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THE DEVELOPMENT AND DEPLOYMENT OF LARGE-SCALE CARBON DIOXIDE MANAGEMENT TECHNOLOGIES IN THE UNITED STATES, INCLUDING TECHNOLOGICAL AND NATURAL CARBON REMOVAL, CARBON UTILIZATION, AND CARBON STORAGE

HEARING

BEFORE THE

COMMITTEE ON ENERGY AND NATURAL RESOURCES UNITED STATES SENATE

ONE HUNDRED SIXTEENTH CONGRESS

SECOND SESSION

JULY 28, 2020

Printed for the use of the
Committee on Energy and Natural Resources

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CONTENTS

OPENING STATEMENTS

	Page
Murkowski, Hon. Lisa, Chairman and a U.S. Senator from Alaska	1
Manchin III, Hon. Joe, Ranking Member and a U.S. Senator from West Virginia	3

WITNESSES

Moniz, Hon. Ernest J., President and CEO, Energy Futures Initiative, Inc.	5
Winberg, Hon. Steven E., Assistant Secretary for Fossil Energy, U.S. Department of Energy	31
Angielski, Shannon, Executive Director, Carbon Utilization Research Council	44
Friedmann, Dr. S. Julio, Senior Research Scholar, Center on Global Energy Policy, Columbia University School of International and Public Affairs	66
Mackler, Sasha, Energy Project Director, Bipartisan Policy Center	90
Hezir, Hon. Joseph, Principal, Energy Futures Initiative, Inc.	107

ALPHABETICAL LISTING AND APPENDIX MATERIAL SUBMITTED

Angielski, Shannon:	
Opening Statement	44
Written Testimony	47
Responses to Questions for the Record	290
Friedmann, Dr. S. Julio:	
Opening Statement	66
Written Testimony	68
Response to Senator King	118
Responses to Questions for the Record	298
Hezir, Hon. Joseph:	
Questions for the Record	276
(The) John Muir Project:	
Letter for the Record	318
Mackler, Sasha:	
Opening Statement	90
Written Testimony	92
Responses to Questions for the Record	306
Manchin III, Hon. Joe:	
Opening Statement	3
Moniz, Hon. Ernest J.:	
Opening Statement	5
Written Testimony	7
Murkowski, Hon. Lisa:	
Opening Statement	1
Westmoreland Mining LLC:	
Statement for the Record	325
Winberg, Hon. Steven E.:	
Opening Statement	31
Written Testimony	33
Responses to Questions for the Record	278

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TUESDAY, JULY 28, 2020

U.S. SENATE,
COMMITTEE ON ENERGY AND NATURAL RESOURCES,
Washington, DC.

The Committee met, pursuant to notice, at 10:08 a.m. in Room SD–366, Dirksen Senate Office Building, Hon. Lisa Murkowski, Chairman of the Committee, presiding.

OPENING STATEMENT OF HON. LISA MURKOWSKI, U.S. SENATOR FROM ALASKA

The CHAIRMAN. Good morning, everyone. The Committee will come to order as we meet this morning to examine the development and the deployment of technologies for large-scale carbon management, such as carbon removal, carbon utilization and carbon storage. This is something that I have personally been interested in for quite some time. I have had briefings over the years, including one very substantive one from one of our witnesses this morning, our former Secretary, Ernie Moniz. It is a subject that should captivate us all in terms of the potential, in terms of just the innovation that we are seeing take place at multiple different levels. So being able to explore that this morning is particularly welcome.

We had actually planned to hold this particular hearing months ago, in March before the COVID–19 pandemic took hold, so I am glad that we are able to return to it as carbon management will very likely prove to be an important option for reducing emissions and the impacts of climate change. Just a few years ago the concept of carbon removal was really focused on planting trees. It was not widely seen as a realistic approach that could be dramatically scaled. I do want to recognize that Senator Barrasso from this Committee has proposed a technology prize for direct air capture for over a decade now. He has been focused on this and has a vision to it as well.

It is now becoming clear that technologies to permanently remove carbon dioxide from the air and the ocean are not only real but they are needed and they are certainly worth pursuing. When coupled with the increased deployment of low- and zero-emission

technologies, carbon removal options can help offset hard to abate sectors and could eventually even help reduce atmospheric carbon dioxide levels. To me, this is very, very exciting. The technologies range from direct air capture facilities which filter carbon dioxide out of the air to techniques that combine natural processes like photosynthesis and the mineralization of rocks while ensuring that carbon dioxide does not reenter the atmosphere. Another crucial aspect of large-scale carbon management will be to ensure that the infrastructure to safely transport and store carbon dioxide is readily available and affordable.

Some companies are already making initial investments in carbon removal. Occidental Petroleum is partnering with the firm, Carbon Engineering, to build a large direct air capture facility in Texas that can utilize carbon dioxide for enhanced oil recovery. Other large companies, including Microsoft, have made significant commitments to invest in carbon removal technologies to physically offset their current and even historical emissions. A recent report from the World Resources Institute estimates that with enough investment across carbon removal technologies and infrastructure the United States could remove up to two gigatons of carbon annually by 2050. That is equivalent to 30 percent of our country's current greenhouse gas emissions. So it really puts it into context, the scale that we are talking about. It is also clear that much, much more research and development will be necessary before a variety of carbon removal technologies are commercially viable and able to operate at scale. I am excited to learn more about the policies that could support them whether it is new research and development or other approaches.

I would point out that our Committee has already taken initial steps to support carbon removal technologies. Senator Manchin's EFFECT Act, which is included in our American Energy Innovation Act, authorizes R&D programs at the Department of Energy to make large-scale carbon management a reality, including programs focused on carbon removal, carbon utilization and carbon storage. While we will focus on issues that are solely within our jurisdiction for this hearing, it is clear that efforts to scale up carbon removal research and development cross many different agencies. In recognition of this, based on recommendations from some of our witnesses here today, I am introducing a new bill with Senator Kyrsten Sinema which we are calling the CREATE Act. This bill establishes an Executive Committee at the National Science and Technology Council to coordinate interagency efforts on carbon removal research and development. That effort will be crucial as we look to effectively deploy resources to advance carbon removal technologies, and I am already looking to build on it with some other measures.

I am very pleased to welcome a great set of witnesses who are with us, in person and virtually, to tell us about the state of large-scale carbon management and what more we can be doing. I will introduce the panel after Senator Manchin gives his opening comments, but I do just want to acknowledge and thank you all for being here, again, at a hearing that I have been looking forward to for some months now, but really, it kind of came together late last year when Senator Manchin and I had an opportunity to meet

with Secretary Moniz and really started to appreciate the immense potential of these technologies.

Senator Manchin, I turn it over to you.

STATEMENT OF HON. JOE MANCHIN III,
U.S. SENATOR FROM WEST VIRGINIA

Senator MANCHIN. Thank you, Madam Chairman, for holding this hearing, and thank all of you for being here and all of you that are on virtually with us today also.

Climate change is not a theme we have shied away from in this Committee, in this Congress. I am happy to have such a distinguished panel before us today to continue the conversation on climate solutions and to do a deep dive into the full array of opportunities for carbon dioxide removal. So I want to thank you, again, for being here.

To frame our conversation today, we first need to agree on the facts, and I have always said this, "We are all entitled to our opinion, we are just not entitled to create our own facts," most importantly that CO_2 emissions are not just coming from the power sector. In fact, in 2018, the transportation sector accounted for 28 percent of the U.S. greenhouse gas emissions, the power generation sector was 27 percent, industry was 22 percent, commercial and residential was 13 percent and agricultural was 10 percent. Those figures make it clear we can't just be focused on the electric sector and power plants. We need to be thinking more broadly in finding solutions across all of these sectors. Concepts like carbon removal include technologies that capture carbon from a power plant, but it also includes capturing CO_2 right out of the ambient air and engineering natural processes like mineralization. Direct air capture technology, once mature, will be able to be deployed anywhere and carbon dioxide removal will help offset the emissions from all of the sectors that I just mentioned. This is necessary, a complement to a work that needs to be done to reduce emissions across the board in order to achieve global climate goals.

Leaders on climate policy and energy technology have noted that carbon capture, utilization and sequestration (CCUS) and CO_2 removal are critical technologies needed to address climate change, and the U.S. is leading on this front, a position we need to maintain and further advance, including allocating resources for these important technologies to get them deployed broadly, both here at home and around the globe. That is why I introduced the EFFECT Act which I am proud was incorporated into our bipartisan energy bill, the American Energy Innovation Act. The EFFECT Act would advance each part of the carbon capture, utilization and storage, including direct air capture and other related carbon removal technologies. Each of these are integrated components and the bill would focus on enhancing research and development and, just as importantly, demonstration and deployment for each piece of the puzzle, and it is backed up with an authorization of over $5 billion, including authorization for carbon capture demonstration projects and to establish a direct air capture test center, to provide testing capabilities for innovative direct air capture and storage technologies. Now I call these pieces of the puzzle, because we only realize the full picture when they are all in place.

Simply capturing the CO_2 is not enough and we have got to do something with it and we have got to be able to move it. I believe that CO_2 is a valuable element that we can put to good use in harnessing the economic systems to further bring down cost of addressing climate change. Scientists at the National Energy Technology Lab (NETL) in Morgantown, West Virginia, are working on novel ways of using CO_2 as we speak both to extract more value from carbon dioxide but also to use it as a way to decontaminate PPE and medical equipment. We are seeing more and more opportunities for carbon dioxide use from commercial, industrial and defense purposes, to medical and pharmaceutical applications. This is where innovation can help the economies of fossil fuel-rich states like West Virginia while also helping to address our climate challenge. Capturing and transforming carbon dioxide that would otherwise be hurting our environment into valuable products, truly, is a win-win, plain and simple. It just makes good sense.

I believe the United States can and should be the world leader in advanced climate solutions. We have the ingenuity to develop and deploy technologies that can put us on the right path to meeting our climate objectives while growing our economy in every state of the union. Given the right tools I know that we can get this done on the ground just as I saw West Virginians tackle SO_X and NO_X and particulate matter decades ago, and then we can export these emissions-reducing technologies around the globe because every country is in need of common solutions. We are all in this together. It is called "global" climate, not "United States" climate. Carbon removal would be a big part of the solution, and we need to have all of our options available to us.

I look forward to hearing from our witnesses today where we have focused our efforts to make that a reality. So thank you, Chairman Murkowski, I appreciate it.

The CHAIRMAN. Thank you, Senator Manchin.

As I mentioned, we have a great panel before us today. We are joined this morning here, in person, by the Honorable Steven Winberg. Mr. Winberg is the Assistant Secretary for Fossil Energy at the U.S. Department of Energy (DOE). We welcome him.

Online we have a friend to the Committee who has been before us many times, the Honorable Ernest J. Moniz, who is now President and CEO of Energy Futures Initiative. We have worked with him in his former capacity as Secretary of Energy. It is good to have you with us, Secretary Moniz. The Secretary is also joined by Joseph Hezir, who is a Principal at Energy Futures Initiative, and we are going to do a little bit of an unorthodox situation with our schedule here this morning to accommodate individuals. Secretary Moniz is going to present his statement first as he has scheduling concerns, and then Mr. Hezir will be here and available to answer questions with regard to the testimony that they have shared from Energy Futures Initiative.

Ms. Shannon Angielski is with us in person. She is the Executive Director for the Carbon Utilization Research Council (CURC). I think I mispronounced it. I believe it is Angielski. Okay, I will try harder on that one, thank you for being here, Ms. Angielski.

Online we have Dr. Julio Friedmann, who is from the Center on Global Energy Policy at Columbia University. We welcome him.

Back here in the Committee room, we have Mr. Sasha Mackler, who is the Director of the Energy Project at the Bipartisan Policy Center (BPC). We appreciate your input.

With that, we will go as I have indicated. We will start first with you, Secretary Moniz. You will provide your statement and then we will move back here to the Committee room and have Assistant Secretary Winberg speak.

So welcome back to the Committee. We look forward to your comments this morning.

Secretary.

STATEMENT OF HON. ERNEST J. MONIZ, PRESIDENT AND CEO, AND THE HON. JOSEPH HEZIR, PRINCIPAL, ENERGY FUTURES INITIATIVE, INC.

Mr. MONIZ. All right, Madam Chair, Ranking Member Manchin, members of the Committee, I share the pleasure of being back before you, and thank you for the opportunity to discuss carbon dioxide removal from the atmosphere and upper oceans. What may seem like a highly technical subject is, in fact, a central part of the portfolio needed to address global warming and provide optionality for mitigating its long-term impact, most especially in a state like Alaska that is exposed to major dislocations from a warming Earth. I'll reinforce many of the themes already put forward by Senators Murkowski and Manchin.

We are moving toward decarbonization of the energy economy and work generally toward massive reduction of greenhouse gas emissions across the economy as a whole. Science and observation provide the motivation. Increasingly, countries, states and cities are adopting very ambitious goals of net-zero emissions by mid-century and eventually net-negative emissions. This will be possible only if negative carbon technologies, in other words, carbon dioxide removal, or CDR, are deployed at gigaton-scale. The CDR Innovation Program needs to be supercharged starting now if we are to have the necessary optionality in time. The necessity of CDR is highlighted by the fact that not just the electricity sector, but also the harder to decarbonize sectors—transportation, industry, buildings, agriculture—must be addressed. CDR enabled optionality is especially important for this.

At the Energy Futures Initiative we laid out the research, development and demonstration program for the next decade. The cost to the federal RD&D program is just over $10 billion for this decade. Implementing such a program entails large-scale deployment over the next decades. The U.S. National Academies concluded that a ramp-up to 10 gigatons of CDR would be needed globally by mid-century to cumulatively constrain global warming. This would compensate for residual emissions that will be too difficult or expensive to eliminate in the necessary timeframe and will enable the possibility of eventually reaching net-negative emissions. The scale is daunting but possible. If all the removed CO_2 were geologically sequestered in its supercritical phase, the sequestration industry would be two to three times the scale of today's global oil production industry. That's why we advocate for a much broader portfolio of CDR options, including utilization of CO_2 in widely used commodities. We also support building the carbon sequestration indus-

try now following carbon capture from concentrated sources such as power plants and industrial facilities. This can be jump started by the 45Q tax credit supported by this Committee and other Congressional colleagues on both sides of the aisle.

There are many approaches to CDR. We bin them into three major categories: natural, such as afforestation; technological, like direct air capture; and technologically-enhanced natural, such as development of new cultivars with very deep root systems or accelerated weatherization of minerals like basalt. Our analysis led to a portfolio with 27 different elements as described in detail in my written statement for the record of this hearing. Considerable innovation is needed in this decade for economic scale-up by mid-century. This portfolio calls for participation by ten federal agencies and especially prominent roles in the Department of Energy, USDA and NOAA. About 45 percent of the funding would be assigned to DOE in our analysis.

Achieving effective coordination and portfolio planning and budgeting in management and evaluation and in reporting to Congress, the scientific community and the public will be challenging. Our recommendation is to establish a committee on large-scale carbon management within the National Science and Technology Council. The committee would develop a technological CDR, RD&D strategic plan, oversee task forces for more detailed RD&D roadmaps, coordinate budget planning and review with OMB, identify CDR candidate technologies or timely large-scale demonstration and provide an annual report at Congress. Each of the lead agencies would organizationally support this all-of-government initiative. In many parts of the portfolio, international cooperation through emission innovation would be effective in advancing our interests.

We have been very encouraged by the Congressional initiative supporting a major CDR program, the EFFECT Act and the American Energy Innovation Act and the recent House Select Committee on Climate Change report support CDR. This Committee's leadership is very much appreciated and is very important. The CREATE Act that Chairman Murkowski just mentioned will be another very important part of establishing a multiagency effort.

Again, thank you for the opportunity to offer these thoughts on CDR. My colleagues and I at the Energy Futures Initiative will be happy to elaborate further on any and all of the elements needed to advance a robust U.S. CDR program.

Thank you.

[The prepared statement of Mr. Moniz follows:]

ENERGY FUTURES INITIATIVE

Statement for the Record

The Honorable Ernest J. Moniz
13th Secretary of Energy

Before the
Senate Energy and Natural Resources Committee
July 28, 2020

Madam Chairman, Ranking Member Manchin and Members of the Committee:

I am pleased to have the opportunity to discuss with you today the issue of carbon dioxide removal (CDR), its role needed in addressing climate change, and the federal investment in Research, Development and Demonstration (RD&D) needed to enable deployment of CDR on a material scale.

My statement today will focus on three major areas, and in summary, makes the following points:

1. As noted in the recent report of the House Select Committee on the Climate Crisis, the world needs to move to a goal of net zero Greenhouse gas (GHG) emissions no later than mid-century and net-negative thereafter. The word "net" is critical. Significant contributions from CDR will be necessary to complement, and not replace, reductions in greenhouse gas emissions needed to meet science-based climate goals;
2. The U.S. will require large scale carbon management solutions – reaching gigaton scale – involving both carbon capture utilization and storage (CCUS) to mitigate current carbon emissions, and CDR to remove carbon previously emitted into the environment; and
3. Further innovation is required to advance all pathways for CDR. This will require a major, multi-year, multi-agency federal RD&D initiative to deliver the portfolio of CDR technological solutions that will be needed. The initiative needs to be goal-oriented, all-of-government, and efficiently and effectively implemented.

Much of this statement draws from the 2019 CDR study and report by the Energy Futures Initiative (EFI). That report, ***Clearing the Air***, provided recommendations and detailed implementation plans for a comprehensive, 10-year, $10.7 billion RD&D initiative to bring new pathways for technological CDR to commercial readiness. I am pleased to see that the report contributed to increasing Congressional awareness and action on this issue, beginning with dedicated RD&D funding for CDR in the FY 2020 (and hopefully FY 2021) DOE appropriations, recognition of the importance of CDR in the recent report of the

House Select Committee on the Climate Crisis and various legislative proposals in process in both Houses of Congress.

The EFI Report presented a CDR RD&D initiative encompassing a broad range of technological pathways and technologically-enhanced natural processes that can remove CO_2 from the environment including direct air capture (DAC); technologically-enhanced carbon uptake in trees, plants, and soils; capture and isolation of CO_2 in coastal and deep ocean waters; and carbon mineralization in surface and subsurface rock formations. Geologic sequestration and CO_2 utilization are essential elements of the CDR RD&D initiative, providing CO_2 disposition options for DAC and bioenergy with carbon capture and sequestration (BECCS) pathways.

The Report found that the wide range of scientific challenges required a whole-of-government approach that reaches the mission responsibilities and research expertise of 12 federal departments and agencies, with the Department of Energy (DOE), Department of Agriculture (USDA), and the National Oceanic and Atmospheric Administration (NOAA) playing key roles. The planning, budgeting, execution, and performance aspects of the CDR RD&D initiative will require effective coordination led by the Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB). At an international level, there are opportunities to collaborate with similar efforts in other countries under an expanded Mission Innovation (MI) initiative, which was launched at the 21st Conference of the Parties (COP21) in 2015.

To provide context for a more detailed discussion of the findings and recommendations in the report, I would first like to frame the discussion of why CDR is essential.

I. The Imperative for Carbon Dioxide Removal

Carbon is the fourth most abundant element on earth, and the natural carbon cycle is well known. Carbon dioxide emissions from the burning of fossil fuels, as well as anthropogenic emissions of other GHGs, has adversely altered the natural carbon cycle. The absorption of anthropogenic CO_2 in the oceans to date has led to ocean acidification with attendant adverse impacts on marine resources. The absorption of anthropogenic CO_2 in terrestrial—or land-based—systems has been relatively more benign and there have been efforts to expand terrestrial absorption by expanded tree planting for example.

A. The Adverse Climate Impacts from Anthropogenic GHG Emissions Are Increasingly Clear

Atmospheric CO_2 concentrations have been increasing at a rate of 2-3 parts per million (ppm) per year,[1] with a commensurate rate of warming of 0.2°C per decade. Consequently, the planet is currently on course to an average temperature increase of 1.5°C by as early as 2030, a level determined by the

Intergovernmental Panel on Climate Change (IPCC) to be a threshold for a range of risks to natural and human systems.[2]

The adverse climate impacts resulting from elevated atmospheric CO_2 concentrations and associated temperature increases, as well as elevated dissolved CO_2 in oceans, have already been observed and are increasingly clear. Over the past several years, the impact of extreme weather across the world, such as floods, hurricanes, and droughts of significant intensity and/or frequency, have underscored both the ferocity and costs of a changing climate and it is therefore un-surprising that support for action on climate change is growing with an increasing sense of urgency.

In 2019 record temperatures were seen in Paris (108.7°F), London (101°F), and Anchorage (90°F). In June 2020 Eastern Siberia registered its highest daytime temperature of 38°C (100.4°F) which, if verified, will be the highest temperature on record in the Arctic.[3] The recent wildfires in California offer another case in point: 12 of the state's 15 largest wildfires have occurred since 2000 and estimated costs of a single fire—the 2018 Camp Fire—are as high as $16.5 billion.[4] A major utility providing electricity and natural gas services, PG&E, was driven to bankruptcy. Climate change is increasingly recognized as a factor in the dislocation of significant populations in the developing world, especially in areas of strife, contributing to major geopolitical and humanitarian challenges. While Earth has seen major climate variation over its history, the pace of change today is well beyond that attributable to natural phenomena and is driven by human activity, especially from energy. These trends are consistent with decades of forecasts and predictions.

