to produce hydrogen from electrolysis (i.e. $2.3/kg of hydrogen produced).[cxxii] This includes projected capital costs of $300/kW. We assume hydrogen production is done via electrolysis because other methods investigated (i.e. coal gasification and steam reforming) did not allow for affordable control of emissions and thus would have substantially increased the life-cycle carbon intensity of the fuel produced and therefore increased the amount of policy support necessary. Furthermore, even if emissions were controlled for in the form of incorporating point-source CO_2

capture (CCS), the decrease in the emissions intensity of the produced fuel did not make up for the added costs of CCS in our policy analysis (when compared to hydrogen produced from electrolysis powered by zero-emissions electricity).

Using our electrolysis cost of \$2.3/kg-H2, we calculate hydrogen production costs on a per-gallon basis, based on the gallon of fuel produced by 1 kg of hydrogen. Using a Fischer-Tropsch process with a carbon efficiency of 85% and a CO_2-to-CO conversion efficiency of 80%, we calculate that 1.02 kg of H2 is needed for every gallon of fuel synthesized in the fuel production process; this equates to hydrogen costs of \$2.25/gallon.

CO_2 Reduction Costs

We assume that CO_2 is reduced through the use of hydrogen via the reverse water-gas shift (RWGS) reaction:

$CO_2 + H2 \rightleftharpoons CO + H2O$

We assume that the hydrogen required for this process is also produced via electrolysis, powered by zero-emissions electricity, at a cost of \$2.30/kg-H2. Incorporating the capital and operating costs to perform this electrolysis, in addition to an assumed 80% conversion efficiency of CO_2 to CO, we calculate CO_2 reduction costs to be \$1.35/gallon.

Fischer-Tropsch Costs

We calculate fuel-conversion costs based on plant parameters for a gas-to-liquid (GTL) plant that utilizes the Fischer-Tropsch process to produce synthetic fuel from natural gas, as analyzed by the Department of Energy.[cxxiii] This DOE analysis is for a plant that produces synthetic fuel, with carbon monoxide and hydrogen produced (in the form of synthetic gas, or "syngas") in a 1:2 ratio using steam reforming. The plant assessed is capable of producing 50,000 barrels of fuel per day.

To calculate our Fischer-Tropsch costs, we subtract out the capital and operation costs associated with syngas production of the GTL process (since CO and H2 production is accounted for elsewhere in our model). We then scale the resulting cost values for a DAC-to-fuels plant that produces fuel from a megaton of CO_2 annually. To calculate levelized capital costs, we use a utilization rate of 90%, lifetime 30 years, and an interest rate of 12%.

We calculate that 77 gallons (or 1.8 barrels) of fuel is produced from 1 ton of CO_2 (assuming a carbon efficiency of 85% for Fischer-Tropsch and an 80% conversion efficiency for CO_2-to-CO conversion). Thus, a megaton-scale DAC plant captures enough CO_2 capable of producing approximately 11% of the fuel that the GTL plant analyzed by DOE is capable of producing. To account for the increased cost of production that arises from smaller-scale operations, we use the high-end estimates of capital costs presented in the GTL study. Ultimately, we calculate Fischer-Tropsch costs to be \$1.09/gallon.

Compression/Sequestration Costs

We calculate compression and sequestration (CCS) costs for the CO_2 emitted due to natural gas combustion during the DAC process. Hence, solid-sorbent technologies do not have compression/sequestration costs, as we assume that no natural gas is combusted for this technology due to steam satisfying heating requirements. For fuel made from CO_2 captured by liquid-solvent technology, however, we include this expense because the CO_2 released when natural gas is combusted has to be captured and sequestered in order for the fuel produced to have a low carbon intensity. If this CO_2 is not captured and sequestered, the carbon intensity of the DAC fuel would almost quadruple, reducing the credits it can qualify for under the 45Q, LCFS and potentially RFS programs.

We assume the cost of compression to be \$8/ton and the cost of sequestration to be \$10/ton (in accordance with cost figures presented in the NASEM study[cxxiv]). For every amount of CO_2 created from natural gas combustion, per ton of atmospheric CO_2 captured, this emitted amount is multiplied by the compression/sequestration rate of \$18/ton and added to the cost of fuel production. For the liquid-solvent technology, we calculate compression/sequestration costs to be \$0.14/gallon.

Overall, we calculate our final cost of production to be \$6.33 - \$8.90/gallon for our low-carbon synthetic fuel. We also calculate our carbon intensity to be 13.8 g-CO_2/MJ for synthetic fuel produced from CO_2 captured via liquid-solvent technology and 8.5 g-CO_2/MJ for synthetic fuel produced from CO_2 captured via solid-sorbent technology.

Carbon Intensity of Synthetic DAC Fuel

The carbon intensity of fuel produced from DAC CO_2 is important to consider in our policy analysis. Certain policy programs such as the LCFS, current RFS and 45Q have benchmarks that low-carbon fuels must meet in order to qualify; the lower the carbon intensity is for a given fuel, the greater the policy support per gallon afforded to that fuel.