B. Efforts to Reduce Anthropogenic GHG Emissions Increasingly Focused on an Endpoint of Net Zero Emissions

In 2015, the U.N. Conference of the Parties (COP21) crafted the Paris Agreement, where some 195 countries agreed to take action to limit the rise in global average surface temperature to no more than 2°C above pre-industrial levels, with further ambition to limit warming to no more than 1.5°C.[5]

At the heart of the Paris Agreement are the Nationally Determined Contributions (NDCs), commitments by all Parties to "strive to formulate and communicate long-term low greenhouse gas emission development strategies". Unfortunately, the 186 countries that have registered NDC's are estimated to address only one-third of the needed emissions reductions for a least-cost pathway to stay below 2°C.[6]

In the U.S., CO_2 emissions from fossil fuel combustion in 2018 rose by 2.7 percent while economywide emissions likely increased by 1.5 to 2.5 percent. The next year, 2019, did see a return to decreased emissions from the 2018 level, but CO_2

emitted to the atmosphere has a cumulative effect, so atmospheric concentrations continued to increase. The COVID-19 induced economic downturn has led to a significant emissions reduction thus far in 2020, but the concern is that emissions will snap back dramatically once economic activity recovers, as was the case after the 2008-2009 Great Recession.

Even with the challenges of meeting the Paris Agreement 2°C target, a number of countries are urging commitment to the more stringent target of 1.5°C. The reasons for the revised target are compelling. According to the special report by the Intergovernmental Panel on Climate Change (IPCC) published only three years after COP21, "limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans" while a 2°C rise would bring with it greater increases in frequency and intensity of heavy precipitation in several regions along with an increase in intensity or frequency of droughts in others. [7]

Equally concerning, the U.S. Fourth National Climate Assessment released in 2019 noted that, "Without significant reductions, annual average global temperatures could increase by 5°C or more by the end of this century compared to preindustrial temperatures."[8] The report found that "Climate change creates new risks and exacerbates existing vulnerabilities in communities across the United States, presenting growing challenges to human health and safety, quality of life, and the rate of economic growth" and that "Without substantial and sustained global mitigation and regional adaptation efforts, climate change is expected to cause growing losses to American infrastructure and property and impede the rate of economic growth over this century."

Momentum has increased toward strengthening and accelerating the global emissions reduction target. Many economies have now shifted their focus toward the establishment of net-zero emissions targets by mid-century.[9] As of June 2020, 20 countries and regions have committed to net-zero emissions economywide or in their power sectors by the middle or end of the century. Of these 20 countries and regions, 12 have committed to net-zero for all GHGs by mid-century. In the U.S., 10 states and 25 cities—representing about 35 percent of the U.S. population—have adopted net-zero emissions targets (either economywide or electricity sector specific) by mid-century.

In 2020, there is growing consensus among scientists, policy makers and citizens that addressing climate change is now an urgent issue, and the reasons are clear. However, failure to take into account the practical aspects of economic and social need will produce political head winds for tackling the climate challenge. Former President Obama made this point in October 2016 during a White House South Lawn Panel Discussion on Climate Change moderated by Leonardo Di Caprio:

"…we're going to have to straddle between the world as it is and the world as we want it to be, and build that bridge…because we're actually recognizing that some people have some real concerns about what this transition is going to do to them…"

C. Carbon Dioxide Removal is Necessary to Meet Net-Zero and Net-Negative Emissions Targets

The IPCC has reported that the ability to stay below 2 °C would require a 25 percent decrease in CO_2 emissions by 2030 and achievement of net-zero emissions by 2070. Staying below 1.5 °C requires significantly more ambition: 45 percent decrease in CO_2 emissions by 2030 and net-zero by 2050. The report also noted that, in addition to mitigation efforts, carbon dioxide removal (CDR) on the scale of 100 to 1,000 gigatons (Gt) of CO_2 (cumulative) by 2100 would be needed to limit any potential temperature overshoot above 1.5 °C and also help compensate for residual emissions that may be too difficult or expensive to eliminate from the economy within the necessary timeframe.[10]

Meeting the target of net-zero emissions by mid-century, and net negative emissions thereafter, will require pragmatism. We face complex multi-dimensional social, technical, and economic challenges along the way and there are no silver bullet solutions. We cannot effect accelerated sustainable change of our massive energy systems without doing the hard work of building broad coalitions. Labor and business; NGOs and financial institutions; religious and military leaders; public and private sectors; and political leaders of all persuasions will need to work together towards a common end. Sustainable major societal changes in democratic countries have always required such broad coalitions. There are no short cuts.

We also need to recognize that the energy needs and challenges vary considerably by region, and clean energy solutions will need to take account of those regional differences, with social justice a key consideration. Insistence on "one-size-fits-all" solutions for all regions are a detriment to practical coalition building.

In the transition to net-zero we need a wide range of measures that will include energy efficiency across all economic sectors. Advanced renewables, such as offshore wind and advanced biofuels, will be essential. Electricity storage will help balance the system but cannot yet complete it; we need practical affordable storage not just for minutes and hours, but also for weeks, months and seasons. Energy security at the national and regional level will necessitate the development of secure supply chains, including for critical minerals and metals needed at much greater scale for expanded deployment of clean energy technologies.

Achieving net zero emissions by solely relying upon complete elimination of carbon from our energy systems likely will not be viable in the timeframes needed to address climate change. We also must develop the tools for large scale carbon management – CCUS and CDR. Negative-carbon technologies will also make possible, in the long term, a reversal of ever-increasing GHG concentrations in the atmosphere, thereby reducing the impact of past actions. CDR can thus compensate for residual emissions in difficult-to-decarbonize sectors like aviation that may be too difficult or expensive to eliminate from the economy, as well as address the problem of historical emissions created by the lack of past action on climate change. Removing CO_2 that previously was emitted to the atmosphere could assist in lowering CO_2 concentrations and help stabilize the climate at safer levels.

II. Large Scale Carbon Management—at Gigaton Scale—with CCUS and CDR

Large scale carbon management encompasses both the capture of carbon emissions from fossil fuel combustion as well as the direct removal of carbon already in the environment as a result of historical emissions. Carbon capture, utilization, and sequestration (CCUS) for both electricity and industrial facilities can be a major enabler of deep decarbonization; it also can foster large scale conversion of methane to hydrogen for cross-sectoral market applications. CDR from the atmosphere and upper ocean, employing a range of natural, technological and hybrid solutions, will enable net-zero and eventually net-negative emissions.

A. Scaling of CCUS is Underway

Regarding CCUS, the International Energy Agency (IEA) reports that "substantial progress has been made in advancing carbon capture, utilization and storage (CCUS) around the world, but current trends still fall well short of what would be needed to meet global sustainable energy goals."[11] The IEA notes that, as of December 2019, CCUS facilities around the world are capturing more than 35 million tonnes of CO2 per year, equivalent to the annual CO2 emissions of Ireland and that recently announced commitments "have the potential to more than double current global CO2 capture capacity." But the IEA's report also calls for a 20-fold increase in annual CO2 capture rates from power and industrial facilities in the next decade in support of climate goals. The IEA analysis underscores the view that international and sector partnerships and coalitions will be critical to achieving these goals.

B. CDR at Scale Also is Essential

CDR approaches also require significant scaling in order to have a material contribution to a goal of net zero emissions. The 2018 National Academies of

Sciences, Engineering, and Medicine (NASEM) report, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda,* estimated the need for CDR at a scale of approximately 10 $GtCO_2$ per year globally by mid-century and 20 $GtCO_2$ per year globally by 2100 to achieve climate goals while accounting for economic growth.

C. Establishing New Large-Scale Carbon Management Industries

Scaling of both CCUS and CDR to the levels needed to achieve net zero emissions will ultimately require the creation of large new carbon management industries as well as the development of substantial geologic storage capacity. The challenges are not insignificant, but the rewards will be substantial in terms of savings to the economy and creation of new jobs.

Capturing carbon from the environment at gigatonne scale, through CCUS and CDR, would require the creation of new industries comparable in size to the steel, concrete, and petroleum industries of today.[12] For example, 1 $GtCO_2$, when liquefied during subsurface sequestration, is nearly 9 billion barrels of supercritical CO_2, equivalent to twice the current annual U.S. domestic oil production. It is worth noting in the context of material scale that three of the major economic sectors in the United States emitted CO_2 at or near the gigaton scale through fossil fuel combustion in 2017: transportation (1.8 $GtCO_2$); electricity (1.7 $GtCO_2$); and industry (0.8 $GtCO_2$).[13] Therefore, an important feature of any comprehensive effort to develop and deploy CCUS and CDR pathways at material scale will be a strategic view of how to incentivize industries to actively support and adopt CDR into their business practices.

D. Scaling Geologic Sequestration Capacity to Support Large Scale Carbon Management

Sequestering CO_2 at the gigatonne scale also will require rapid development of geologic sequestration capacity. Fortunately, the U.S. has extensive geologic sequestration resource capacity and the technology for sequestration can be readily adapted from the experience of oil and gas production. Estimates of U.S. carbon storage potential range from 2,000 to 15,000 $GtCO_2$, with the vast majority in saline aquifers.[14] Other countries do not appear to have as abundant storage capacity: China, for instance, is estimated to only have storage space for roughly 140 $GtCO_2$ in its saline aquifers.[15] Several areas of the U.S. contain suitable geological formations, with ideal locations located on both sides of the Rocky Mountains, the Midwest, the Gulf Coast, and offshore of both the East and West Coasts. Development of an extensive CO_2 pipeline system would be necessary to connect other areas of the country to geologic storage operations.

The pathway identified by the IPCC to limit temperature changes under 1.5°C by the end of the century foresees a gradual shift in emissions from 40 $GtCO_2$–equivalent per year today to *negative* 20 $GtCO_2$ per year by the end of the century.[16] To put that in perspective, ***if the U.S. deployed 20 $GtCO_2$ CDR today, it***

could meet the entire planet's end-of-century sequestration needs every year for the next century, with room to spare.

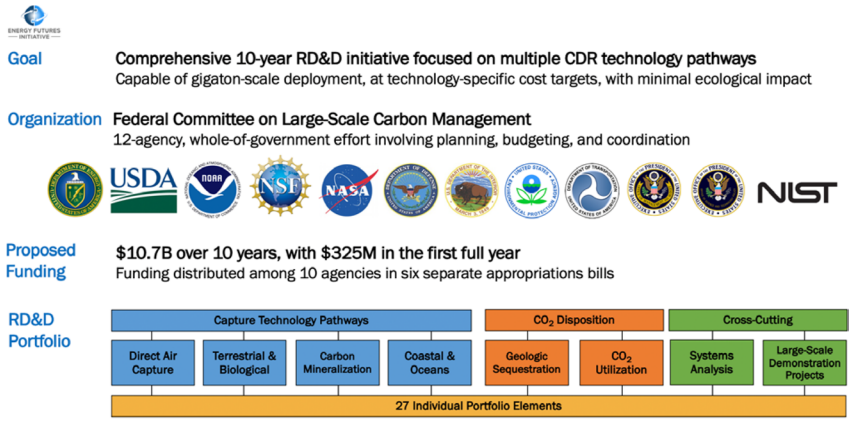
While the geologic capacity is available and the technology is known, there are economic and social challenges. The costs of drilling, compressing, injecting, and monitoring are estimated to be in the range of $20-25 per ton of CO_2.[17] When adding the cost of carbon capture, the total cost makes it difficult to break even with the current $50/ton 45Q tax credit for geologic sequestration, which itself is further complicated by time limitations on the credit. There could also be non-technical societal issues that would need to be resolved for Gigatonne scale U.S. sequestration. Consequently, many of the initial CCUS projects have focused on utilization of CO_2 for enhanced oil recovery, where the utilization sites were well established and the cost was offset from the value added from incremental crude oil production

III. The Proposed CDR RD&D Initiative

In 2019, the Energy Futures Initiative (EFI) published a major assessment of the need for, and design of a government-wide CDR RD&D initiative. The assessment drew heavily from a series of emerging reports on CDR, beginning with a 2016 Report by the Secretary of Energy Advisory Board and a 2018 Report by the National Academies of Science, Engineering and Medicine (NASEM). The EFI Report, ***Clearing the Air***, led by EFI principal Joseph Hezir, provided recommendations and detailed implementation plans for a comprehensive, 10-year, $10.7 billion RD&D initiative to bring new pathways for technological CDR to commercial readiness (Figure 1).

ENERGY FUTURES INITIATIVE

Figure 1
Overview of CDR RD&D Initiative



The CDR RD&D initiative is proposed to span 10 years and involve multi-agency collaboration and coordination.
Source: EFI, 2019.

A. Strategic Framework for the Technological CDR RD&D Initiative

The proposed technological CDR RD&D initiative is both goal-focused and time-focused.

The ***overarching goal*** of the CDR RD&D initiative is to provide policymakers a suite of technological CDR approaches that can safely augment the natural carbon cycle to complement mitigation efforts and reduce atmospheric CO_2 concentrations.

The ***strategy*** to achieve this overarching goal is to implement a comprehensive 10-year CDR RD&D initiative that will demonstrate the commercial readiness of multiple technological and technologically enhanced CDR pathways that can be deployed at or near gigaton scale.

The ***strategic elements*** necessary to enable successful achievement of the goal are summarized in Box 1. Several of these elements—the scope of technology options, the span of innovation support, cost targets, and deployment scale—merit further elaboration.

Box 1

Strategic Elements of the Carbon Dioxide Removal RD&D Initiative

- An effectively coordinated "whole-of-government" approach in addressing and coordinating CDR research needs;
- Incorporation of CDR into the strategic research mission objectives of the participating federal departments and agencies in a manner that creates synergy and complementarity with other national goals that can garner broad acceptance and be readily translated into specific projects with measurable progress and outcomes;
- A comprehensive and robust portfolio that:
  1.) Reflects the full range of potential CDR pathways;
  2.) Spans the full innovation spectrum from fundamental research to demonstration at scale;
  3.) Addresses near-, mid-, and longer-term research opportunities; and
  4.) Incorporates regional variation among technological CDR approaches.
- Clearly defined technology-specific cost objectives and commercial application potential;
- Carefully defined research protocols to fully address and promote collateral environmental and resource benefits and minimize any adverse environmental impacts;
- A logical and transparent initiative structure, with clearly defined management roles and responsibilities, and supporting budget plans, that can garner broad-based acceptance and be readily translated into specific projects with measurable progress and outcomes;
- Engagement with the international scientific community to accelerate the pace of RD&D progress and promote the application of CDR technologies on a global scale;
- A budget planning process reflecting the long-term nature of research projects, interagency coordination needs, and specific budget line item allocations;
- Effective and efficient utilization of the nation's technology innovation infrastructure; and
- Disciplined program management and accountability, including stage-gated processes and independent evaluations of program performance, with sufficient flexibility to change course when informed by research outcomes.

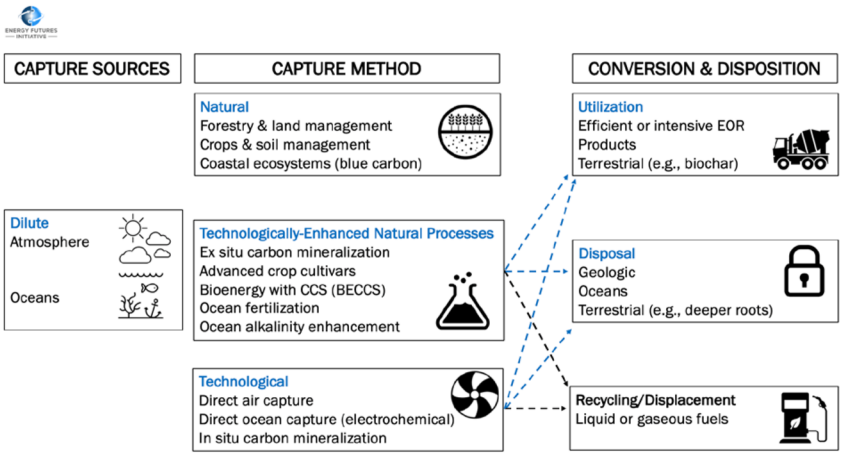
ENERGY FUTURES INITIATIVE

B. CDR Involves Multiple Technological Pathways

The three broad approaches to CDR, illustrated in Figure 2, are **natural, technologically enhanced natural processes** (or hybrid), and **technological** CDR from the atmosphere and oceans.

Natural CDR includes pathways such as afforestation, reforestation, soil carbon sequestration, and coastal ecosystem carbon uptake ("blue carbon"). Natural CDR pathways remove carbon from the atmosphere at gigaton (Gt) scale but are currently insufficient to offset anthropogenic emissions and thus cannot keep the carbon cycle in a net-neutral balance. The natural carbon cycle can be enhanced for example by expanding forested areas, avoiding deforestation, and preserving and expanding wetlands. These pathways already are the subject of considerable research studies and policy discussion. The potential scale of expansion ultimately is limited by competing uses of land for food and fiber production and human habitat.

Figure 2
Selection of Pathways for CDR from Dilute CO_2 Sources



There are a variety of natural, technologically-enhanced natural processes, and technological pathways that can facilitate CDR through the capture of CO_2 from dilute sources. Source: EFI, 2019.

The functioning of natural systems, however, can be ***technologically enhanced*** in various ways. Technologically enhanced natural processes include elements of

both natural and technological CDR and include pathways such as ex situ carbon mineralization, advanced crop cultivars, ocean alkalinity enhancement, and BECCS. The technologically enhanced CDR options (other than BECCS) also have the advantage or providing both capture and sequestration in the same process.

The third pathway is ***direct technological capture***, including DAC and electrochemical separation of CO_2 from seawater. These pathways do require some form of sequestration or utilization in order to achieve permanent disposition of the captured CO_2. Since some of these technological CDR pathways can capture CO_2 in a relatively pure form, there are a range of CO_2 utilization options that might be available.

It is extremely important to note that the scope of various pathways for CDR is distinct from geoengineering. Consistent with the IPCC methodology, CDR pathways discussed in the EFI Report focus on managing carbon as the means to address climate change, while geoengineering involves techniques that modify climate through other means, such as the management of solar radiation, but do not affect CO_2 fluxes or CO_2 atmospheric concentrations.

C. The Program Portfolio Structure for the CDR RD&D Initiative

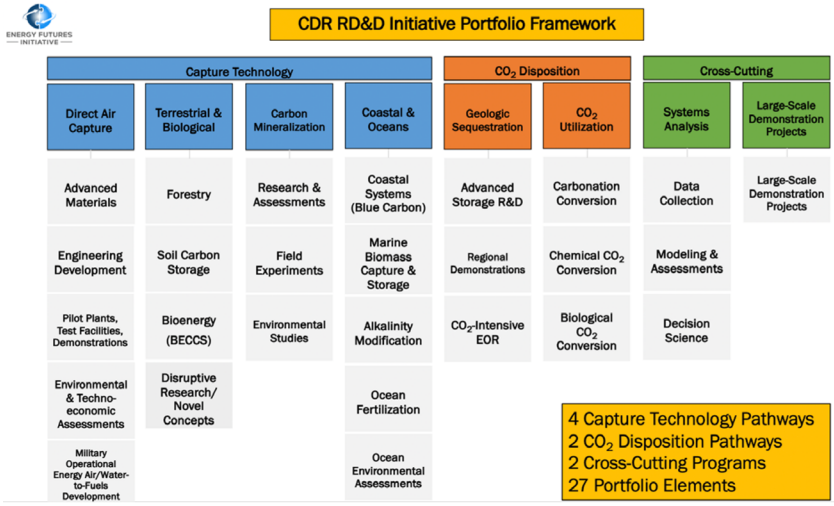
The proposed technological CDR RD&D portfolio framework consists of:

- ***Four capture technology pathways*** (DAC, terrestrial and biological, carbon mineralization, coastal and oceans). For the terrestrial and biological, carbon mineralization, and many coastal and oceans CDR pathways, sequestration is an integral part of the capture mechanism;
- ***Two CO_2 disposition pathways*** (geologic sequestration, CO_2 utilization). The two CO_2 disposition pathways are needed primarily to support DAC, BECCS, and oceans direct capture options; and
- ***Two cross-cutting programs*** (systems analysis, large-scale demonstration projects) that provide holistic or common support to all of the CDR pathways.

Figure 3 illustrates the portfolio design. The organization of the four capture technology pathways largely stems from those discussed in the NASEM report but were expanded to include CDR in the deep oceans. In total, the RD&D portfolio comprises 27 separate elements.

ENERGY FUTURES INITIATIVE

Figure 3
CDR RD&D Initiative Portfolio Framework



The CDR RD&D portfolio consists of four capture technology pathways, two CO_2 disposition pathways, and two cross-cutting programs. Source: EFI, 2019.

D. Direct Air Capture (DAC)

DAC uses heat and electricity to separate CO_2 from ambient air with various sorbent or solvent materials. DAC processes are energy intensive; low-cost, carbon-free process heat is a key requirement. Current cost estimates for DAC vary widely and are subject to considerable uncertainty. Little is known about its longevity under real-world conditions. However, DAC has a very large potential scale for CDR. The overarching RD&D objective for DAC is to reduce the cost and energy use and improve the performance and durability of DAC technologies to be a viable option for CDR. The components of the RD&D portfolio include: (1) fundamental research on the development of new sorbent and solvent materials; (2) applied research and development on components and system-level integration; (3) full-system scale up and manufacturing research; (4) research on cost, lifecycle emissions, and environmental impacts; and (5) applied technology development of air-to-fuels and seawater-to-fuels systems for military use at forward operating bases and at sea.