We calculate the carbon intensity of the DAC fuel in our model by looking at the emissions of greenhouse gases that occur during the production process. The main sources of emissions are as follows from hydrogen production, fuel production (Fischer-Tropsch) and methane leakage. We also account for the emissions associated with land-use, construction, and CO_2 capturing.

Hydrogen Production

For hydrogen production, we assume an electrolyzer that operates at 80% efficiency, resulting in energy consumption of 49,300 kWh per ton of hydrogen produced.[10,cxxv] For our zero-emissions electricity, we assume an emissions factor of 11 gCO_2/kWh, consistent with the emissions factor for wind energy assumed in the NASEM report.[cxxvi] Given our calculations that 0.08 tons of hydrogen is required per ton of CO_2 used, we determine that the emissions impact from hydrogen production is 6.2 g CO_2 per MJ of fuel produced.

Fuel Production

For fuel production, we derive our emissions values from the GTL paper, which also included a life-cycle analysis of the fuel produced from the examined GTL plant. In this paper, emissions due to the Fischer-Tropsch process is estimated to be 1.6 g CO_2/MJ when synthetic diesel is being produced.[cxxvii]

Methane Leakage

Because the solid-sorbent technology does not combust natural gas for heating, we assume that there is no methane leakage for DAC fuel created from CO_2 captured by this technology. However, for the liquid-solvent technology, we assume a methane leakage rate of 215,800 metric tons methane/Quad, an average of the 2021-2050 predicted methane-leakage estimates from the Clean Air Task Force. This is equal to an overall leakage rate of 1.1%, in accordance with the level of methane leakage mitigation that is expected by 2050. We multiplied this value by the 100-year global warming potential of methane, resulting in a CO_2-equivalent leakage rate of 5.1 g-CO_2-eq per MJ of natural gas combusted. For our DAC synthetic fuel, this translates to 5.2 g CO_2-eq emitted per MJ of synthetic fuel created.

Emissions impact due to land-use construction and CO_2 capturing are also incorporated. We derive our estimation of land-use emissions from the GTL paper, which claims that land-use and construction accounts for 0.4 g CO_2 emitted for every MJ of synthetic fuel produced.[cxxviii]

For the capturing process, even though we assume the use of zero-emissions electricity and the sequestering of any emitted CO_2, we still calculate a small amount of emissions intensity from this step of the fuel production process. This is because we assume a small amount of emissions when considering the life-cycle of zero-emissions electricity sources (11 g CO_2/kWh as used in the NASEM report). We multiply this small emissions factor by the electrical requirements of our DAC process, resulting in DAC emissions being 0.3-0.4 g CO_2 emitted per MJ of fuel created.

Policy Pathways

We quantitatively analyzed three main policy pathways for the report. For all policies we assess the level of support needed by assessing the gap between the market value of the product plus other existing policy support and the 30 year levelized cost of DAC which we term the "break-even cost" in the policy analysis. We assume being able to recoup the break-even costs via product value and policy support will lead to commercial viability. For our policy analysis we examine the necessary policy support of the 1st and 9th plant using our median cost values. The key assumptions for the various policy pathways are described below.

Pathway 1: Federal Procurement

For the federal procurement pathway, we analyzed the average additional cost of a gallon of fuel for the lifetime of the procurement program. For each of the 9 plants assumed to be supported by the procurement program we calculated the average annual differential for the cost of DAC-to-fuel production and the amount of revenue from selling the fuel product. This is a similar methodology to how we determine the policy support needed under Pathway 3 below except we assume these plants are not able to take advantage of the LCFS program. We then calculate the average differential across the 9 plants to determine the average increase in cost per gallon that would be incurred via a procurement pathway.

Pathway 2: Revisions to the Tax Code

We consider an expanded 45Q tax credit for carbon sequestration with a higher credit value and a 30-year payout period. In this scenario, plants can also take advantage of the

[10] The higher heating value of hydrogen is 283.74 MJ/kmol-H2 or 32,800 kWh/t-H2 (IEA, 2015b)

California Low-Carbon Fuels Standard (LCFS) under the carbon-capture and sequestration pathway. For the LCFS, we assume the credit values projected by the California Air Resources Board (CARB) and a 10% reduction in the credit price post 2030.[cxxix] For reference, credit prices through 2030 are shown in Table A

TABLE A.6.
LCFS Credit prices

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
($/ton)	$150	$200	$200	$85	$85	$85	$85	$85	$100	$115	$115	$115

For our analysis of the policy support needed for the first plant, we assume that 45Q could not be expanded until 2021 at the earliest and due to the lead-time to build a plant that a direct air capture facility could not take advantage of the credit until 2023 at the earliest. We assume that the 9th plant would take advantage of 45Q and the LCFS starting in 2030. The amount of policy support needed is calculated as the difference between the levelized cost of sequestration and the average policy support from the LCFS over the lifetime of the plant. We assume that the utilization credit will also get expanded in line with a sequestration credit expansion but we did not include an analysis of what policy support is needed for utilization in the report because we found that the necessary credit value is higher than that of sequestration.