E. Terrestrial and Biological CDR

Terrestrial and biological pathways include increased growth of trees to store carbon as living or dead woody biomass (afforestation and reforestation), increased storage of carbon in the soil by crops and other herbaceous plants (soil carbon), and BECCS. Forest-related techniques require improved monitoring systems and expanded utilization and disposal options for woody biomass; soil carbon techniques require improved monitoring systems, the development of high-carbon-input crop cultivars, and better understanding of soil treatments; BECCS requires advances in biomass supply (including algae), as well as conversion to liquid fuels and electricity with carbon capture. Terrestrial and biological techniques are relatively mature, but their potential scale for CDR is limited by land availability and long-term permanence. The overarching RD&D objective for terrestrial and biological CDR is to develop new approaches for enhanced carbon uptake in trees, plants, and soils, in a manner consistent with advancing traditional food and fiber mission objectives. The components of the RD&D portfolio include: (1) enhanced monitoring systems, integrating modeling, and frontier techniques for forest carbon storage; (2) fundamental and applied research on carbon-relevant soil properties, soil carbon monitoring, advanced cultivars, biochar and reactive mineral impacts in agricultural soils, optimizing cultivation systems for carbon, and predictive modeling tool development; and (3) enhanced methods for biomass supply and pre-treatment (including algal biomass), and advanced technologies for biomass conversion to fuel, biochar, and biopower. High-risk, high-reward research on advanced CDR technologies relevant to agriculture are proposed for support through the Agriculture Advanced Research and Development Authority (AGARDA).

F. Carbon Mineralization

CO_2 naturally reacts with a variety of minerals to form carbonates, a process that leads to long-term solid storage of carbon. These reactions cause natural weathering of rock formations over thousands of years; carbon mineralization CDR techniques seek to accelerate this process, by using various sources of minerals and exposing them to CO_2 in a variety of ways. Challenges for these techniques include identifying sufficient supplies of reactive minerals, minimizing energy and transport costs for CO_2 exposure and carbonate disposal, and understanding environmental impacts from the process. The overarching RD&D objective for carbon mineralization is to enhance the understanding of the feasibility and potential for carbon mineralization as a CDR technology pathway. The components of the RD&D portfolio include: (1) fundamental research on geochemistry and rock physics to improve understanding of reaction rates and potential scale of CDR; (2) resource assessments to identify sustainable sources of reactive minerals; (3) applied research and field tests of surface and subsurface carbon mineralization methods (including mine tailings and industrial waste); and (4) research on environmental impacts.

G. Coastal and Oceans CDR

The oceans interact extensively with the atmosphere, and currently absorb a quarter of anthropogenic CO_2 emissions directly from air.[18] Coastal CDR techniques (also referred to as "blue carbon") include the growth of plants in coastal environments such as salt marshes, mangroves, and seagrass meadows, and subsequent natural burial of their biomass in coastal soil. Ocean CDR techniques aim to accelerate the absorption of atmospheric CO_2 by the oceans, storing it as dissolved bicarbonate and/or carbon exported to the deep ocean; other techniques focus on cultivating macroalgae at sea and using the resulting biomass for a variety of purposes, accompanied by CO_2 capture and storage. These techniques are all relatively immature, with some being almost entirely untested. There is little information about the potential costs, but the theoretical scale is extremely large, reflecting the fact that the oceans naturally regulate planetary atmospheric CO_2 levels over millennia. The overarching RD&D objective for coastal and oceans techniques is to develop a better understanding of carbon removal processes in coastal areas and deep ocean waters to provide the basis for determining feasibility of future CDR implementation measures. The components of the RD&D portfolio include: (1) fundamental research and resource assessment for blue carbon coastal techniques; (2) regional field trials and database development for coastal CDR; (3) applied research on aquatic biomass cultivation, harvesting, and conversion; (4) fundamental research and small-scale applied field trials of ocean alkalinity modification; (5) fundamental research and preparation for small-scale applied field trials of ocean iron and macronutrient fertilization; and (6) fundamental research and modeling on environmental impacts from ocean and coastal CDR techniques.

H. Geologic Sequestration

Sequestration of CO_2 in geologic formations is a critical enabling technology for CDR; without validated, at-scale sequestration capability, removed CO_2 cannot be permanently kept out of the atmosphere. Techniques for geological sequestration are relatively well understood, although new approaches beyond saline aquifer storage are in development. Key issues include accurate and low-cost resource characterization, monitoring, and at-scale demonstration. The overarching RD&D objective for geologic sequestration is to determine the potential for large-scale (at or near Gt scale) geologic sequestration as a permanent storage option for captured carbon. The components of the RD&D portfolio include: (1) applied research on a range of advanced storage topics including reduction of seismic risk, improved site monitoring, secondary trapping, and CO_2 fate and transport simulation; (2) augmenting the existing DOE CarbonSAFE program by adding additional sites and accelerating the timetable for full site characterization; (3) regional large-scale CO_2 injection demonstrations at multiple sites characterized under CarbonSAFE; and (4) applied research and demonstration of techniques to co-optimize CO_2 injection and oil production in enhanced oil recovery (CO_2-EOR).

I. CO_2 Utilization

There are multiple technology pathways currently under development to utilize CO_2 for economically beneficial purposes. The largest of these by current volume is CO_2-EOR, but others include the production of liquid fuels, building materials, plastics, commodity chemicals, and advanced materials; accelerating plant and algal growth; and food & beverage production. Many of these techniques remain energy intensive or cost prohibitive. While the feasible potential scale of CO_2 utilization will not reach the total required for CDR as discussed above, utilization can provide revenues to compensate for the costs of early CDR deployment and help with technology development. The overarching RD&D objective for CO_2 utilization is to accelerate development of innovative carbon conversion processes and new carbon-based materials through carbon mineralization, chemical, and biological conversion. The components of the RD&D portfolio include: (1) fundamental and applied research on carbonation reactions and process integration with CO_2 capture; (2) resource assessment on alkalinity sources for carbonation; (3) applied research and demonstration of CO_2-based construction materials for buildings and roads; (4) fundamental research and systems integration for chemical conversion of CO_2 including catalyst development and reactor design; (5) fundamental research on engineered organisms for biological CO_2 conversion and bioprospecting; and (6) applied research on co-products from biological CO_2 conversion.

J. Cross-Cutting Programs

The portfolio design highlights activities that span all CDR pathways and disposition options. An expanded carbon data collection effort is proposed to develop comprehensive lifecycle data on carbon flows in the economy. Independent techno-economic assessments will provide the capability to periodically assess technological CDR alternatives on a common basis with the credibility of a third-party perspective. The integrated carbon systems modeling program will assess systems-level impacts of large-scale CDR deployment, reflecting environmental, social, and economic issues. The decision science program will assess socio-economic issues, such as risk analysis and societal acceptance, associated with large-scale deployment of CDR approaches such as geological sequestration.

The proposed CDR RD&D portfolio includes a major cross-cutting element for large-scale demonstration projects. The CDR technology demonstration program is proposed as a cross-cutting initiative because it incorporates an innovative program design. Specifically, the CDR technology demonstration program:

- Will be a technology-neutral program, supported by a separate fund; major technology demonstration programs are not budgeted separately within each CDR pathway portfolio;

ENERGY FUTURES INITIATIVE

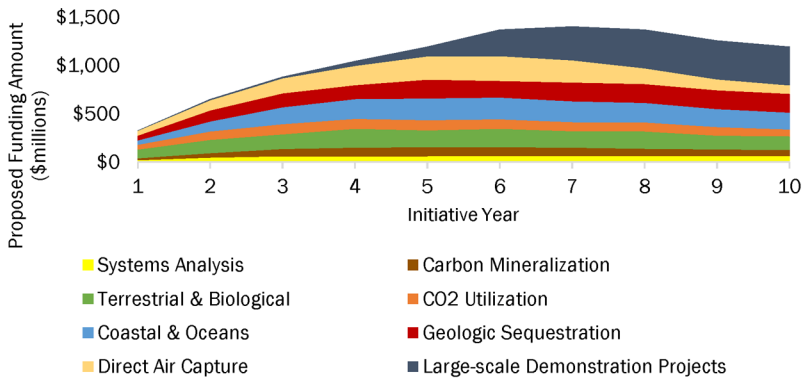
- Will support demonstration projects competitively, based on threshold qualification criteria; not all CDR technologies will qualify for large-scale demonstration;
- Will be initiated several years after the start of the CDR research programs, to take advantage of early research results and not commit prematurely to technology concepts that may need further maturation;
- Will be operated with flexible and innovative cost-sharing arrangements to take maximum advantage of the Section 45Q tax credits and emphasize incentives for demonstration project performance; and
- Will be managed centrally by a new demonstration program office with robust project management expertise.

K. Estimated Budget Planning Targets

Budget planning estimates were developed for each of the 27 portfolio elements. One or more agencies were identified to lead the RD&D work within each element, and the budget planning estimates reflect the proposed scope of work for that element.

The total RD&D initiative budget is estimated at $10.7 billion over the proposed 10-year span of the program (Figure 4). The proposed funding level for the first full year of the initiative is $325 million, with total initiative funding allocated among 10 federal departments and agencies.

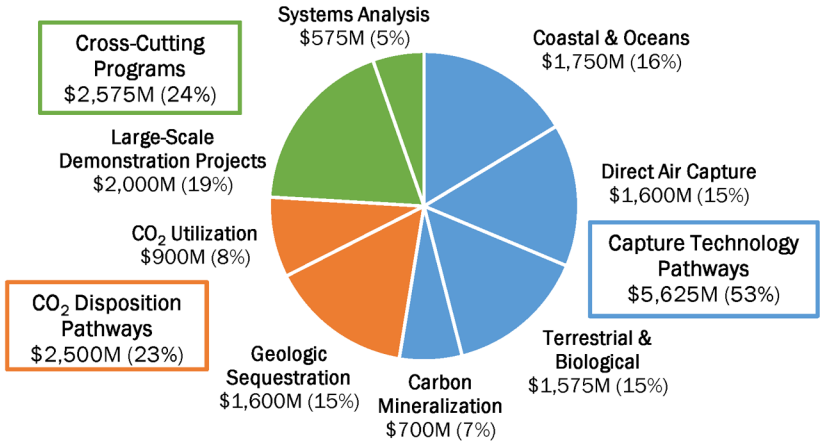
Figure 4
CDR RD&D Initiative Proposed Total Funding by Year



Proposed funding ramps to $325 million in Year 1 and peaks at $1,404 million in Year 7. Source: EFI, 2019.

The distribution of funding by portfolio component is illustrated in Figure 5. Funding for the four capture technology pathways totals $5,625 million over 10 years (53 percent), while funding for the two CO_2 disposition pathways and two cross-cutting programs totals $2,500 million (23 percent) and $2,575 (24

Figure 5
CDR RD&D Initiative Proposed Total Funding by Portfolio Categories



Proposed funding is divided between four capture technology pathways, two CO_2 disposition pathways, and two cross-cutting programs. Source: EFI, 2019

percent), respectively.

Achieving a diversified RD&D portfolio is essential, for several reasons.

- First, the alternative CDR pathways have widely varying degrees of technological maturity; the differences were clearly highlighted in the NASEM report. In short, it is too soon to declare a "winner."
- Second, because of the complexity of the carbon cycle, it is critical to understand the movement and interactions of carbon among the atmosphere, terrestrial biosphere, and oceans in response to removal of carbon in any one ecosystem.
- Third, while the various elements in the technological CDR portfolio may have Gt-scale deployment potential, there will be technology-specific limitations on deployment due to many factors. The NASEM report articulated the major factors, including land use and other environmental

constraints, energy requirements, and public support and institutional issues.[19]

- Finally, CDR pathways have strong regional characteristics that need to be reflected in the CDR RD&D initiative.

The CDR RD&D initiative will involve proposed funding for 27 offices or organizations across 10 federal agencies, with a prominent role for DOE, USDA, and NOAA. DOE is proposed to receive more than $4.8 billion in funding (45 percent of the total), while USDA, NOAA, and the National Science Foundation (NSF) are each proposed to receive over $900 million. Funding would be enacted through six appropriations bills: Agriculture; Commerce, Justice, Science; Defense; Energy and Water; Interior and Environment; Transportation, Housing and Urban Development (HUD).

I am pleased to see that Congress has made substantial down payments on the budget for the CDR RD&D initiative in the case of DOE. The FY 2020 Energy and Water Development Appropriations Act provided a total of $60 million to DOE across three appropriations accounts: $20 million in Fossil Energy (FE), $20 million in Energy Efficiency and Renewable Energy (EERE) and $20 million in Science. The pending FY 2021 Energy and Water Appropriations bill in the House would provide a further substantial increase to DOE, with $50 million to FE, $20 million in EERE and $25 million in Science. Hopefully the Senate will follow suit when it takes up FY 2021 appropriations. It is important that Congress consider the funding estimates for the other federal agencies as well.

L. Effective Federal Agency Organization and Management Structure and Processes

The proposed RD&D portfolio identifies research responsibilities for 10 federal departments and agencies, along with the participation of OSTP and OMB for the purposes of planning, budgeting, execution, and performance-tracking for the CDR RD&D initiative (Figure 6).[a]

Achieving effective coordination in portfolio planning, budgeting, performance management and evaluation, and reporting to Congress, the scientific community, and the public will be challenging. This challenge is not unique; the federal government has successfully implemented other interagency science and technology initiatives in the past, and the lessons learned can serve to guide the technological CDR RD&D initiative.

[a] A previous analysis identified a baseline of nine federal agencies that historically supported RD&D activities related to CDR, which could help provide a framework for a federal CDR RD&D initiative. Individual RD&D projects related to CDR were funded in 23 separate appropriations accounts contained in five different appropriations bills.

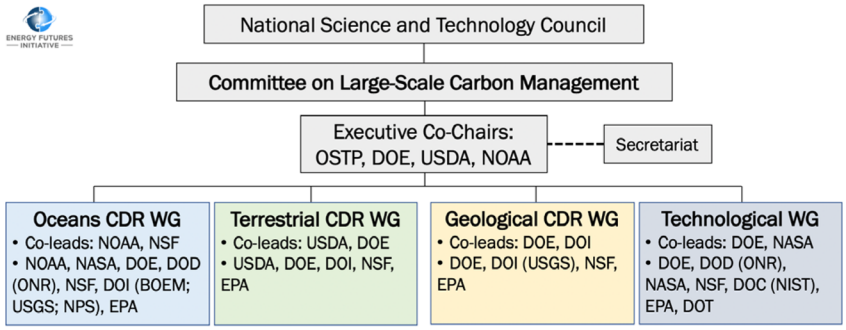
ENERGY FUTURES INITIATIVE

Figure 6
Federal Participation in CDR RD&D Initiative

Federal participation in the CDR RD&D initiative includes 10 agencies and EOP. Source: EFI, 2019.

Best practices were identified through a survey of lessons learned by experts involved in the implementation of prior federal interagency RD&D initiatives. Drawing from this assessment, the recommended organizational framework for the technological CDR RD&D initiative is outlined in Figure 7.

Figure 7
Interagency Integration and Coordination



The CDR RD&D initiative would be governed by a new entity within the National Science and Technology Council. Source: EFI, 2019.

The proposed initiative would be governed by a new entity, the ***Committee on Large-Scale Carbon Management***, to be established within the National Science and Technology Council (NSTC). The new committee would be co-chaired by an Executive Committee comprised of the OSTP Associate Director for Science, and senior officials from DOE, USDA, and NOAA. Co-leadership is essential to reflect the key roles and responsibilities of these organizations in the overall planning of the initiative.

The Committee would have a broad set of responsibilities including:

- Developing a technological CDR RD&D strategic plan;
- Overseeing task forces responsible for more detailed RD&D road-mapping;
- Coordinating budget planning with the agencies and budget review with OMB;
- Identifying candidate CDR technologies for large-scale demonstration;
- Overseeing independent evaluations of program performance; and
- Providing an annual report to Congress and the public.

It is recommended that OMB assist in the coordination of the technological CDR RD&D initiative by conducting an annual budget crosscut review. The budget crosscut would have two principal objectives: ensure that budget proposals from the program offices with technological CDR RD&D responsibilities are integrated with the overall budget for each participating department and agency, and ensure that the various OMB staff review and act on agency budget proposals for technological CDR RD&D elements in a holistic fashion. The OMB budget crosscut process can thus act as the "glue" to ensure that the CDR RD&D initiative is implemented in a fully integrated manner.

Implementation of these recommendations could be initiated by Presidential Executive Order. Congressional authorizing legislation would ultimately be desirable.

Three federal agencies in particular—DOE, USDA, and NOAA within the Department of Commerce (DOC), are proposed to be responsible to lead major elements of the CDR RD&D initiative. These three agencies have extensive existing research infrastructure and relatively large research and development (R&D) budgets that will require some realignment in order to effectively incorporate CDR RD&D into their mission objectives.

The recommended organizational structural and process changes for DOE, USDA, and NOAA include:

- ***DOE***: Establish an interim organization for Large-Scale Carbon Management within the Office of Fossil Energy, headed by a new Deputy Assistant Secretary selected on the basis of scientific qualifications appointed for a term basis. Longer term, Congress should consider re-establishing the Office of Under Secretary for Science and Energy, which,

among other benefits for Departmental management, would provide a more appropriate longer-term organizational home for the CDR program.

- ***NOAA***: Incorporate CDR as a new strategic objective within its Oceans Research Plan and establish a new Office of Ocean Technologies within the Office of Oceanic and Atmospheric Research, headed by the Chief Scientist.
- ***USDA***: Incorporate CDR as a new strategic element within the Department's research focus, incorporate CDR in appropriate existing research programs across the Department, and designate the Under Secretary for Research, Education, and Economics as the lead coordinator for all CDR-related research activities. USDA also should stand up the newly authorized AGARDA and assign CDR a high priority for this organization.

M. International Collaboration on Technological CDR RD&D

Other countries are currently moving forward with research initiatives on technological CDR approaches. Innovation in CDR technologies and approaches could be accomplished more effectively and rapidly if countries create durable RD&D collaborative frameworks that facilitate pooling of both intellectual and monetary resources. The implementation process emerging from the 2015 Mission Innovation initiative appears to have the characteristics needed to foster an effective and efficient international collaboration in technological CDR RD&D.

There are also facets of CDR that will specifically require international collaboration because they could have legal and regulatory impacts that cross borders. Several CDR pathways involve practices that are already governed by international law, such as ocean fertilization[b] or biological sequestration with genetically modified organisms.[c] Other pathways pose issues that are common to any country contemplating deployment of geologic sequestration. These include technical issues, such as induced seismicity, as well as legal and regulatory issues, such as monitoring, reporting, and verification (MRV) for sequestered carbon. Common legal and regulatory frameworks around these issues, built upon a shared understanding of the science and technology base, will be essential to ensure effective deployment of CDR on a gigaton scale globally.

Another important component of building durable international collaboration efforts is establishing ground rules for the management and sharing of intellectual property (IP). Safeguarding U.S. IP is crucial to stimulating innovation around CDR; without those protections, the economic motivation for innovation could be diminished. At the same time, knowledge-sharing across international borders is important to global deployment of CDR methods. The federal government will need to work closely with international partners to find the appropriate balance

[b] The London Convention/Protocol applies to this topic. The U.S. is a signatory to both agreements.
[c] The Cartagena Protocol applies to this topic, although the U.S. is not a party to this agreement.

between protecting the IP of CDR innovators while ensuring that all countries have the opportunity and incentives to deploy CDR at the needed Gt-scale.

Conclusion: Value Proposition from the Proposed CDR RD&D Initiative

The proposed CDR RD&D initiative is designed to offer significant value in several ways:

- The proposed initiative is highly focused to deliver commercial-ready CDR innovations within a decade to address the climate crisis. A $10.7 billion investment is small compared to the potential range of economic damage resulting from unchecked climate change.
- The CDR technological pathways provide additional optionality and flexibility to achieve net zero GHG emissions in order to limit temperature increases to a target of 1.5 degrees Celsius in the most cost-effective manner possible, as well as reverse atmospheric CO_2 concentrations resulting from past emissions.
- CDR RD&D innovations can also benefit other national research objectives in ocean ecosystems and fisheries restoration and management, forest and agriculture productivity, and resource conservation; and national security.
- The large-scale deployment potential for CDR innovation offers significant economic benefits in terms of new industries and new jobs on a global scale.

All of these factors shape the value proposition for a new federal CDR RD&D initiative.

I want to thank the Committee for its leadership in holding this hearing, and appreciate the opportunity to discuss this important issue with you today.

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[1] https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
[2] https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/
[3] https://earthobservatory.nasa.gov/images/146879/heat-and-fire-scorches-siberia
[4] "Extreme storms, wildfires and droughts cause heavy [insurance] losses in 2018," *Munich RE*, January 8, 2019, https://www.munichre.com/en/media-relations/publications/press-releases/2019/2019-01-08-press-release/index.html?ref=Twitter&tid=%23Natcat2018%20Year%20End%20report
[5] https://unfccc.int/news/finale-cop21
[6] https://www.unenvironment.org/resources/emissions-gap-report-2017
[7] https://www.ipcc.ch/sr15/chapter/spm/
[8] https://nca2018.globalchange.gov/
[9] https://www.wri.org/blog/2019/09/what-does-net-zero-emissions-mean-6-common-questions-answered

[10] https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/
[11] https://www.iea.org/news/carbon-capture-technologies-ready-to-make-major-contribution-to-climate-goals
[12] http://web.mit.edu/chemistry/deutch/policy/2018-ResOppCO2Utiliz-Joule.pdf
[13] https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf
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[16] https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf
Figure 2.5
[17] Redacted
[18] https://sos.noaa.gov/datasets/ocean-atmosphere-co2-exchange/
[19] https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda

The CHAIRMAN. Thank you, Secretary Moniz, and we appreciate your leadership in this arena. It is appreciated that you have taken the time to provide this this morning, and we will look forward to addressing our questions to Mr. Hezir with regards to your statement.

With that, we will now turn to the Assistant Secretary Winberg to update us on all the exciting things that are happening within the Fossil Energy Department over at DOE.

STATEMENT OF HON. STEVEN E. WINBERG, ASSISTANT SECRETARY FOR FOSSIL ENERGY, U.S. DEPARTMENT OF ENERGY

Mr. WINBERG. Chairman Murkowski, Ranking Member Manchin and members of the Committee, thank you for the opportunity to discuss the Department of Energy's work to advance large-scale carbon management. The Office of Fossil Energy is focused on R&D to maximize the energy and value that can be responsibly extracted from fossil energy resources. That R&D includes our flagship carbon capture, utilization and storage program. The International Energy Agency (IEA) describes CCUS as a linchpin technology in the lowest cost transition to a low-carbon economy. The U.S. continues to be the world leader in developing CCUS technologies. DOE is committed to advancing CCUS across the U.S. economy which is why the Department asked the National Petroleum Council to develop a study outlining the necessary policy required and investments, both government and industry, that would be necessary to broadly deploy CCUS over the next 25 years.

The actions recommended in the report which are consistent with the CCUS R&D happening at DOE would support major reductions in carbon dioxide emissions while supporting the growth of our economy. This year alone DOE has provided roughly $85 million for five projects through our CarbonSAFE initiative to develop geological storage sites that can hold a minimum of 50 million metric tons of CO_2 from industrial sources. We also plan to announce up to $46 million for engineering scale testing of next generation carbon capture technologies for coal and gas plants as well as engineering design studies for industrial sources and up to $12 million for technologies that directly capture CO_2 from the atmosphere—DAC technologies.

We're also conducting R&D on technologies to transform CO_2 into valuable products. At the same time, our Coal FIRST initiative is developing coal power plant designs with carbon neutral and even net-negative emissions when coal and biomass are combined with CCUS. These plants will have the flexibility that allows them to support our evolving electricity grid and some will be able to produce hydrogen which can play a significant role for electricity production, manufacturing and transportation, especially in heavy duty vehicles. On average, producing hydrogen from fossil energy with CCUS is less expensive than production from renewables, so we're focused on coupling Coal FIRST plants with CCUS technologies to enable carbon neutral hydrogen production from fossil fuels. This is in addition to our longstanding hydrogen R&D portfolio focused on solid oxide fuel cells, gasification and reforming technologies, hydrogen transport infrastructure, hydrogen storage

and technologies to use hydrogen for electricity generation, fuels and manufacturing.

Through our "coal to products" R&D we're developing technologies to use coal to produce products including carbon fiber, roofing tiles, foam products and substitute lumber. This isn't just theoretical, so I brought along a few examples with me to show you what we can do.

This is a decking material. This is a carbon foam material with a carbon fiber base on it. This can be used for fireproof wall material and aerospace applications. I also have a roofing tile made out of coal. Can you imagine building a house that is fireproof? With coal, that will be reality in the not too distant future.

[Mr. Winberg displays various samples of products made with coal.]

A recent DOE market analysis concluded that a mature coal to products manufacturing industry could employ hundreds of thousands of people and create over $1 billion in products, all from coal. Our coal R&D to expand coal's value chain is critical to realizing that potential.

We're also focused on developing a domestic supply of critical minerals, including rare earths, from coal and coal byproducts. Our goal is to validate the commercial production of these minerals. To that end, last month we announced our intent to provide $122 million to establish coal innovation centers that will focus on manufacturing products from coal and developing new methods to extract and process coal-based rare earths and critical minerals.

Chairman Murkowski, Ranking Member Manchin and members of the Committee, DOE is advancing clean energy technologies for carbon utilization and management across all of our energy resources. We appreciate the Committee's support for our efforts, and I look forward to answering your questions. Thank you.

[The prepared statement of Mr. Winberg follows:]

Testimony by Steven E. Winberg
Assistant Secretary for Fossil Energy
U.S. Department of Energy

Before the
U.S. Senate Committee on Energy and Natural Resources

Hearing to Examine the Challenges and Opportunities for Large-Scale Carbon Management

July 28, 2020

Thank you, Chairman Murkowski, Ranking Member Manchin, and Members of the Committee. I appreciate the opportunity to be here today and am excited to share with you the transformative work being done at the Department of Energy (DOE) to advance large-scale carbon management. A lower carbon economy will not be based on a single fuel or technology. Rather, it will require an "all of the above" approach employing nuclear, renewables, fossil fuels, carbon capture and storage, and efficiency, to ensure that the United States can achieve its energy and environmental goals, while simultaneously providing economic opportunity for all Americans.

Fossil fuels, which are primarily comprised of carbon and hydrogen, supplied roughly 80% of America's energy in 2019.[1] The Office of Fossil Energy's (FE) portfolio is focused on maximizing the energy and value that can be extracted from fossil energy resources in an environmentally responsible manner. This includes: advancing the development and deployment of carbon capture, utilization, and storage (CCUS); using natural gas, coal, biomass, and organic waste to produce hydrogen with carbon-neutral or even net-negative carbon emissions; and exploring innovative ways to convert carbon dioxide (CO_2) and "carbon ore" into value-added products.

[1]U.S. Energy Information Administration, U.S. energy facts explained (May 7, 2020), *available at* https://www.eia.gov/energyexplained/us-energy-facts/

DOE is leading the world on carbon management research and development. This year, DOE's Clean Coal and Carbon Management Program is making approximately $484 million available for innovative technology research and development. With this funding DOE expects to make up to 112 awards that will support the United States' carbon management efforts.

Carbon Capture, Utilization and Storage (CCUS)

Analysis by the International Energy Agency[2] (IEA) makes it clear that fossil fuels will play a major role as an energy resource throughout this century, and that CCUS is a linchpin technology.

If governments around the world decide to adopt the goal of a low-carbon economy, or the even more ambitious net-negative carbon future, then governments and industry must be even more serious about research and development (R&D) to advance CCUS technologies. It would be false hope to bet on any single fuel solution. While this Committee has a keen interest in and knowledge of energy technologies, many people do not fully appreciate the complexities, and scale, of the U.S. and global energy system.

The United States, through DOE, is leading the world in developing emissions reduction technologies with more than $4 billion invested since 2010 in carbon capture and storage technologies. With this investment and the largest carbon capture demonstration projects in the world, the United States will be in position to deploy low-carbon technology here at home, and export much of that technology to the rest of the world.

This year alone, DOE:

- Funded five projects through our CarbonSAFE initiative totaling approximately $85 million. These projects focus on development of geologic storage sites. Each site will have the capacity to hold a minimum of 50 million metric tons of CO_2 from industrial

[2]International Energy Agency, World Energy Outlook 2019 (Nov. 2019), *available at* https://www.iea.org/reports/world-energy-outlook-2019

sources. CarbonSAFE projects will improve the understanding of site selection, and geologic characterization, permitting and monitoring strategies for commercial-scale projects.

- Plans to announce up to $46 million in awards for engineering scale testing of next generation carbon capture technologies for coal- and gas- plants, as well as engineering design studies for industrial sources; and up to $12 million for technologies that directly capture carbon dioxide from the atmosphere (often referred to as DAC technologies).

These Funding Opportunity Announcements (FOAs) are summarized in the table below.

FOA Name / Brief Description	**$ Value (anticipated or actual)**	**# Selections (anticipated or actual)**
Carbon Storage Assurance Facility Enterprise (CarbonSAFE): Site Characterization and Post-Combustion CO_2 Capture Assessment	$85,320,375	5
Crosscutting Research for Coal-Fueled Power Plants	$4,500,000	3
Novel Concepts for the Utilization of Carbon Dioxide from Utility and Industrial Sources	$15,000,000	11
Carbon Capture R&D: Engineering Scale Testing for Carbon Capture from Coal- and Natural Gas-Based Flue Gas and Initial Engineering Design for Industrial Sources	$46,000,000	10
Novel Research and Development for the Direct Capture of Carbon Dioxide from the Atmosphere	$12,000,000	9
Research for Innovative Emission Reduction Technologies Related to Coal Combustion Residuals	$4,000,000	6
Energy Storage for Fossil Power Generation	$2,900,000	16
Total	**$169,720,375**	**60**

Developing nations rely and will continue to rely upon coal and other fossil fuels to power and grow their economies. Currently, the number of coal-fueled power plants developing nations are planning and constructing is double the amount that exist today in the United States. The U.S. Energy Information Administration (EIA) projects that by 2050, 9.5 billion short tons of coal will be used around the world. That is an increase of approximately 1.4 billion short tons a year from 2019. EIA also projects that natural gas and coal will generate nearly half the electricity around the world in 2050.

It often goes unrealized that the United States is the only country with major investments in the technologies needed to reduce CO_2 emissions from the world's coal-fueled and natural gas-fueled electricity fleet and industrial sources. These investments will enable coal and natural gas power plants as well as industrial facilities to one day operate at, or near, carbon-neutral levels. DOE's Coal FIRST (Flexible, Innovative, Resilient, Small, and Transformative) Initiative is developing coal-fueled power plant designs, with carbon neutral emissions, or net negative when coal and biomass are combined as a fuel. Coal FIRST plants are also being designed with operating flexibility that allows them to support the needs of the 21st century U.S. electricity grid including facilitating the increased use of intermittent renewable electricity technologies. Some of the designs also allow the production of hydrogen. DOE is making significant progress on Coal FIRST. This year, we have:

- Completed feasibility studies (also called pre-FEED studies) for seven advanced coal fueled power plants.
- Announced $37 million for R&D to advance component technologies for Coal FIRST power plants necessary to accelerate their development.
- Announced $81 million to support advanced engineering studies (also called FEED studies) for several Coal FIRST systems, including one or more studies on hydrogen production from mixed fuels (i.e., coal, biomass, and plastic waste) that will be carbon neutral or even have net negative CO_2 emissions.

The table below summarizes the FOAs.

FOA Name / Brief Description	$ Value (anticipated or actual)	# Selections (anticipated or actual)
Critical Components for Coal FIRST Power Plants of the Future	$37,000,000	7
Design Development and System Integration Design Studies for Coal FIRST Concepts	$81,000,000	3
Extreme Environment Materials for Power Generation	$20,000,000	2
University Training and Research for Fossil Energy Applications	$5,994,000	12
Small-Scale Solid Oxide Fuel Cell Systems and Hybrid Energy Systems	$30,000,000	10
Total	**$173,994,000**	**34**

In addition to reducing emissions from coal, natural gas and industrial sources, DOE recognizes the need to address orphaned oil and gas wells to reduce methane emissions. Historically, FE partnered with the Interstate Oil and Gas Conservation Commission (IOGCC) to address orphan oil and gas wells. DOE's involvement with IOGCC and states helped craft a priority system to identify the most potentially problematic orphan wells and make sure the highest safety and environmental at-risk wells were plugged first. DOE also co-funded the first Orphan and Idle wells report from the IOGCC. Additionally, investments have been made in drone technology to identify orphan wells that may not be visible to the naked eye.

Coal to Hydrogen

DOE is working collaboratively across its program offices, including FE, the Office of Energy Efficiency and Renewable Energy (EERE), the Office of Science, and the Advanced Research Projects Agency-Energy (ARPA-E) to further reduce the cost of many technologies to produce hydrogen. FE hydrogen-related R&D programs are focused on four major areas including the development of 1) gasification and reforming technologies for low-cost, carbon-neutral hydrogen production; 2) large scale hydrogen transport infrastructure, including system requirements to utilize existing pipelines and future pipeline infrastructure; 3) large scale on-site and geological

hydrogen storage; and 4) technologies to use hydrogen for electricity generation, for production of fuels, and in manufacturing processes.

Integral to our Coal FIRST program is the ability to produce hydrogen. Hydrogen will play a significant role in a low-carbon future, because it does not emit CO_2 when converted into electricity or heat. The transportation sector is now the largest carbon emitting sector in the U.S. economy and with its mobile sources is a difficult sector in which to address emissions. Electric vehicles are part of the solution, but hydrogen-fueled vehicles are also important to transportation carbon management.

DOE is also conducting R&D on Solid Oxide Fuel Cells (SOFC) to produce hydrogen from water electrolysis. Operated in reverse, SOFCs are called Solid Oxide Electrolysis Cells (SOECs). SOECs would enable a hydrogen production source for carbon-neutral transportation, industrial fuel, and energy storage. There are also applications for reversible SOFC/SOECs that generate hydrogen for storage in off-peak electricity periods and generate electricity during peak periods. Market analyses project significant growth in near-term to mid-term hydrogen demand and SOECs show the technical potential to be a versatile, clean, and reliable source of hydrogen.

CCUS technologies can enable carbon-neutral hydrogen production from fossil fuels by capturing CO_2 from gasification or steam methane reformation. This hydrogen can be used to produce electricity and thereby reduce carbon emissions throughout the electrified portions of the economy, and when used in fuel cells can transform the transportation sector, especially heavy-duty trucks, construction equipment, locomotives, and ships.

One of the challenges to increasing the utilization of hydrogen throughout the economy is the cost of production. The United States produces over 10 million metric tons of hydrogen per year primarily used in the petrochemical and chemical industries. One of DOE's major CCUS projects in Port Arthur, Texas combines carbon capture with steam methane reforming to produce hydrogen while capturing a million tons of CO_2 a year and storing it in a depleted oil field. Since 2013, the project has captured and stored over six million tons of CO_2. On average,

producing carbon-neutral hydrogen from fossil energy with carbon capture and storage is several times less expensive than using renewable electricity to produce hydrogen.

DOE's robust CCUS R&D program has produced some impressive successes. In selected applications CCUS is technically proven. DOE is working to reduce challenges for commercializing CCUS. The most significant challenge is the cost associated with carbon capture. DOE is working to reduce this cost to $30 a metric ton by 2030 in order for the technology to be economically justified in the commercial applications.

DOE understands that fundamental changes are necessary to the operating and economic environment in which fossil energy plants function. Also of critical importance is the need for a robust financing environment that provides market certainty to support the development of CCUS supply chains, commercial infrastructure, and private sector investment as our nation's infrastructure transforms over the next 30 to 50 years.

Commercializing and deploying CCUS technologies is a realistic and necessary path to reducing CO_2 emissions on a large scale. Financial incentives will be integral for jumpstarting CCUS deployment. One such incentive is utilizing section 45Q of the Internal Revenue Service code, which provides a tax credit on a per-ton (metric) basis for projects that successfully store or utilize captured CO_2 or other qualified carbon oxides. DOE has played an integral role in providing the Department of the Treasury with the technical expertise needed to advance the implementation of 45Q tax credits.

Much like renewable technologies twenty years ago, CCUS technology, while technically viable, is not yet broadly commercially viable. More work is needed to reach full commercialization, and a critical piece of this work is incentives such as 45Q. Industry is beginning to realize the value of CCUS because tax credits like 45Q contribute to making the technology financially viable, similar to how industry viewed solar and wind power decades ago. Continued investment from government and industry will continue to drive the price down. With such incentives, the private sector will greatly accelerate the time to widespread commercialization.

Another area of our R&D program is the work we are conducting through our Carbon Utilization Program to develop technologies to transform CO_2 and carbon-based wastes into valuable products in an efficient, economical, and environmentally-friendly manner. Research and development activities address the potential opportunities and challenges associated with integrating CO_2 utilization with various power and industrial plants, such as waste heat integration, wastewater reduction, flue gas contaminant reduction, and reduced energy demand. Developing advanced catalysts, reactor systems, and processes for more efficient conversion of CO_2 to valuable chemicals will provide a viable alternative to conventional manufacturing processes.

A critical challenge across utilization technology platforms is the cost-effective and energy-efficient utilization of CO_2 to make valuable products such as building materials, chemicals, and polymers. The efficiency of reaction conversion, the amount of CO_2 stored in a product, and energy use of these utilization processes also represent critical challenges that DOE can address.

The emerging field of CO_2 utilization encompasses many possible products and applications including fuels, organic and inorganic chemicals, food and feeds, construction materials, enhanced resource recovery (e.g., oil, gas, water, and geothermal energy), energy storage, and wastewater treatment. DOE recently announced $17 million in awards to 11 projects for the utilization of CO_2 from utility and industrial sources. These technologies will utilize CO_2 as the primary feedstock to reduce emissions and create valuable products to offset the cost of capture.

Coal to Products

The National Coal Council highlighted in its "Coal in a New Carbon Age" report last year, that there are growing opportunities to utilize coal in ways that go beyond fueling power plants or steel production. These opportunities include the development of advanced materials and advanced manufacturing and can provide a strong future for coal without end-use carbon emissions. With new opportunities to utilize the carbon value of coal, rather than the heating value as in power generation, FE is developing transformational technologies to enable domestic

manufacturing of building products such carbon fiber, graphene, and carbon foam from U.S. coal that have no end-use emissions, a superior product performance, and a better lifecycle.

For example, DOE has partnered with the Ohio State University to develop building materials that are made from coal and plastic that could be used for decking and other applications. DOE is also working with CFOAM in Triadelphia, West Virginia to develop non-combustible carbon foams made from coal. These foams can be shaped and machined into virtually any configuration and have the potential to be used in a wide variety of applications including fireproof wall materials and aerospace uses.

A recent DOE market analysis concludes that a mature coal-to-products manufacturing industry could consume over 200 million tons of coal annually, employ hundreds of thousands of people, and create over a $100 billion in valuable products from coal. DOE's coal to products research and development portfolio is critical to offering coal-reliant communities an alternative market for coal that focuses on coal's carbon value instead of its heating value.

This year DOE has taken several steps to advance the technologies for coal-to-products with awards of $14 million for Advanced Coal Processing Technologies for the research and development of coal-derived products, such as building materials and infrastructure components; technologies capable of continuously producing a carbon-based rigid foam from a coal-derived feedstock; and the application, validation, and integration of several carbon-based building products into carbon-based building structures

Critical Minerals and Rare Earth Elements

DOE is exploring the opportunity to develop an economically competitive and sustainable domestic supply of critical minerals (CMs) – including rare earth elements (REEs) – from coal. REEs, and the other 34 minerals designated as critical by the Department of the Interior, are integral to the way we live – and are important for America's economic growth and national security. Currently, the United States relies almost exclusively on China as our source for CMs

and REEs. This overreliance is unacceptable. DOE is working hard to reduce this reliance and to ensure a stable supply of U.S-produced and processed CMs, including REEs.

Research indicates that coal, as a carbon ore, holds great potential for sourcing CMs and REEs domestically in the United States The United States has the largest coal deposits in the world and the National Energy Technology Laboratory (NETL) estimates that U.S. coal deposits could hold nearly 11 million metric tons of REEs, which could sustain the U.S. market for many years to come. Regionally, the estimates are nearly 5 million metric tons from Appalachia and 6 million metric tons from western state basins in Montana, Wyoming, Utah, New Mexico, Arizona, and Colorado.

DOE, in partnership with universities, national laboratories, and industry, is developing technologies to test the economic viability of extracting these valuable REEs in a sustainable manner. In June 2020, DOE announced its intent to fund $122 million to establish coal innovation centers through the new Carbon Ore, Rare Earths, and Critical Minerals (CORE-CM) Initiative. These innovation centers will focus on manufacturing value-added, carbon-based products from coal, as well as developing new methods to extract and process REEs and CMs from coal. In addition, the CORE-CM initiative will assess regional differences in resource availability and opportunities for the recovery and processing of raw materials; develop new technologies for assessment of recoverable resources onshore and offshore; and develop advanced mineral extraction technologies that maximize production of mineral feedstocks to advance U.S. industrial interests and reduce the vulnerability to foreign supply chains.

The table below summarizes the FOAs.

FOA Name / Brief Description	**$ Value (anticipated or actual)**	**# Selections (anticipated or actual)**
Carbon Ore, Rare Earths, and Critical Minerals (CORE-CM) Initiative	$122,000,000	5

Economic Improvement of Rare Earth and Critical Materials Production from Domestic Coal-Based Resources in Pilot-Scale Facilities	$4,000,000	2
Coal-Derived Carbon Materials for Building, Infrastructure, and Other Applications	$14,000,000	11
Total	**$140,000,000**	**18**

DOE's ultimate goal is to conduct R&D that enables the commercial domestic production of CMs, including REEs, from coal and coal by-products in the 2030 to 2035 timeframe. DOE's R&D into U.S.-produced CMs and REEs is an investment in America's future economic growth and our national security.

Conclusion

DOE is making progress in advancing clean energy technologies that harness all forms of energy, including oil, natural gas, coal, nuclear and renewables. From utilizing coal to making products such as decking material, roofing tiles and wall board, to transforming coal into a carbon-neutral fuel like hydrogen, to lowering the cost of CCUS, DOE's research and development into these areas is transforming the world by creating economic growth opportunities, making air cleaner, and reducing energy poverty.

COVID-19 has created a period of significant economic uncertainty across this great Nation. Despite the challenges we may face in the coming months DOE remains committed to advancing energy technologies that will change the world.