Pathway 3: Legislative Fuels Policy

The legislative fuels policy pathway considers a broader effort to reauthorize and/or reform the Renewable Fuels Standard (RFS) or a standalone fuels mandate. In this pathway, we assume that the plant would also be able to take advantage of the LCFS under the fuels pathway where the level of credit support is based on the carbon intensity of the fuel created. With regards to the LCFS, fuels sold in California must be below a certain carbon-intensity benchmark. Each year has a determined overall carbon intensity to be achieved for all fuels sold on the California fuels market. Table A.7 shows the CI benchmark that needs to be reached throughout the program to 2030 (we assume that the CI benchmark remains at 80.3 gCO_2/MJ after 2030).

TABLE A.7.
LCFS carbon intensity standard

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CI Benchmark (gCO_2/MJ)	94.2	92.9	91.7	90.4	89.2	87.9	86.6	85.4	84.1	82.9	81.6	80.3

Based on the calculated carbon-intensity adjustment (i.e. the difference in carbon intensity between the DAC fuel and the benchmark carbon intensity), we multiply this CI adjustment by the proposed amendments to the credit prices to calculate the LCFS policy support given to a gallon of fuel. We assume that the RFS would not be revised until 2023 and therefore the first plant able to take advantage of the credit would come online in 2025. Similar to the 45Q revision analysis, we assume the 9th plant is first operating in 2030. We then calculate the average annual difference between the LCFS policy support plus the revenue from the wholesale price of the fuel to calculate the gap that needs to be filled in via policy support from the revised RFS. The wholesale price of diesel is a projection taken from our Taking Stock 2018 analysis.[cxxx] For the purpose of calculating an example Renewable Identification Number (RIN), the credit trading mechanism under the RFS, we assume diesel would be awarded 1.7 RINs per gallon based on the current RFS RIN assignments and there will be no carbon intensity adjustment under a congressional revision.

Comparison With Historical Policy Support

To contextualize the hypothetical expenditure on federal tax credits for DAC, we compare federal expenditures on DAC from our analysis to historical government spending on ITC and PTC tax credits.

The investment tax credit (ITC), also known as the federal solar tax credit, allows producers of solar energy to deduct 30% off the cost of installing a solar energy system from their federal taxes. It is done on a per-kW basis, compared to the production tax credit (PTC) that is done on a per-kWh basis. The PTC is a tax credit for electricity generated by qualified energy resources; the analysis done on the PTC for this report focuses on tax dollars spent on wind energy technology. For wind plants installed before 2017,

$24.13/MWh is awarded for the first ten years of operation; the tax credit rate decreases over time for wind plants installed after 2017 and stood at $19.03/MWh for wind plants installed in 2017.

For the ITC and solar energy, we get annual capacity installed and annual generation from Form EIA-860 and Form EIA-923 data, which gives installed capacity and annual generation for every utility-scale wind and solar plant in the US.[cxxxi] We obtain the installation costs of solar from public data files from Lawrence Berkeley National Lab.[cxxxii] We then calculate the total tax cost, which is calculated as follows:

Tax Cost = annual capacity installed * installed price of utility-scale PV for that given year * 30% ITC rate

A similar methodology is used to calculate PTC costs. To calculate PTC costs for wind technology, we calculate tax costs as follows:

Tax cost per plant = (Generation for first 10 years for a given plant) * PTC rate

The generation for the first 10 years of a given plant is found in Form EIA-860 and Form EIA-923 data. For plants less than ten years old, their annual generation thus far is averaged and multiplied by 10 to determine an estimated 10-year generation. Tax costs are then summed for all plants installed in that year to find total tax costs for that given year.

TABLE A.8.

US Deployment of Utility-Scale Electric Generating Technologies Data

Technology	First Commercial Year	Average unit size (MW)
Coal Steam	1942	239
Natural Gas Combined Cycle	1957	142
Onshore Wind	1991	69
Solar PV	2007	10

Comparison With Historical Deployment

As a frame of reference, we compare our projected DAC deployment consistent with a 83by50 or 100by45 pathway with the historical deployment of electricity generating units. In order to make this comparison we needed to normalize two characteristics 1) the size of the unit that was comparable to a DAC plant and the 2) determination of the first commercial deployment year for a given technology. In order to normalize the size of the units we calculated the average unit size over the time period from 1921 (the year of the first coal steam unit) to present. We consider the first year of commercial deployment for a given technology to be the first year in which a plant of average size was built. All of these data were derived from EIA's form 860 database.[cxxxiii]

Then to calculate the cumulative amount of typical units deployed in a given year we took the cumulative amount of total capacity for each technology deployed each year and divided by the average unit size. Starting years and average unit sizes for each of the four generating technologies considered are presented in Table A.8

Endnotes

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