We appreciate the Committee's interest, support, and commitment to providing DOE with the tools necessary to advance the Department's mission. I look forward to answering your questions.

Thank you.

The CHAIRMAN. Thank you, Assistant Secretary. That is a great update from the Department.

We will now turn to Ms. Shannon Angielski, who is the Executive Director, again, of the Carbon Utilization Research Council. Welcome to the Committee.

STATEMENT OF SHANNON ANGIELSKI, EXECUTIVE DIRECTOR, CARBON UTILIZATION RESEARCH COUNCIL

Ms. ANGIELSKI. Thank you, Chairman Murkowski and Ranking Member Manchin for the invitation to participate in today's hearing and with my friends on this distinguished panel.

By way of background, the Carbon Utilization Research Council is an industry coalition focused on technology solutions for the responsible use of our fossil energy resources. CURC's members span the entire value chain of the electric utility industry as well as state, university and technology research organizations, NGOs and labor unions. Members of CURC are at the forefront of their industries and partnering with the Department of Energy, or DOE, to develop and commercialize technologies that will transform the way the world uses fossil fuels. The reason we are participating in this hearing today is because international authorities recognize that fossil fuels will continue to be used both here in the U.S. and globally. It is how we manage the carbon dioxide, or CO_2, produced from the use of fossil fuels that will determine whether we are able to cost-effectively achieve mid-century emissions reduction goals and simultaneously enable all nations to prosper and benefit from economic growth and energy security.

It's already been said that the U.N. modeling shows that carbon capture, utilization and storage, or CCUS, is a necessary part of that solution set. In addition, the International Energy Agency modeled the contributions of different technologies to meet that mid-century two-degree scenario, and it shows that CCUS accounts for approximately 100 gigatons of needed global CO_2 emissions reductions by 2060. To put this into perspective, this would be achieved by the operation of 1,100 carbon capture systems on the equivalent of 500-megawatt coal-fired units or 3,200 natural gas combined cycle units which would need to be operating for the next 30 years.

So why is all of this important? CCUS is an ecosystem of several distinct processes, as Senator Manchin already pointed out. If there is one thing I want to leave you with today, it's to recognize the scale of infrastructure comprising the CCUS ecosystem, this includes the equipment necessary to capture CO_2, the transport method to move CO_2 to a storage site and the storage facility, whether the captured CO_2 is used for enhanced oil recovery, converted to other valuable byproducts or stored in a saline reservoir. Many CO_2 sources are not located near a storage reservoir so much of the CO_2 will be transported by pipeline, but this is nothing new in this country. It's transported daily throughout the country with over 4,500 miles of pipelines in operation. However, for CCUS to be successful, it would be necessary to permit and construct additional pipelines. That's why legislation has been introduced, a bill sponsored by Senators Barrasso and Whitehouse, the Utilizing Significant Emissions with Innovative Technologies (USE IT) Act, that

would ensure CO_2 pipelines are eligible for review, permitting review processes established by the FAST Act of 2015.

The second take-away from my testimony today is that solutions for large-scale CO_2 storage underpin the entire CCUS value proposition. Without large-scale CO_2 storage, the climate benefit of CCUS, including direct air capture and bioenergy with carbon capture and storage, cannot be realized. The good news is that the U.S. is recognized as a global leader in CO_2 storage with a mature U.S. oil industry and aided by DOE's world class carbon storage program. The U.S. has stored more than ten and a half million metric tons of CO_2 in saline and other geologic storage reservoirs to prove out the capability of safe and effective CO_2 storage. The regional carbon sequestration partnerships and the CarbonSAFE Initiative are two key components of the DOE program that will enable broad-scale geologic storage in the U.S.

CURC commends the Committee for advancing legislation that would support the entire CCUS ecosystem incorporated in the American Energy Innovation Act (AEIA), the EFFECT Act, sponsored by Chairman Murkowski and Ranking Member Manchin, will accelerate improvements to each of the critical components of CCUS that we have already described. CURC encourages passage of the AEIA and to continue efforts to conference the USE IT Act. I also want to point out that the U.S. is already paving the way for a CCUS industry. Approximately nine power sector projects are currently in different stages of development supported through grants provided by DOE. Many of these projects are being designed as the source of CO_2 that will be stored in CarbonSAFE projects, including like Project Tundra and the North Dakota CarbonSAFE project or the Basin Electric Dry Fork Station that will be coupled with the Wyoming CarbonSAFE project. In addition, approximately 14 non-power projects have been announced that are in various stages of development and cover other industries that we've already described. One in particular, the Wabash Valley Resources project in Indiana, for example, will capture CO_2 from their gasification plant and store the CO_2 in the Wabash Valley CarbonSAFE Reservoir. The project will be the first to produce zero carbon hydrogen from fossil fuels that will be used to generate electricity and produce hydrogen fuel for mobility.

There are a few federal policies that I'd like to highlight that can continue to promote CCUS deployment amidst the COVID–19 pandemic—two are enhancements to the Section 45Q tax credits. Many energy project developers do not have tax liability that enables the developer to benefit from tax credits and need to employ tax equity structures that create a revenue stream to the developer in return for tax equity investments into a partnership. Implementing elective direct payments would enhance monetization of those tax credits and allow project developers to elect to receive a direct cash payment from the Treasury instead of resorting to the tax equity market. There is precedent for providing this from the Recovery Act in 2009, but these payments were provided only for renewable energy projects. The other is that CCUS has only had a significant financial incentive in place since the passage of the FUTURE Act in 2018. While stakeholders are encouraged by the recent issuance of proposed regulations, the IRS did not propose regulations until

June 1 of this year. Extending the commence construction deadline by another five years will greatly enhance project deployment, particularly in a post-pandemic environment. Senators Capito, Whitehouse, Barrasso and Cramer introduced a bipartisan amendment to the American Energy Innovation Act to extend 45Q for five years, an effort supported by CURC.

In closing, CCUS and carbon dioxide removal technologies have not been deployed at the rate needed to achieve targets set out by international authorities, and sustained and robust policy support particularly through legislation like the EFFECT Act and coupled with Section 45Q tax credits will allow the U.S. to maintain leadership in carbon management technologies. Thank you.

[The prepared statement of Ms. Angielski follows:]

CARBON UTILIZATION RESEARCH COUNCIL
ADVANCING FOSSIL ENERGY SOLUTIONS

Written Testimony of Shannon Angielski

Executive Director

Carbon Utilization Research Council (CURC)

Before the

Senate Energy and Natural Resources Committee

Hearing to "Examine Development and Deployment of Large-Scale Carbon Dioxide Management Technologies"

CURC Testimony:

Policies in Support of the Carbon Capture, Utilization and Storage Ecosystem

Washington, D.C.

July 28, 2020

INTRODUCTION AND BACKGROUND

The Carbon Utilization Research Council (CURC) is an industry coalition focused on technology solutions for the responsible use of our fossil energy resources in a balanced, low-carbon generation portfolio. CURC's members include electric utilities and power generators that rely upon diverse sources for their electricity production, equipment manufacturers and technology innovators, national associations that represent the power generating industry, labor unions, fossil energy producers, and state, university and technology research organizations. Members of CURC believe that American fossil fuels and ingenuity in technology innovation will satisfy the world's growing appetite for affordable energy, improve energy security, improve trade through increasing exports of U.S. resources and manufactured energy equipment, create high-paying jobs, and improve environmental quality. To meet these important objectives, members of CURC are at the forefront of their industries and partnering with the Department of Energy to develop and commercialize technologies that will transform the way the world uses fossil fuels. Successfully achieving these objectives will require a robust and sustained set of policies to incentivize the development and deployment of low and zero-carbon fossil energy technologies that are necessary to achieve global climate targets and that can also contribute to a robust U.S. economy.

On behalf of CURC, I am pleased to testify before the Senate Energy and Natural Resources Committee to discuss efforts to develop and deploy large-scale carbon dioxide management technologies in the United States. Given the nature of CURC and our mission, my testimony will focus on technology innovation efforts in the power sector, particularly with respect to carbon capture, utilization and storage (CCUS), and how those efforts can be leveraged with other industrial uses of fossil fuels. Throughout my testimony, note that I refer to carbon capture, utilization, and storage as either "CCUS" or "carbon capture", and carbon dioxide as "carbon" or "CO_2.".

ROLE OF CARBON MANAGEMENT TECHNOLOGIES IN A DECARBONIZED FUTURE

The reason we are participating in this hearing today is because international authorities recognize that fossil fuels, due to its lower cost and widespread availability, will continue to be used both here in the U.S. and globally. It is how we manage the carbon dioxide produced from the use of fossil fuels that will determine whether we are able to cost-effectively achieve midcentury emissions reduction goals and simultaneously enable all nations to benefit from economic growth and energy security.

Fossil fuels will continue to play an essential role towards reaching a decarbonized future. The U.S. Energy Information Administration (EIA) projects that fossil fuels will still account for 50% of U.S. power generation[1] and 77% of total U.S. energy consumption in 2050 under current policies.[2] Moreover, EIA

[1] U.S. Electricity Information Administration. 2020 Annual Energy Outlook, Electricity and Renewable Fuel Table #54
[2] U.S. Electricity Information Administration. 2020 Annual Energy Outlook, Energy Consumption by Sector and Source

projects that, despite substantial projected renewable energy deployment, fossil fuel consumption will more than double globally by 2050, as fossil fuels are low cost, abundant and widely available in emerging economies.

The imperative and economic impact for building out carbon management technologies is clear. The United Nations Intergovernmental Panel on Climate Change (IPCC) has run several models for stabilizing emissions by 2050. Many models cannot limit warming to below 2°C above preindustrial levels if bioenergy, CCUS and their combination are limited.[3] In scenarios that could meet that objective without CCUS, mitigation costs rise by 138% compared to those with CCUS (IPCC AR5 report, 2014 table 3.2).

Mitigation cost increases in scenarios with limited availability of technologies [percent increase in total discounted mitigation costs (2015-2100) relative to default technology assumptions]				
Year 2100 CO_2 concentrations (ppm CO_2 – eq)	No CCS	Nuclear phase-out	Limited solar/wind	Limited bioenergy
Price increase to reach 450 (430-480)	138% (29 to 297%)	7% (4 to 18%)	6% (2 to 9%)	64% (44 to 78%)
Number of models that can achieve climate objective with the limitation of the technology	4	8	8	8

Figure 1: Summary of table 3.2 from IPCC AR5 Report showing that omitting CCS from the mitgation portfolio causes orders of magnitude higher costs than limiting other technologies. In addition, some models cannot even reach climate goals without CCS

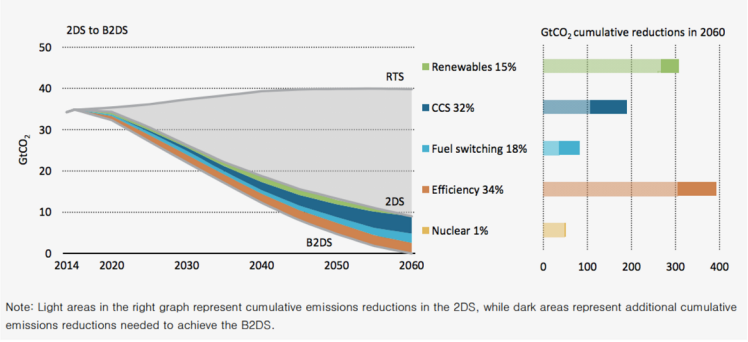

Figure 2: Technology Area Contribution to Global Cumulative Carbon Dioxide Reduction (Source: International Energy Agency)

[3] IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Figure 2 above shows the results of International Energy Agency (IEA) modeling and the contributions of different technologies towards achieving the emissions reductions required under IPCC modeling for a 2°C scenario and a below 2°C scenario. The graphic on the left shows the emissions reductions by a percentage total of each technology's contribution to achieving emissions reductions necessary to meet the below 2°C scenario. The solid bands in the graphic on the right show the emissions reductions measured in metric tons that would be achieved from each technology area to meet the 2°C target. CCUS accounts for approximately 100 gigatons of global CO_2 emissions reductions required to meet the goals of the 2°C scenario by 2060. To put this into perspective, this amount of emissions reductions would be achieved by the installation of 1,100 carbon capture systems on 500 MW coal-fired units or 3,200 natural gas combined cycle units by 2030 and operating those systems for the next 30 years.[4] At higher capture rates and/or when combined with sustainable biofuels or plastics, power generated from fossil fuels can achieve net-zero or even negative carbon emissions, which is important to the broader discussion of achieving deep decarbonization from dispatchable grid technologies.

The applications for CCUS also extends beyond the power sector. CCUS has a substantial role to play in the reduction of CO_2 emissions in the industrial sector, one in which fossil fuels will still account for 77% of U.S. energy consumption by 2050.[5] While some of these industrial processes can be electrified, many (e.g. steel production, some chemicals production, etc.) will continue to require the use of fossil fuels or other low- or zero-carbon sources of hydrogen. This is because the energy requirement for these industry sectors is high-temperature heat, for which there are currently few cost-effective and available alternatives to the direct use of fossil fuels. Moreover, certain manufacturing processes (e.g., cement production) release CO_2 as a byproduct of the materials used and apart from energy production. CCUS technologies are one in a limited set of technologies with the potential to dramatically reduce industrial sector emissions by capturing the emissions associated with these processes, helping to decarbonize a traditionally difficult-to-decarbonize sector.

IPCC modeling also shows that in order to achieve deep decarbonization goals, CCUS is required with carbon dioxide removal (CDR) technologies such as bioenergy with carbon capture and storage (BECCS) or direct air capture (DAC).[6] Importantly, both BECCS and DAC must be coupled with geologic storage of CO_2.

The U.S. is well-positioned to take a leadership role in the development of these CDR technologies. CCUS processes for bioenergy are similar to those used in conventional fossil fuel applications, and DOE has already incorporated BECCS into its traditional CCUS programs. While global deployment of projects

[4] This calculation assumes the coal plant operates at 75% capacity factor, the natural gas combined cycle plant at 60% capacity factor, and each with a 90% capture rate.
[5] U.S. Electricity Information Administration. 2020 Annual Energy Outlook, Energy Consumption by Sector and Source
[6] IPCC, 2018: Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. *World Meteorological Organization, Geneva, Switzerland, 32 pp.* https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf

utilizing BECCS is limited at this time, there is a commercial-scale demonstration project currently in operation in Decatur, Illinois (the Illinois Industrial Carbon Capture and Storage Project). There are also technology pathways by which biomass can be co-fired with coal (directly or gasified) or natural gas to create net-negative fossil fuel-fired power generation when combined with CCUS. Through its Coal FIRST program, DOE recently issued a funding opportunity soliciting proposals that evaluate technology pathways for co-firing of coal and biomass with carbon capture to create electricity and zero-carbon hydrogen at a competitive cost.

The U.S. is also making progress in the development of DAC technologies. Last year, Oxy Low Carbon Ventures and Carbon Engineering announced that they would partner to construct the first U.S. DAC demonstration facility in Texas, and DOE also continues to advance DAC technology research and development activities. Importantly, both traditional point source carbon capture, combined with NETs like BECCS and DAC, provide opportunities to leverage existing oil and gas industry expertise and infrastructure for CO_2 transport and storage, which together will enable us to achieve national and global decarbonization objectives.

INFRASTRUCTURE SCALE OF CARBON CAPTURE, UTILIZATION, TRANSPORT, AND STORAGE

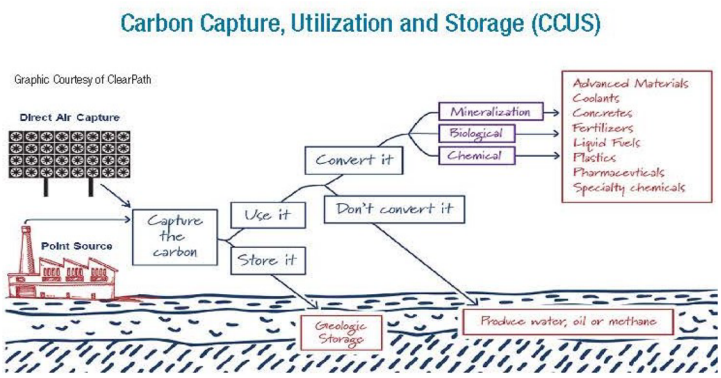

Figure 3: Carbon Capture, Utilization, and Storage (Source: ClearPath)

CCUS is an ecosystem of several distinct processes, each of which are necessary to prevent CO_2 from being released or to capture it directly from the atmosphere for permanent storage. It is therefore important to recognize the scale of infrastructure comprising an entire CCUS project – this includes the source at the site of capture, the transport method to move the carbon dioxide to the site of storage, and the storage facility – whether the captured CO_2 is used for enhanced utilization of oil, converted to other valuable products, or stored in a saline reservoir.

Ideally, CO_2 capture sites will be nearby, adjacent to, or co-located with the site of the CO_2 utilization or storage reservoir. This could be a distinct advantage for direct air capture facilities, which have more siting flexibility. While many industrial sources of CO_2 are close to feasible storage sites, a large majority

are not. That is why innovation must take place to identify new methods for converting carbon dioxide into useful products, such as cement, where the carbon dioxide is permanently stored in the product. It is important to recognize that the development of a CCUS industry is dependent on more than capture technologies. Large-scale storage sites for captured CO_2 and the infrastructure to deliver that CO_2 from source to sink are critical to the success of a CCUS industry.

As many CCUS projects cannot be co-located with large-scale storage reservoirs, the majority of CO_2 will be transported by pipelines to storage sites. For example, the Petra Nova project had to build an 82-mile pipeline to transport its CO_2 to the enhanced oil recovery (EOR) fields where the CO_2 is permanently stored. CO_2 is already being transported throughout the country for CO_2 use in EOR, with over 4,500 miles of CO_2 pipelines in operation. To access other industrial sources of CO_2 and transport it to geologic storage locations, it will be necessary to permit and construct additional miles of pipelines. Having streamlined and coordinated pipeline permitting will be important for CO_2 pipelines and large-scale deployment of CCUS.

Legislation has been introduced in both chambers of Congress, and cosponsored by Members of this Committee, that would authorize agency coordination for streamlined permitting of CO_2 pipelines. S. 383, the Utilizing Significant Emissions with Innovative Technologies (USE IT) Act, would ensure that CO_2 pipelines and other CCUS infrastructure are eligible for permitting review processes established by the FAST Act of 2015 and would direct the White House Council on Environmental Quality (CEQ) to establish guidance to assist projects developers and operators of that infrastructure. Adding CO_2 pipelines to the ten other industry sectors covered by the FAST Act is particularly important, as it would allow for early consultation and enhanced interagency coordination towards satisfying environmental reviews and meeting statutory deadlines.

The 2015 FAST Act also created the Federal Permitting Improvement Steering Council (FPISC). The FPISC is an independent oversight council to oversee the cross-agency Federal environmental review and authorization process. Currently, the FPISC oversees 21 current and prospective projects covering conventional energy production, electricity transmission, pipelines, renewable energy production, and water resources. These projects total $58.5 billion in current investment and project to provide 52,050 temporary construction jobs. Unfortunately, authorization for the FPISC under the FAST Act expires in 2022. Congress should permanently authorize the FPISC to ensure that these and future CCUS projects are best positioned to navigate complicated federal permitting processes.

As mentioned, there are also niche opportunities to convert CO_2 into other products, including chemicals, fuels, and cement. Figure 4 below illustrates most of the current and potential uses of CO_2. However, many of these uses are smaller in scale in terms of the volumes of CO_2 that are utilized and stored. Some of the more significant current and potential uses of CO_2 are highlighted in the research underway in this focus area, shown below.

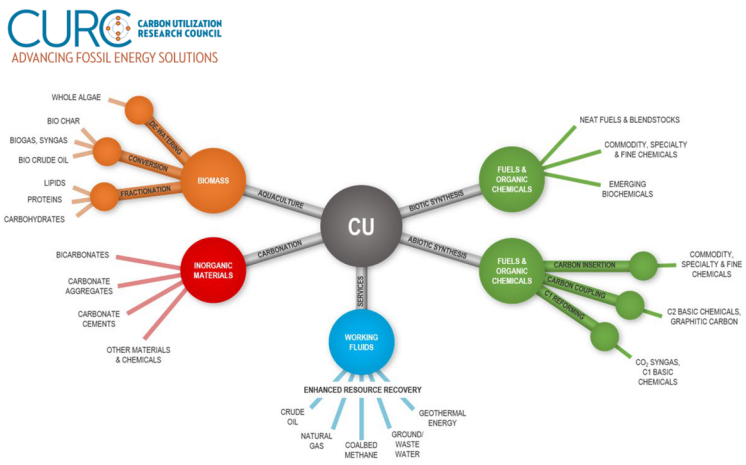

Figure 4: Carbon Utilization Pathways (Source: National Energy Technology Laboratory)

Solutions for large-scale storage underpin the entire CCUS ecosystem. Without large-scale CO_2 storage, the climate benefit of CCUS – including with DAC and BECCS – will not be realized. This is why the CURC-EPRI Roadmap recommends a broad program for CO_2 storage in geologic reservoirs in partnership with DOE.

The U.S., through DOE, is recognized as a global leader in the development of CCUS technology, aided by the DOE's world class carbon storage program. Over the nearly 20 years of the DOE carbon storage program, the United States has stored more than 10.5 million metric tons of CO_2 in a variety of geologic reservoirs to prove out the capability of safe and effective CO_2 storage[7]. The Regional Carbon Sequestration Partnerships (RCSPs) and the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) initiative are two key components of the DOE program recommended and advocated by CURC and being implemented by DOE that will enable broad scale geologic storage in the U.S.

The RCSPs have established a solid foundation for the success of CCUS deployment. Through R&D and a successful history of large-scale pilot tests across the country, the RCSPs have developed – and continue to develop – the geologic framework and infrastructure standards needed to validate carbon storage within each region of the U.S. The RCSPs focus on technology evaluation, resource assessment, regulations, and infrastructure needs working with industry and public stakeholders. The RCSPs have provided regional and technical expertise to identify a regional network of qualified sub-regions and locations for CarbonSAFE and commercial projects. The RCSPs also play a key part in characterizing CO2

[7] Sullivan, M, Rodosta, T, Mahajan, K, Damiani, D. An overview of the Department of Energy's CarbonSAFE Initiative: Moving CCUS toward commercialization. *AIChE J.* 2020; 66:e16855. https://doi-org.proxygw.wrlc.org/10.1002/aic.16855

storage resources and reserves, which is essential for locating projects with long-term storage certainty and creating increased business confidence.

Figure 5: DOE CarbonSAFE and RCSP Projects (Source: National Energy Technology Laboratory)

Early on, CURC members recognized the critical need for large-scale storage necessary to store the volumes of CO_2 anticipated to be captured from industrial processes, which is why prior CURC-EPRI Roadmaps recommended advancing carbon storage efforts that led to the CarbonSAFE Initiative. Building on the foundation and utilizing the expertise of the regional partnerships, this program is designed to advance large-scale carbon storage resources through development of integrated storage complexes that will characterize, monitor, and develop the data necessary for storage sites to apply for Class VI permits and be constructed for operation. These facilities will be designed to have high storage capacity potential in excess of 50 million metric tons of CO_2 over 30 years per storage site and will serve as regional repositories of CO_2. In alignment with the Roadmap, the CarbonSAFE initiative also takes into account the efforts for storage management (e.g., stacked storage, pressure management, storage hubs), storage complex modeling data, site development plans, regulatory issues, and public outreach, as well as efforts to transition to future commercial ventures. Importantly, the CarbonSAFE initiative will be synchronizing the sources of industrial CO_2 with the storage reservoir, as well as identifying, evaluating, and assisting in the permitting of the transport of CO_2 to the storage facility.

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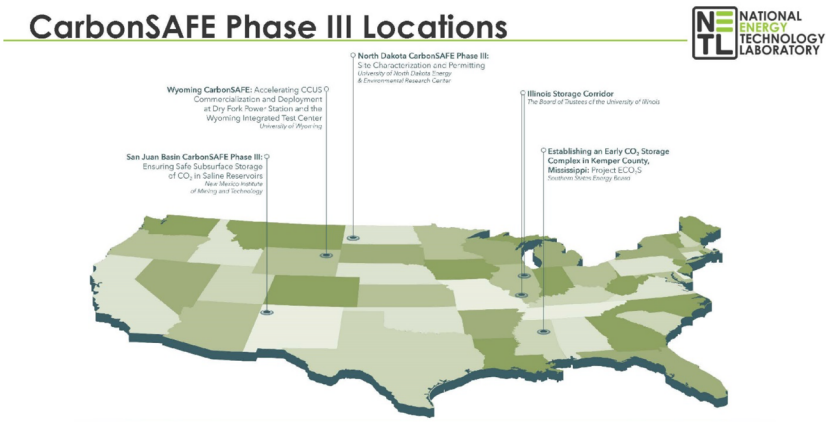

Figure 6: CarbonSAFE Phase III Locations (Source: National Energy Technology Laboratory)

CarbonSAFE Phase I awarded thirteen projects to undertake pre-feasibility and feasibility studies. Phase II awarded six projects to collect data, analyze the geology of the reservoirs including subsurface modeling and risk assessment, analyze contractual and regulatory requirements, and undertake public outreach. Phase III will undertake detailed site characterization, obtain Class VI permits for site injection wells, assess CO_2 capture systems, and obtain necessary NEPA approvals. Phase IV will obtain Class VI permits to inject, drill and complete injection and monitory wells, and complete construction of the sites.

There are currently five Phase III projects (See Figure 6). Due to limited funding, DOE was only able to select four Phase III projects, and a combined Phase II and III project. Increased federal funding would not only enable these projects to be accelerated but would also allow additional projects to be funded in other regions of the country. Funding for projects should be prioritized based on proximity of industrial sources to available geologic storage capacity, both onshore and offshore, to advance the commercial opportunities for CO_2 storage in the near term.

Policy Support for the CCUS Value Chain

CURC commends the Committee for advancing legislation that would support the entire CCUS ecosystem. The American Energy Innovation Act (AEIA), which includes the Enhancing Fossil Fuel Energy Carbon Technology (EFFECT) Act cosponsored by Chairman Murkowski and Ranking Member Manchin, will accelerate improvements to each of the critical components discussed above through increased funding and new program direction for the Department of Energy. Specifically, the bill would provide a much-needed reauthorization of DOE's Fossil Energy Research and Development program, authorizing funding for a coal and natural gas carbon capture technology program that includes new research and development activities, establishes a large-scale pilot project program, provides significant funding to support commercial demonstration projects of new CCUS technologies, and accelerates CCUS project

development by authorizing a front-end engineering and design (FEED) study program. Coal, natural gas, and negative emissions applications like co-firing of coal and biomass are all included in the program. The bill also includes funding and program direction for a new Carbon Storage Validation and Testing program which directly aligns with the CarbonSAFE initiative, the success of which will underpin all carbon capture efforts including BECCS and DAC. Finally, the bill would authorize first-of-a-kind Carbon Utilization and Carbon Removal programs at DOE, centralizing research on those technologies within the Office of Fossil Energy, where the appropriate expertise is currently housed.

CURC encourages the Senate to pass the AEIA as well as the USE IT Act. When taken as a whole, these pieces of legislation would make a dramatic impact on the entire CCUS ecosystem and spur the development of a CCUS industry in the United States, along with the jobs that would come with it. Enactment of the 45Q carbon sequestration tax credits is another key policy tool for catalyzing a carbon capture industry in this country, as seen by the number of CCUS projects in development. This policy is designed to lower the cost of implementing carbon capture by providing a tax credit for every metric ton of CO_2 that is captured from industrial processes or through DAC and stored in geologic reservoirs including oil reservoirs, or when the CO_2 is converted into other products like chemicals or used in cement production.

Project developers as well as investors are encouraged by the recent issuance of proposed regulations by the Department of the Treasury to understand how to be eligible for the Section 45Q tax credits. While there are still some outstanding issues that have yet to be resolved, the proposed regulations provide the guidance needed for investment to flow into projects and meet the commence construction deadline to claim the 45Q tax credits. For the record, there remain concerns that project developers are already up against the commence construction deadline, particularly in a post COVID-19 environment. To ensure this tax credit can be used in the way it was intended by Congress, it will be necessary to extend the deadline.

CCUS PROJECTS IN DEVELOPMENT

Several projects are in development due to the tax credit market established by the 45Q tax credits and DOE program support. The graphic below identifies nine projects that are developing FEED studies supported grants provided by DOE with federal funding appropriated by Congress in 2019. Many of these projects are being designed as the source of CO_2 that will be stored in the Phase III CarbonSAFE projects, including Project Tundra and the North Dakota CarbonSAFE project; the Basin Electric Dry Fork Station project that will be coupled with the Wyoming CarbonSAFE project, and the Prairie State Generating Station project that will be coupled with the Illinois Geologic Storage Corridor CarbonSAFE project, to name a few (a full list of CarbonSAFE projects are included in Appendix A to this testimony). Each FEED study project is an electric power sector project. Five projects will retrofit carbon capture on existing coal units, and four projects will retrofit carbon capture onto existing natural gas combined cycle units.

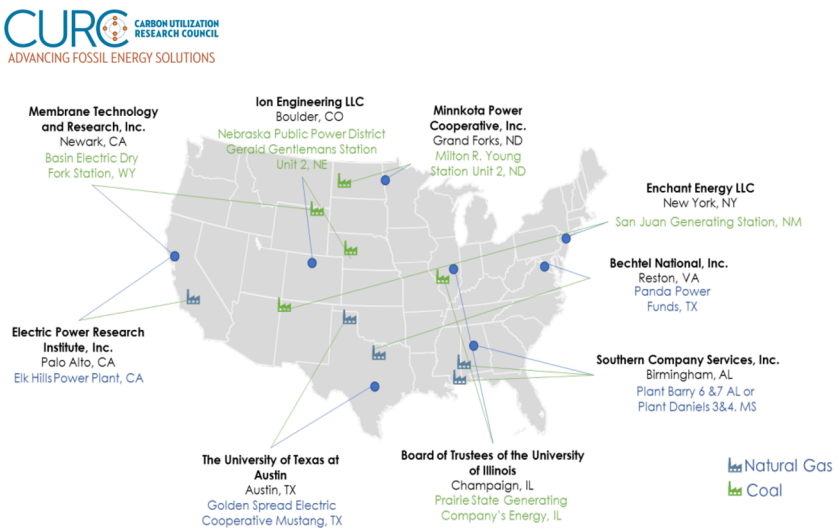

Figure 7: Existing FEED Study Projects (Source: U.S. Department of Energy)

At least 14 non-power projects have been announced that are in various stages of development and cover other industries, including ethanol and other biofuel production, petrochemical production, low-carbon hydrogen production, cement, and natural gas processing. The Wabash Valley Resources Project in Terre Haute, Indiana, for example, will capture and sequester approximately 1.75 million tons of CO_2 annually from their gasification plant and will store the CO_2 in the Wabash Valley CarbonSAFE reservoir. The project will produce zero-carbon hydrogen that will be used to generate electricity and produce ammonia with a zero-carbon footprint. This was the first U.S. investment made by the Oil & Gas Climate Initiative (OGCI). Several other projects are supported by OGCI as well as other investors including Oxy Low Carbon Ventures, which has several projects in development, and is an investor in new technologies such as CURC member NET Power's Allam cycle. A full list of U.S. projects in development is included in Appendix B.

FEDERAL POLICIES THAT CAN PROMOTE CCUS DEPLOYMENT AMIDST THE COVID-19 PANDEMIC

The COVID-19 pandemic has slowed global economic activity, leading to a drop in energy demand and prices. Quarantine conditions in nearly every country around the globe has also reduced manufacturing capacity, creating significant lags in supply chains. This is creating uncertainty in financial markets, where investors are less willing to make investments in first-of-a-kind projects that may have construction delays.

Direct Pay

Many owners of energy development projects do not have tax liability that enables the owner of the project to benefit from tax credits. For example, rural electric cooperatives and public utilities do not pay federal income taxes and therefore cannot benefit from tax credits themselves, though several rural

electric cooperatives and public utilities are developing CCUS projects. In such situations, project developers typically employ tax equity structures that create a revenue stream to the owner of the credit in return for tax equity investment into a tax equity partnership. Under these structures, tax equity investors take on a significant portion of the tax credit value in return for equity investment. Under normal circumstances, this is not an ideal financial arrangement. Implementing an elective direct pay mechanism would enhance monetization of the 45Q tax credits for CCUS project developers by allowing tax credit recipients to elect to receive a direct cash payment from the Treasury instead of resorting to the tax equity market to provide a discounted tax credit. This may be necessary as the COVID-19 pandemic may result in reduced tax liability and appetite for investors, which could dry up equity markets, making even tax equity partnerships difficult to secure. This would also open up CCUS project developers to the world of capital markets. Importantly, the COVID-19 pandemic is not impacting investment capital, so providing access to private sector investment capital can be achieved with direct pay.

There is precedent for providing a mechanism similar to direct pay for energy projects from the Recovery Act in 2009, which provided a grant in lieu of a tax credit, but these grants were provided only for renewable energy projects. The Congressional Research Service estimated that the cost of the Treasury Grant in Lieu of Tax Credit program was $31.4 billion between 2008 and 2017 (in 2018 dollars). Given that CCUS is still an emerging technology and in early stages of developing an industry in the U.S., providing treatment equivalent to the wind and solar industry could act to stimulate needed investments in CCUS and achieve similar results over the next decade.

Extension of Commence Construction Date for 45Q

CCUS has only had a significant financial incentive in federal law since passage of the FUTURE Act in February 2018. Moreover, IRS did not propose regulations related to the implementation and guidance of the 45Q credits until June 1, 2020. What was originally considered to be a six-year window for CCUS projects to begin construction to qualify for the credit has now been reduced to less than four.

Other low and zero-carbon technologies have benefitted from substantial federal support for decades. The Production Tax Credit (PTC) for wind energy was first enacted nearly 30 years ago in the Energy Policy Act (EPACT) of 1992, and the Investment Tax Credit (ITC) for solar energy became law 15 years ago as part of EPACT 2005. According to Congressional Research Service, the total tax expenditure for the ITC, PTC, and the Recovery Act grant in lieu of tax credit program from 2000 thru 2018 is $74.15 billion (2018 dollars). This does not include the robust federal investments in research and development that were made in renewables or the state and regional policies that helped by requiring purchases of renewable power over that same period. While CCUS is further along in the cost and deployment curve than wind generation was 15 years ago, it has not had the benefit of similar support until the enactment of the 45Q tax credits in 2018. The successful commercialization of renewable energy technologies offers powerful evidence for the critical role that government incentives play in scaling up needed technology deployment when given sufficient time to leverage private capital in the marketplace.

Extending the commence construction deadline for eligibility for the 45Q tax credits by another five years will greatly enhance project deployment, particularly in a post-pandemic environment, and will

come at a fraction of the cost of the wind and solar tax credit extensions. The Moving Forward Act (H.R. 2), which was passed by the House of Representatives on July 1, included a two-year extension of the 45Q commence construction date championed by Representative Terri Sewell (D-AL) coupled with direct pay. These provisions have a revenue estimate of only $493 million. A similar provision was included in the Growing Renewable Energy and Energy Efficiency Now (GREEN) Act (H.R. 7330) developed by the Democratic majority on the House Ways and Means Committee.

Senators Shelley Moore Capito (R-WV), Sheldon Whitehouse (D-RI), John Barrasso (R-WY) and Kevin Cramer (D-ND) also introduced a bipartisan amendment (S. Amdt. 1374) to the American Energy Innovation Act (S. 2657) to extend 45Q for five years, which was supported by CURC.

Section 48A Tax Credits

In 2005, Congress authorized $1.3 billion in investment tax credits designed to significantly improve coal generation efficiency, which in turn reduces emissions. Another $1.25 billion in tax credits were added to this program by Congress in 2008 but, to be eligible, a project had to install CCUS. Congress did not edit the underlying 2005 efficiency requirements for existing coal plants when it added the requirements for CCUS, so the tax credits have been ineffective for retrofit projects. As a result, there are approximately $2 billion of tax credits that have been reallocated by IRS and that remain available in the program. As there are no plans to build new coal plants in the U.S. today, the only opportunity to use these tax credits will be to retrofit existing coal plants. If changes are made to the statute and the tax credits are unlocked for use in retrofit projects, these tax credits could support six or more projects and could significantly reduce emissions of CO_2 from the existing fleet.

Bicameral and bipartisan legislation, the Carbon Capture Modernization Act (S. 407 / H.R. 1796), has been introduced that would remove the efficiency requirement and make some other technical changes to the eligibility criteria for effective utilization of the tax credits. This legislation was introduced in the Senate by Senators John Hoeven (R-ND) and Tina Smith (D-MN) and is cosponsored by Members of this Committee including Ranking Member Manchin (D-WV), John Barrasso (R-WY), and Steve Daines (R-MT). Enacting this legislation will unlock the nearly $2.0 billion in tax credits that remain in the program and support the application of carbon capture retrofits on existing coal plants.

Federal Grants

The federal government can also provide grant funding to deliver needed, up front capital investment for large-scale CCUS demonstration projects. As noted, the global market impact of the coronavirus pandemic will limit markets from financing several large, capital-intensive CCUS projects, putting them at risk of not being able to access private sector capital. Providing grants from the federal government will act as a substitute to the private sector capital that will be needed to finance CCUS projects. Federal grant support should also be provided to fully fund CarbonSAFE projects through Phase IV and provide additional funding for new projects, as the CarbonSAFE projects will act as the sink for the CCUS and NET demonstration projects, as well as provide continued funding for the Regional Partnerships to conduct relevant surveys and site characterizations to prepare regions for commercial CCUS deployment.

When combined with the 45Q tax credit, these projects will jump start a CCUS industry nationwide, assist the U.S. to meet its decarbonization objectives, and position the U.S. as a world leader in an emerging CCUS industry. Congress should consider enacting elements of the American Energy Innovation Act that would provide the necessary funding for these activities as an economic stimulus measure. There is existing precedent from the American Recovery and Reinvestment Act of 2009 that similar federal investments can spur economic growth and lead to job creation in the energy industry.

CONCLUSION

To date, CCUS and carbon dioxide removal technologies have not been deployed at the rate needed to achieve targets set out by the IPCC. The United States has taken a leadership role in the development of these critical technologies with a foundation already laid over the past 20 years. With sustained and robust policy support, particularly through legislation like the EFFECT Act and the LEADING Act, the U.S. can accelerate CCUS deployment and is doing so with the support of policies already enacted by Congress like the Section 45Q tax credit and targeted federal funding for a world-class research and development program at the Department of Energy (DOE).

IEA Executive Director Fatih Birol testified before this very Committee last year that U.S. leadership on CCUS is "extremely important". Passage of the AEIA, coupled with the Section 45Q tax credit model, will allow the U.S. to maintain this leadership and deploy CCUS technologies that can be used around the world.

CURC CARBON UTILIZATION RESEARCH COUNCIL
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APPENDIX A – CarbonSAFE Projects*

Phase I

1. Nebraska Integrated Carbon Capture and Storage Pre-Feasibility Study
2. Integrated Pre-Feasibility Study for CO2 Geological Storage in The Cascadia Basin, Offshore Washington State and British Columbia
3. Integrated Mid-Continent Stacked Carbon Storage Hub
4. Integrated Carbon Capture and Storage in The Louisiana Chemical Corridor
5. Northern Michigan Basin CarbonSAFE Integrated Pre-Feasibility Project
6. CarbonSAFE Rocky Mountain Phase I: Ensuring Safe Subsurface Storage of Carbon Dioxide in The Intermountain West
7. Integrated Pre-Feasibility Study of a Commercial-Scale Commercial Carbon Capture Project in Formations of The Rock Springs Uplift, Wyoming
8. Integrated Commercial Carbon Capture and Storage Prefeasibility Study at Dry Fork Station, Wyoming
9. CarbonSAFE Illinois East Sub-Basin
10. CAB-CS: Central Appalachian Basin CarbonSAFE Integrated Pre-Feasibility Project
11. Integrated Carbon Capture and Storage in Kansas
12. Integrated CCS Pre-Feasibility in The Northwest Gulf of Mexico
13. California CO2 Storage Assurance Facility Enterprise (C2SAFE)

Phase II

14. CarbonSAFE Illinois Macon County
15. Establishing an Early Carbon Dioxide Storage (ECO2s) Complex in Kemper County, Mississippi: Project ECO2S
16. North Dakota Integrated Carbon Storage Complex Feasibility Study
17. Wabash CarbonSAFE
18. Integrated Midcontinent Stacked Carbon Storage Hub
19. Commercial-Scale Carbon Storage Complex Feasibility Study of Dry Fork Station, Wyoming

Phase III

20. Illinois Storage Corridor
21. San Juan Basin CarbonSAFE Phase III: Ensuring Safe Subsurface Storage of CO_2
22. Establishing an Early CO_2 Storage Complex in Kemper County, Mississippi: Project ECO_2S
23. North Dakota CarbonSAFE Phase III: Site Characterization and Permitting
24. Wyoming CarbonSAFE: Accelerating CCUS Commercialization and Deployment at Dry Fork Power Station and the Wyoming Integrated Test Center

Source: National Energy Technology Laboratory

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APPENDIX B – U.S. Carbon Capture Projects in Development*

Projects in Early Development

Panda Energy
Facility Category: Large-scale CCS facilities
Operational: DOE FEED grant awarded
Facility Industry: Power – NGCC

California Resources Corporation / OGCI
Facility Category: Large-scale CCS facilities
Operational: DOE FEED grant awarded
Facility Industry: Power – NGCC

City of Farmington, NM / Enchant Energy
Facility Category: Large-scale CCS facilities
Operational: DOE FEED grant awarded
Facility Industry: Power – Coal

Nebraska Public Power / Ion Engineering
Facility Category: Pilot and demonstration CCS facilities
Operational: DOE FEED grant awarded
Facility Industry: Power – Coal

Basin Electric Dry Fork Station
Facility Category: Large-scale CCS facilities
Operational: DOE FEED grant awarded
Facility Industry: Power – coal

Minnkota Power
Facility Category: Pilot and demonstration CCS facilities
Operational: DOE FEED grant awarded
Facility Industry: Power – coal

Mustang Station of Golden Spread Electric Cooperative (GSEC)
Facility Category: Pilot and demonstration CCS facilities
Operational: DOE FEED grant awarded
Facility Industry: Power – NGCC

DTE Energy
Facility Category: Large-scale CCS facilities
Operational: N/A – multiple projects
Facility Industry: Industrial – biorefinery

Pacific Ethanol
Facility Category: Large-scale CCS facilities
Operational: N/A – pre-FEED, multiple sites
Facility Industry: Industrial – ethanol

Source: Clean Air Task Force

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Elysian / Starwood Energy Group
Facility Category: Pilot and demonstration CCS facilities
Operational: N/A – unavailable
Facility Industry: Unavailable

Clean Energy Systems
Facility Category: Pilot and demonstration CCS facilities
Operational: N/A – pre-FEED
Facility Industry: Power - BECCS

Glenrock Petroleum
Facility Category: Large-scale CCS facilities
Operational: N/A – unavailable
Facility Industry: Power - BECCS

Great River Energy Coal Creek Station
Facility Category: Large-scale CCS facilities
Operational: DOE FEED grant awarded
Facility Industry: Power – coal

Blue Flint Ethanol
Facility Category: Large-scale CCS facilities
Operational: DOE FEED grant awarded
Facility Industry: Industrial – ethanol

Red Trail Energy
Facility Category: Large-scale CCS facilities
Operational: DOE FEED grant awarded
Facility Industry: Industrial – ethanol

Illinois Clean Fuels
Facility Category: Large-scale CCS facilities
Operational: N/A – unavailable
Facility Industry: Industrial – BECCS

LafargeHolcim Cement Carbon capture
Facility Category: Large-scale CCS facilities
Operational: Mid 2020s
Facility Industry: Cement Production

OXY and Carbon Engineering Direct Air Capture and EOR Facility
Facility Category: Large-scale CCS facilities
Operational: Mid 2020s
Facility Industry: N/A

OXY and White Energy Ethanol EOR Facility
Facility Category: Large-scale CCS facilities

Operational: 2021
Facility Industry: Ethanol Production

Project ECO$_2$S: Early CO$_2$ Storage Complex in Kemper County
Facility Category: Large-scale CCS facilities
Operational: 2026
Facility Industry: Under evaluation

Velocys' Bayou Fuels Negative Emission Project
Facility Category: Large-scale CCS facilities
Operational: 2024
Facility Industry: Chemical Production

Project Under Construction

The ZEROS Project
Facility Category: Large-scale CCS facilities
Operational: Late 2020s
Facility Industry: Power Generation

Projects in Advanced Development

Cal Capture
Facility Category: Large-scale CCS facilities
Operational: 2024
Facility Industry: Power Generation

CarbonSAFE Illinois – Macon County
Facility Category: Large-scale CCS facilities
Operational: 2025
Facility Industry: Various

Dry Fork Integrated Commercial Carbon Capture and Storage (CCS)
Facility Category: Large-scale CCS facilities
Operational: 2025
Facility Industry: Power Generation

Fuel Cell Carbon Capture Pilot Plant
Facility Category: Pilot and demonstration CCS facilities
Operational: ?
Facility Industry: Power Generation

Gerald Gentleman Station Carbon Capture
Facility Category: Large-scale CCS facilities
Operational: Mid 2020s
Facility Industry: Power Generation

Integrated Midcontinent Stacked Carbon Storage Hub

Facility Category: Large-scale CCS facilities
Operational: 2025 - 2035
Facility Industry: Various

Lake Charles Methanol
Facility Category: Large-scale CCS facilities
Operational: 2022 (Institute estimate)
Facility Industry: Chemical Production

Mustang Station of Golden Spread Electric Cooperative Carbon Capture
Facility Category: Large-scale CCS facilities
Operational: Mid 2020s
Facility Industry: Power Generation

Plant Daniel Carbon Capture
Facility Category: Large-scale CCS facilities
Operational: Mid 2020s
Facility Industry: Power Generation

Prairie State Generating Station Carbon Capture
Facility Category: Large-scale CCS facilities
Operational: Mid 2020s
Facility Industry: Power Generation

Project Tundra
Facility Category: Large-scale CCS facilities
Operational: 2025 - 2026
Facility Industry: Power Generation

San Juan Generating Station Carbon Capture
Facility Category: Large-scale CCS facilities
Operational: 2023
Facility Industry: Power Generation

Supercritical CO_2 Pilot Plant Test Facility
Facility Category: Utilization Facilities
Operational: 2020
Facility Industry: Power Generation

Wabash CO_2 Sequestration
Facility Category: Large-scale CCS facilities
Operational: 2022
Facility Industry: Fertilizer Production

The CHAIRMAN. Thank you, Ms. Angielski.

We will now turn to Dr. Julio Friedmann, who is with us online. Good morning, Dr. Friedmann, welcome.

STATEMENT OF DR. S. JULIO FRIEDMANN, SENIOR RESEARCH SCHOLAR, CENTER ON GLOBAL ENERGY POLICY, COLUMBIA UNIVERSITY SCHOOL OF INTERNATIONAL AND PUBLIC AFFAIRS

Dr. FRIEDMANN. My pleasure. It is a delight to be here. Thank you, Madam Chairman, thank you, Ranking Member Manchin and thank you to the whole Committee.

Let me start by saying that already there are enormous good provisions around carbon management and related technologies in the American Energy Innovation Act, as many have said. These strong and important provisions include the five demos by 2025, including two in natural gas plants, those would be the first in the world. They include additions of CO_2 use and CDR to an innovation plan. They include the clean manufacturing provisions, reauthorizing ARPA-E for five years. These are all well worth doing. The provisions within the EFFECT Act, your leadership is extraordinary and welcome. In other committees, the Growing Climate Solutions Act, the LEADING Act, CITA, Carbon Capture Improvement Act, the enhancements to 45Q that Shannon Angielski just mentioned and, of course, the new CREATE Act introduced today by Chairman Murkowski. All of these are part of what we need to do. I cannot underscore enough that we simply are not where we need to be. We need to take greater actions and make swifter progress.

You have my detailed testimony and technical appendix. I want to highlight a few key aspects of it. The most important is the understanding of what net-zero means as framing. Net-zero is now the curve we're being graded on. It is the yardstick of merit, and net-zero is a clarifying concept. For any climate target of any kind at any stabilization level, any carbon taken from the earth must be returned to the earth. It must go back to the geosphere. This means, among other things, access to subsurface pore volumes as an essential component of the work. And again, things like the CarbonSAFE program that was mentioned by Assistant Secretary Winberg help provide that kind of insight and access.

Net-zero means that any residual emissions must be balanced by removal, as Secretary Moniz said. It means that reduction of CO_2 emissions and removal of CO_2 emissions are complementary but distinct actions and that both are necessary. The National Academies and the IPCC find that this must be done at enormous scale, exceeding the size of the global oil and gas industry today. We are not where we need to be to make this real. Toward net-zero, carbon management is the Swiss Army knife. Carbon management is versatile, flexible and, in many cases, it is the lowest cost option for CO_2 removal. We are working at the Center on Global Energy Policy to make this clear through a set of metrics called levelized cost of carbon abatement. That report will be coming out shortly.

But in many markets, for many applications, carbon management is the fastest and the cheapest pathway forward. This is particularly true in heavy industry, including steel, cement, chemicals, for LNG export, for refining. It is simply the fastest, cheapest way

to reduce emissions. It is also the case for making zero carbon hydrogen, as was mentioned by Assistant Secretary Winberg. Hydrogen is versatile and can be used for transportation, for heavy industry, for heating. Zero carbon hydrogen can be brought online quickly, in partnership with CCS. In the power sector, we recently did an analysis showing what kind of policy enhancements are necessary to get widespread deployment. They build on and move beyond the National Petroleum Council's recent report. You can find these at the Center on Global Energy Policy and in affiliation with Columbia University's new Climate School.

I want to spend the rest of my time talking about CO_2 removal, CDR. This is the climate counterstrike, and I ask the Committee to think about CO_2 removal as the biggest market of all time. We need all approaches, both engineered systems which I'm happy to discuss in depth as well as the work in managed ecosystems. This proof creates a concept of working lands where the work is done above and below. It's on the surface and in the subsurface. Direct air capture is the simplest to scale. Although it is the most expensive today, it is the one that is best suited to an innovation agenda, and the Energy Futures Initiative and Rhodium Group recently published reports on this. Again, access to the pore volume is essential.

I was pleased to hear Ranking Member Manchin discuss carbon mineralization. The U.S. has enormous reserves and opportunity and potential for this. Good work for the U.S. Geological Survey to consider. Bioenergy with CCS, BECCS, the United States is currently the leader on this worldwide and has opportunities to grow it and scale it dramatically in partnership with the U.S. Department of Agriculture. Forests, soils, also important, also worth pursuing and things within the purview of this Committee.

I would ask the Committee in closing to consider these as export opportunities and industrial opportunities for the U.S. Bringing CCS and CO_2 removal solutions to the world markets is good work that Americans want to take on. With that, I look forward to your questions and thank you for your attention.

[The prepared statement of Dr. Friedmann follows:]

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CONGRESSIONAL TESTIMONY OF **DR. S. JULIO FRIEDMANN**

Senior Research Scholar, Center on Global Energy Policy, Columbia Univ. School of International & Public Affairs

BEFORE A JOINT HEARING OF THE **COMMITTEE ON ENERGY AND NATURAL RESOURCES**, UNITED STATES SENATE, 2ND SESSION, 116TH CONGRESS

Chairman Murkowski, Ranking Member Manchin and Members of the Committee, thank you for inviting me here today to discuss issues of Carbon Management. My name is Julio Friedmann. I am a Senior Research Scholar at Columbia University's Center on Global Energy. From 2013-2016, I served as Principal Deputy Assistant Secretary for the Office of Fossil Energy at DOE, and before that served at Lawrence Livermore National Lab for 15 years.

It is an honor to appear again before this Committee to discuss carbon management broadly. Since my last congressional testimony 14-months ago, the nation and the world have changed dramatically, and I am compelled to acknowledge this extraordinary moment and its circumstances. The unprecedented COVID-19 pandemic has taken the lives of more than 143,000 Americans. It has damaged the US and global economy. and underscored inequity, racial strife and problematic aspects of our health care and judicial systems. It has also accentuated the central need for science and fact-based policy making, which adds import and salience to this hearing. Climate change is a looming threat – and a challenge that will strain greatly every aspect of our society and economy. The challenges demand courage, ingenuity, humility, and generosity to meet and overcome them.

These demands advise my own research at the Center on Global Energy Policy where I lead the Carbon Management Research Initiative. Our team draws on the broad and interdisciplinary expertise of scholars across Columbia University, including scientists, lawyers and former policymakers at the Earth Institute, the Sabin Law Center, and the Schools of Earth Science, Engineering, Law, Medicine, International and Public Affairs, as well as Columbia's burgeoning School of Climate,

It is abundantly clear that if we are to counter the risks of climate change, protect our economy and maintain our global competitiveness, we must pursue technologies that manages emissions by reducing and removing CO_2. These include conventional carbon capture and storage (CCS), CO_2 use and recycling, and CO_2 removal (both through managed ecosystems and engineered approaches). All are essential components of combining rapid, deep decarbonization with a muscular economy.

These technologies are essential for the energy sector, especially for power generation and heavyl industries. They are beginning to contribute to every other sector of our economy –

manufacturing, forestry, farming and high tech. Our research shows these technologies often present the lowest-cost, most actionable pathway for profound emissions reduction and that in some sectors they are the only pathway.

New studies by groups like the International Energy Agency,[1] Global CCS Institute,[2] Goldman Sachs,[3] McKinsey[4] and the Energy Transition Commission[5] have underscored carbon management's essential component to supporting both economic growth and rapid, deep decarbonization. It should be clear from all of this that carbon management deployment is not some greenwashing or a license to pollute. Quite the opposite – it is an overt, committed pathway to deeply and quickly reduce greenhouse gas (GHG) emissions in a cost-effective way while sustaining economic growth and communities at risk – from Alaska Natives living a subsistence lifestyle along the North Slope and the fishermen and oil workers in Prudhoe Bay to the miners, roughnecks, and biotech workers in West Virginia and Kentucky. Leading US companies and institutions have adopted carbon management strategies as part of their business plans, creating new companies and services to provide carbon management to rapidly growing global markets.

My testimony will focus on large-scale carbon management, including carbon capture and storage (CCS); CO_2 use and recycling; CO_2 removal, including engineered and managed ecosystem approaches; the need to invest in innovation; and the implications for competitiveness & industrial productivity. I'll also comment on how government agencies can help the US maintain leadership, sustain jobs and communities, innovate quickly, and rapidly reduce carbon pollution.

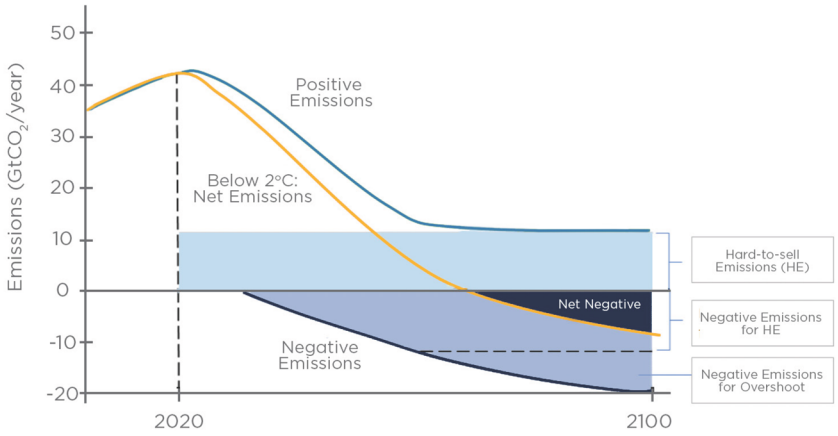
Net-zero Framework: Climate and US Competitiveness

Core to the continued and growing interest in carbon management is the recognition that national and global economies must achieve net-zero greenhouse gas emissions. Importantly, this is required to achieve ANY climate stabilization target. If net-zero emissions are not achieved, atmospheric concentrations of greenhouse gases will increase, as will the risks and damages from climate change, with which you are familiar. That is true for stabilization at 1.5°C, 2°C, 3°C or higher. Net-zero is the core arithmetic to stabilize climate: ***any residual CO_2 emissions must be balanced by an equal amount of CO_2 removal***.

$$CO_2 \text{emissions} - CO_2 \text{removals} = 0$$

By definition, achieving net-zero emissions requires that any emissions that are not *reduced* must be *removed*. To achieve net-zero emissions, all emissions trajectories must decrease (figure 1). However, if there are any residual emissions that are not reduced or mitigated, net-zero requires an equal mass of CO_2 removal. In many scenarios and descriptions, residual emissions are considered "hard-to-abate," meaning either the cost is extremely high (e.g., for aviation) or the technology does not exist (e.g., application of fertilizer).

Figure 1: Representative pathway to net-zero and net-negative emissions. The orange line represents emissions trajectory as the sum of the green and blue trajectories



Source: J. Wilcox et al. 2020..

This sensibility has led to specific policy decisions by nations, states and municipalities. Multiple nations now have legislated net-zero economies by 2050, and others have legislated net-zero for key sectors (e.g., electric power generation). That is also true of many states – nine have legislated 100% net-zero power standards, and several have committed to net-zero economies (e.g., CA & NY). These represent substantial markets, and the growth in commitments produces a growing fraction of the national and global market that demands net-zero goods & services.

National and regional policies of these kinds have helped prompt leading companies to make commitments to net-zero emissions as well. These include:

- Tech giants such as Microsoft & Amazon
- Industrial giants like Dow and Unilever
- Oil & Gas companies including Occidental and Shell
- Power companies like Southern and Xcel
- Airlines like Delta
- Retailers like Nike

These commitments include operations, supply chains and products – all net-zero. Some companies, such as Microsoft, have committed to removing their legacy of emissions representing their whole corporate history – more than 200 million tons in total! All have realized that they need all tools available to achieve these goals, including carbon management in all its forms.

Technical and Commercial Status of Carbon Management

Since my testimony before this Committee 14 months ago, a great deal has changed for all carbon management approaches. In fact, a signature aspect of the carbon management landscape is rapid and sometimes revolutionary change. In this, there are similarities to carbon management now and solar & EV enterprises in 2005. Fifteen years ago, both enterprises were considered prohibitively expensive, immature, hard to scale and reliant on market aligning policies. Instead, steady investments in innovation, changing consumer culture and international markets, and multiple market-aligning policies created opportunities, jobs, wealth, and a cleaner energy system and environment. Carbon management can deliver these benefits even more quickly but will require a similar mix of innovation, policy incentives, and a national posture of development and commercialization.

I have streamlined this section for clarity and have added substantial additional materials on all these topics in a technical appendix at the end of this testimony for completeness.

Carbon Capture and Storage (CCS)

CCS represents a set of technologies that capture & separate CO_2 from large point sources, transport them to sites of geological storage, compress & inject them deep in the earth's crust, and monitor them to validate safe and secure storage operations. Today, 21 large-scale CCS facilities operate worldwide, safely and securely keeping more than 40 million tons of CO_2 from the air and oceans every year. In total, the world has managed more than 260 million tons of man-made CO_2 this way.[6] More information can be found in the technical appendix.

CCS can and will play a critical role in managing the emissions from these key sectors:

- Heavy industry, including cement, steel, chemicals, refining, ethanol, pulp & paper, and glass[7]
- Existing power stations, most notably coal- and gas-fired electricity production[8]
- In the near-term production of low-carbon and zero-carbon hydrogen, as is currently done in five facilities worldwide,[9] including the Air Product project in Port Arthur, Texas

Although these applications are very important for the US, they have enormous potential applications in China, India, Southeast Asia, Europe and the Middle East. These provide commercial opportunities to US manufacturers and companies to provide carbon management goods & services, as detailed in a recent NPC report.[10]

CO_2 Use and Recycling

For good reasons, many seek to find ways to use CO_2 to create economic value in a climate-

positive way. Today, the primary use of CO_2 is for enhanced oil recovery. This is an important near-term pathway and provides opportunities to finance projects, scale-up technologies and reduce costs. Many see the value in turning CO_2 into goods for scale - that will be essential at some point for a circular carbon economy.[11] The main types of valuable products made from CO_2 include synthetic fuels; chemical feedstocks like carbon monoxide, syngas & methanol;[12] CO_2-based cement, concrete & aggregates; and durable CO_2-based-products, including carbon fiber/tubes, plastics and composites, etc. While it is unlikely that these approaches and products will lead to profound GHG emissions reductions, they are engines for growth and are already supporting hundreds of US companies making and selling these products.

CO_2 Removal

Driven in part by the science, market forces and arithmetic discussed above, CO_2 removal has gained dramatic and profound increased prominence as an enterprise and as a necessary component of climate action. The National Academies has described the different pathways and what is needed for them to scale and succeed.[13] They include both engineered and managed ecosystem approaches.

- *Engineered pathways:* These approaches use machinery and conversion equipment to separate CO_2 from ambient air. This can involve direct-air capture with storage (DACS), bioenergy with carbon capture and storage (BECCS), and carbon mineralization. The US currently has one operating BECCS facility (the ADM ethanol plant at Decatur, IL) with many more announced projects. There are seven DAC companies, with plans under development for projects in West Texas (Carbon Engineering + Occidental Petroleum), Huntsville, Alabama (Global Thermostat & Coca-Cola), and others.
- *Managed Ecosystems:* Sometimes called "nature-based solutions," managed ecosystems include modifying working forest operation, reforestation, adding forests (afforestation), soil carbon storage and wetland restoration including mangrove plantation ("blue carbon"). In addition to removing CO_2, these approaches often have ancillary benefits (e.g., water quality, biodiversity, soil health). Many companies, including technology companies (e.g., Pachama, Indigo, LandLife), are executing projects in the US and seeking to expand their markets.

A number of large US companies have made commitments to CO_2 removal, both as an environmental goal and as an investment opportunity. These include technology giants Microsoft, which just last week announced a request for proposals as part of its action plan and $1 billion investment strategy;[14] Amazon, which has announced a $2 billion investment strategy;[15] Nike & Unilever, which have joined Microsoft in creating a buyers club for CO_2 removal services;[16] and Dow, which has committed to a net-zero footprint.[17] Several US companies, including Winrock and American Carbon Registry, serve to certify and authenticate these services and will help mature CO_2 removal as an industry.

Key Policy Concerns

To maintain leadership and global competitiveness in these markets and to achieve important climate goals, strong policies are needed to bring carbon management tools, technologies

and practices to market. In my last testimony, I discussed a wide range of potential policies. I will focus today on a subset of those approaches and additional new policies that this Committee and this Congress can consider.

Incentives for Deployment

In the past, the US has stimulated market adoption of clean energy technologies through incentives, such as investment tax credits and production tax credits, augmented by state-level mandates (e.g., renewable portfolio standards). The value of these has ranged from $60-$150/ton for the wind production tax credit to ~$40-$120/ton for the solar investment tax credit.

For carbon management, the only national incentive is the 45Q tax credit, worth $50/ton for saline formation storage and $35/ton for CO_2 reuse (e.g., EOR) and recycling and for direct-air capture. Recent analyses including our own at Columbia[18] and the National Petroleum Council[19] make clear that this is insufficient for widespread market adoption. Our work estimates that for utility-owned gas-fired power plants to deploy CCS, they would require $80/ton incentives and for merchant power plants closer to $110/ton, in line with existing renewable tax credit provisions. Important enhancements to 45Q are under consideration in Congress today, including these provisions to:

- Extend the construction eligibility criteria 2-5 years (or to make the credit permanent)
- Increase the value of direct-air capture to $65/ton or higher
- Increase the value of saline formation storage
- Make the credits fully refundable (e.g., under Section 1603), as was done during the 2009 stimulus response.

Incentives of these kinds are vitally important for CCS projects to receive project financing. The greater the incentives, the more CO_2 capture systems will be deployed and the more tons of CO_2 reduced or removed.

Augmenting Policies

Many other important policy options fall within the jurisdiction of this Committee, affecting opportunities around many forms of carbon management. Three important options merit consideration and legislative treatment:

Land Use (Forests)

The US Forest Service has programs and authorization to prioritize forest health and disburse funds. One action to consider would be to prioritize and augment funding for states to expedite implementation of elements of State Forest Action Plans required under the 2008 Farm Bill and present in every state. In addition to creating jobs for forest workers (many in rural communities), it would improve forest resilience and increase rates of carbon drawdown. These funds would provide critical financial support to states addressing high wildfire risk (including fuel clearing and other labor-intensive forest health treatments).

A related action would be to lift the cap on the Reforestation Trust Fund (RTF). The fund was established in 1980 to regrow and replace US forests impacted by wildfire, pests, disease or timber harvests. Today, RTF is funded by existing tariffs imposed on imported timber and wood products but is capped at $30 million. Lifting the cap to $60 million would not lift tariffs and would allow important existing funds to flow to forest restoration projects.

Pore Space Access

CCS, DACS and BECCS all require access to subsurface pore volumes. For saline formation, access and injection rights commonly belong to the surface owners. This means the rights to enormous CO_2 storage capacity, potentially over a trillion tons, belong to the US Government on Federal lands. The BLM should establish a program to provide access to pore volumes on Federal Lands, ideally at low-cost or zero-cost, and begin to create processes to resolve issues of pore-volume access for projects with multiple landowners and post-injection site care.

Resource Assessment

The US Geological Survey has done an excellent job assessing the potential CO_2 storage resources in conventional geology,[20] notably saline formations and depleted oil & gas fields. The US Department of Energy has similarly done an excellent job in assessment through the Regional Partnerships Programs,[21] and is greatly improving the confidence and resolution of these assessments through the CarbonSAFE program.[22] This work is the global standard of excellence for geological storage resource assessment. This Committee should consider expanding the CarbonSAFE program's funding and continuing the USGS assessment work.

That work should expand into carbon mineralization assessment. Although the USGS has made an initial effort to map and assess US CO_2 mineralization resources that is very helpful,[23] it is too coarse for states or companies to consider policies and investments. A more detailed representation of key ultramafic and mafic rock bodies, including detailed mineralogy and petrology assays, would provide data both scientists and entrepreneurs could use.

Finally, BOEM within the Department of the Interior could undertake similar assessments for the continental shelf region, starting with the near-shore Gulf of Mexico. As discussed above, they could also provide zero-cost or near-zero cost access to saline formation pore volumes in federal waters.

Infrastructure

As I have indicated in prior testimony,[24] CO_2 infrastructure is essential to deployment. A new study by the Great Plains Institute,[25] supported by 17 governors through a multi-state working group, shows just how valuable that infrastructure could be, reducing 280-670 million tons each year (Table 1), supporting hundreds of large-scale projects and creating tens of thousands of jobs. The projected network size would be 30,000 miles (only six times what exists today) and would cost roughly $15 billion. This would launch some of the fastest and cheapest abatement the US could undertake, including from ethanol, hydrogen and fertilizer production.

Table 1: CO_2 storage, land-use and investment across primary scenarios. Source: Great Plains Inst., 2020

Scenario	CO_2 Stored	Miles of Transport Network	Capital Investment	Project Labor Investment	Annual O&M Spending
Near- and Medium-Term	281 million metric tons	29,710 miles	$16.6 billion	$14.3 billion	$252 million
Midcentury	669 million metric tons	29,922 miles	$19.3 billion	$15.3 billion	$254 million
Impact of midcentury planning horizon	x 2.38 mroe CO_2 stored	+0.7%	+16.3%	+7.0%	+0.8%

The EFFECT Act has provisions to authorize the Department of Energy to provide grants for CO_2 pipelines. The Invest CO_2 Act would do the same with the Department of Transportation. This Committee could support these bills and could also expand the authorization of the DOE Loan Program Office to include investments in CO_2 pipeline infrastructure.

Innovation

Innovation is our nation's strong suit, and sustained, substantial support by the Federal Government has always played an important role, ranging from basic science to applied science to funding of pilots and demonstrations. A pending report from the Center on Global Energy Policy explains both the history and the opportunity innovation investment could play in maintaining US competitiveness as well as enabling and achieving deep carbon reductions.

In no area is this clearer than in carbon management. The report calls for dramatic increases in funding for both CCS and CO_2 removal, and adding that funding to multiple agencies. These recommendations follow the lead of the Energy Futures Initiative report from last year,[26] which lays out specific line items and budgets for US agencies. This recommendation is matched by the Rhodium Group recommendations around capturing leadership for direct-air capture.[27] Dramatic increases in carbon management innovation support represent a no-regrets pathway.

The same is true for data gathering & analysis around carbon management. Gathering data & information and undertaking analysis remain core government functions, and themselves enable opportunities that would not otherwise come to light. As one example, a recent report on achieving net-zero emissions for California by Lawrence Livermore National Lab[28] reveals key opportunities for CO_2 removal, both engineered and through managed ecosystems, and was only possible due to the decade of data made available on crops, forests, geological resources of all kinds, municipal solid waste and water. This Committee should empower agencies to gather key data (e.g., on industrial heat use, power market data, land use and facility engineering) to enable new carbon management technologies and projects.

Industrial Opportunities

In two reports on industrial decarbonization and in my recent House Testimony, my co-authors and I make a set of recommendations regarding how to rapidly and cost-effectively reduce emissions from heavy industry. New scholarship which we will publish soon shows unambiguously that CCS is one of the lowest-cost, most actionable pathways for profound emissions reduction, especially in the cement, steel, chemical and refining sectors. One important and under-utilized approach involves government procurement authorities, since governments buy 50% of the concrete, 20% of the steel and 5% of fuel in the US. Legislative opportunities include the Army Corp reauthorization, Highway bill reauthorization and Defense authorization. The Government can purchase low-carbon production from these industries, stimulating market competition and new products. This has often been the path for advanced technologies entering the marketplace. Importantly, these kinds of industrial investments and incentives will protect the US against border carbon adjustments and position US manufacturers for emerging global market opportunities.

Similarly, low-carbon hydrogen will be a major workhorse for a net-zero global economy. Policy measures that support low-carbon hydrogen production and use, including low- and zero-carbon production using hydrocarbons & CCS, will further US interests in many ways. In addition to procurement, infrastructure investments, tax credits for low-carbon hydrogen production and investments in innovation will all support this key industrial pathway.

Closing Thoughts

Carbon management is both the industry of the future and a keystone to a just, verdant world. The technology, physics and chemistry are well understood, and other aspects of the science are gaining clarity every day. A dedicated, committed effort by the US Government would lay the cornerstone for commercial activity, high-paying jobs, helping communities at risk, and tackling the hardest, most stubborn aspects of climate change. US leadership in this space is not inevitable but is very much possible by taking the right measures.

With that, I look forward to your comments and questions.

Notes

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CONGRESSIONAL TESTIMONY OF **DR. S. JULIO FRIEDMANN**

Senior Research Scholar, Center on Global Energy Policy, Columbia Univ. School of International & Public Affairs

APPENDIX: TECHNICAL AND COMMERCIAL STATUS OF CARBON MANAGEMENT

Net-zero Framework: Climate and US Competitiveness

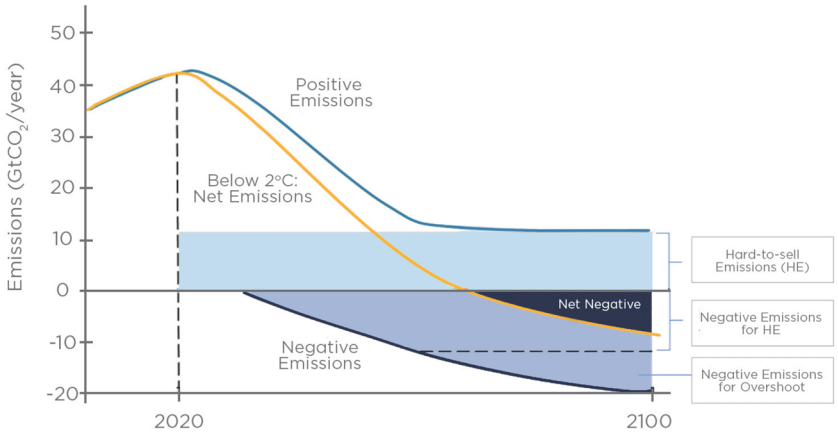
By definition, achieving net-zero emissions requires that any emissions that are not *reduced* must be *removed*. Emissions reduction and removal are distinct in nature and are different from emissions avoided:

- *Avoided emissions* are those that might have occurred but do not (for example, by not building a steel-mill due to overcapacity or by building a solar PV power station instead of a natural gas generation).
- *Reduced emissions* are existing emissions that no longer occur. Emissions may be reduced through many means, including conservation, efficiency, carbon capture & storage, or by shutting down or displacing existing emissions sources.
- *Removed emissions* are those that were emitted and are retrieved from the air and oceans. These can be from natural processes (e.g., mineral weathering), managed ecosystems (e.g., afforestation) or engineered systems (e.g., bioenergy with CCS).

To achieve net-zero emissions, all emissions trajectories must decrease (figure 1). However, if there are any residual emissions that are not reduced or mitigated, net zero requires an equal mass of CO_2 removal. In many scenarios and descriptions, residual emissions are considered "hard-to-abate", meaning either the cost is extremely high (e.g., for aviation) or the technology does not exist (e.g., application of fertilizer). This is the core arithmetic of a net-zero emissions plan: ***any residual CO_2 emissions must be balanced by an equal amount of CO_2 removal.***

$$CO_2 \text{emissions} - CO_2 \text{removals} = 0$$

Figure 1: Representative pathway to net-zero and net-negative emissions. The orange line represents emissions trajectory as the sum of the green and blue trajectories



Source: J. Wilcox et al. 2020.

However, most analysis finds that it is not possible to achieve zero-emissions soon enough to stabilize global average temperature below 2 degrees Celsius through reduction alone. In particular, the IPCC found that to achieve emissions consistent with a 2°C limit to man-made warming would likely require 85% emissions reduction by 2050 and annual removal of gigatons CO_2 before 2100. To limit man-made warming to 1.5°C, 100% emissions reduction and annual removal of 5-10 gigatons CO_2 must occur around mid-century.[1]

By 2050: CO_2emissions(residual) - CO_2removal < 0

After 2050: CO_2emissions(residual) - CO_2removal = (-5 to -10 Gt/a)

The scale of the problem

When it comes to climate change arithmetic, the numbers are staggering and hard to understand or internalize. To help understand the numbers, it's useful to understand the nature of a gigaton.

- **All the people on earth combined weight roughly 1/2 a gigaton.**
- **The global annual production of plastic is about one gigaton**
- **Global consumption of meat is ~1/3 a gigaton.**

Unsurprisingly, managing many gigatons of emissions is extremely daunting. For example, the global oil market is roughly 5 Gt of material. To remove 5 Gt of CO_2 from the air and oceans requires an industry the size of the oil and gas industry operating in reverse.

This core arithmetic produces difficult corollaries. For example, the hard-to-abate sectors commonly are expressed as an irreducible annual sum of 8-10 Gt CO_2e. The persistence of residual emissions is founded on the lack of alternatives, especially for land-use emissions, shipping, and aviation. Although some analysis has laid the foundation for innovation and progress in these arenas (e.g., ETC, 2018), the lack of realistic plans for deployment means that these emissions appear across almost all analyses. Other difficult corollaries include:

- Any failure to reduce emissions must be balanced by CO_2 removal. For example, a failure to scale-up renewables, efficiency improvements, or EVs will lead to a larger removal burden.
- Achieving an 85% reduction in greenhouse gas emissions by mid-century requires a 50% emissions reduction each decade between now and 2050. Given the long capital lives of existing infrastructure and facility stock, it is not clear how this might be achieved.
- A 1.5°C trajectory requires 5-10 Gt removal by 2050 and greater volumes thereafter. The National Academies (2018) find that this is not possible through reforestation alone given the limits of land and current technology.

The core arithmetic produces an uncomfortable finding: existing capital stocks will overwhelm 1.5 or 2°C carbon budget. The IEA (2018) analyzed the global energy infrastructure either built or under construction. Assuming a natural capital life for facilities, just the existing capital stocks would emit 95% of the CO_2 emissions allowable under their sustainable development scenario, which is roughly 2°C of warming, and a 1.5°C budget was not possible without 100-1000 Gigatons of CO_2 removal by 2100.

Carbon Capture and Storage (CCS)

CCS represents a set of technologies that capture & separate CO_2 from large point sources, transport them to sites of geological storage, compress & inject them deep in the earth's

crust, and monitor them to validate safe and secure storage operations. Today, 21 large-scale CCS facilities operate worldwide, safely and securely keeping more than 40 million tons of CO_2 from the air and oceans every year. In total, the world has managed more than 260 million tons of man-made CO_2 this way.[2]

Figure 2: Global CCS Facilities. Source, GCCSI 2019

CCS can and will play a critical role in managing the emissions from these key sectors:

- Heavy industry, including cement, steel, chemicals, refining, ethanol, pulp & paper, and glass[3] Application of CCS to these industries captures both process emissions and heat-related emissions. Of the 21 facilities capturing CO_2 worldwide today, 19 of them are on heavy industry.[4]
- Existing power stations, most notably coal- and gas-fired electricity production. Although some of existing fleet will be retrofit in the U.S.,[5] the majority will be in developing nations, notably in Asia.[6] This is an enormous market opportunity for US companies as part of industrial policy (see below).
- Production of low-carbon and zero-carbon hydrogen (commonly called "blue" hydrogen), as is currently done in five facilities worldwide,[7] including the Air Product project in Port Arthur, Texas. Today in the U.S., blue hydrogen production with low-cost natural gas costs only 20-60% more than unabated hydrogen production and is 2-4x cheaper than "green" hydrogen made with zero-carbon electrolysis.

Although these applications are very important for the US, they have enormous potential applications in China, India, Southeast Asia, Europe and the Middle East. These provide

commercial opportunities to US manufacturers and companies to provide carbon management goods & services, as detailed in a recent NPC report.[8]

CO_2 Use and Recycling

For good reasons, many seek to find ways to use CO_2 to create economic value in a climate-positive way. Today, the primary use of CO_2 is for enhanced oil recovery. This is an important near-term pathway and provides opportunities to finance projects, scale-up technologies and reduce costs. Many see the value in turning CO_2 into goods for scale - that will be essential at some point for a circular carbon economy.[9] The three main types of valuable products made from CO_2 are:

- *CO_2-based cement & aggregates:* these are thermodynamically favored, and over 50 companies existing today that sell products into these markets, including US based Solidia Tech and Canada-based CarbonCure. This market is valued at over $1 trillion,[10] and could realistically accept as much as 1-2 Gt CO_2 each year.
- *CO_2-derived fuels and chemicals:* This would include intermediate chemical feedstocks like carbon monoxide, syngas & methanol.[11] The total market size is greater than $4 trillion, most as synthetic fuels, and could absorb 1-3 Gt CO_2. Depending on the feedstock and process life-cycle analysis, these could be carbon neutral or even carbon negative and could serve as alternative drop-in fuels, especially for hard-to-abate sectors (e.g., aviation and shipping). However, they require very large amounts of zero-carbon heat and electricity to synthesize. Many US companies large and small, including BASF, 3M, and Opus-12, are developing these technologies and products.
- *Durable CO_2-based-products:* including solid, stable carbon including carbon black (which goes into tires), carbon polymers, carbon fiber, carbon nanotubes, graphene and other graphitic materials, and carbon composites. These are long-lived forms and would keep carbon out of the atmosphere for centuries, and which may someday serve as cost-effective substitutes for steel and other emissions-intensive materials. Several US companies, including Monolith, Solid Carbon Products, NewLight, and Novomer, are developing and selling these materials.

Ultimately, it is unlikely that these approaches and products will lead to profound GHG emissions reductions. However, many nations (including Canada, Denmark, UAE and the Netherlands) are investing in development and market entry of these approaches as a deliberate industrial policy. CO_2 conversion, reuse, and recycling are potential engines for growth and are already supporting hundreds of US companies making and selling these products.

CO_2 Removal

Driven in part by the science, market forces and arithmetic discussed above, CO_2 removal has gained dramatic and profound increased prominence as an enterprise and as a necessary component of climate action. The National Academies has described the different pathways and what is needed for them to scale and succeed,[12] including substantial Federal investments in innovation, development, and demonstration.[13] They include both engineered and managed

ecosystem approaches, both of which are more advanced than commonly realized and both of which would create jobs and opportunities at home and abroad.

Engineered pathways

These approaches use machinery and conversion equipment to separate CO_2 from ambient air. Three approaches appear to have the highest potential market application and potential:

- *Direct-air capture with storage (DACS):* This approach separates and removes CO_2 from ambient air. When combined with geological CO_2 storage, it withdraws CO_2 from the air and ocean permanently.[14] When combined with CO_2 use and recycling, DAC can provide a zero-carbon feedstock. There are seven DAC companies, with plans under development for projects in West Texas (Carbon Engineering + Occidental Petroleum), Huntsville, Alabama (Global Thermostat & Coca-Cola), and others. One Swiss company, Climeworks[15] has 14 operating DAC facilities and has offers commercial CO_2 removal services using DACS. Analysis reveals that modest investments and policy support would lead to dramatic cost reductions, remove millions of tons CO_2 every year, and create hundreds of thousands of jobs in the coming decades.[16]
- *Bioenergy with carbon capture and storage (BECCS):* This process involves harvesting plants that have removed CO_2 from the air and oceans and combining them with conversion, energy production, and geological CO_2 storage. When done correctly, BECCS is able to create low-carbon, zero-carbon, and even net-negative hydrogen, fuel, and chemicals by transferring CO_2 from the air to the geosphere.[17] The US currently has one operating BECCS facility (the ADM ethanol plant at Decatur, IL) with many more announced projects in Texas, California, and North Dakota.
- *Carbon mineralization (CMin):* Over very long timescales, CO_2 reacts with silicate minerals at the earth surface to make carbonate minerals. Humans can accelerate this process by adding heat and energy, grinding reactive rocks to increase surface area, or by combining air with the most reactive mineral fractions in the subsurface.[18] This binds CO_2 in mineral form. The enormous volumes of reactive minerals at the earth's surface and near subsurface make the volume potential for carbon mineralization effectively limitless. Recent work has identified locations where mineral resources, low-carbon energy, and existing infrastructure are available to support carbon mineralization projects.[19]

One additional approach to engineered pathways is ocean alkalinity enhancement.[20] Although important, and recommended by Energy Futures Initiative as a focus for innovation investment, deployment today faces challenges from international law and public acceptance that also merit continued work and attention.

Managed Ecosystems

Sometimes called "nature-based solutions" or "natural climate solutions,"[21] managed ecosystems involve changing land-management practices to increase standing stocks of carbon in living biomass within complex ecosystems.[22] Two overarching approaches are most commonly discussed:

- *Forest-based approaches:* These include adding new forests (afforestation), restoring recently lost forests (reforestation), avoiding deforestation, and enhancing the carbon uptake of working forests through new practices.
- *Soil-based approaches:* These include modifying agricultural practice in farm and grazing lands, including no-till farming, adaptive multi-paddock grazing (AMP), growth of cover crops, shifting to perennial crops, and adding trees to the margins of agricultural land.

In addition to removing CO_2, these approaches often have ancillary benefits (e.g., improving water quality, sustaining biodiversity, increasing soil health etc). However, substantial questions remain around accurate accounting of carbon uptake, particularly in soils. ARPA-E has a program[23] dedicated to improving accuracy and reducing costs of soil carbon monitoring, which today are estimated to be $1000's per ton.

Many companies, including technology companies (e.g., Pachama, Indigo, LandLife), are executing projects in the US and seeking to expand their markets. In some cases, these projects receive certification through qualifying registries, such as American Carbon Registry (ACR), Verra, Gold Standard, and Climate Action Reserve (CAR).

There are additional approaches to managed ecosystem pathways, including "blue carbon" (adding mangroves to coast waterways, wetland restoration, enhanced peat production, enhanced terrestrial or oceanic uptake (e.g., through genetically modifying plants[24] or cultivating macroalgae like kelp), amendment of soil systems with biochar.[25] These approaches are promising but have not yet reached the level of maturity necessary to easily enter the market today. This also suggests an innovation and scientific agenda[26] to further explore their potential and to accelerate their entry into voluntary and regulatory markets.

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The CHAIRMAN. Dr. Friedmann, thank you. I appreciate your analogy here, carbon management is our Swiss Army knife. A good way to think about it.

We will now turn to Mr. Sasha Mackler, again, with the Bipartisan Policy Center. Welcome and thank you for the good work of the Center.

STATEMENT OF SASHA MACKLER, ENERGY PROJECT DIRECTOR, BIPARTISAN POLICY CENTER

Mr. MACKLER. Chairman Murkowski, Ranking Member Manchin and members of the Committee, thank you for convening this hearing. It's a pleasure to be part of such a pragmatic solutions-oriented conversation, and I am delighted to be here this morning on behalf of the BPC to discuss large-scale carbon management technologies and the important role that they can play in a future low carbon energy system. BPC's energy project has a number of initiatives underway that relate directly to carbon management. My remarks today will focus mostly on natural solutions, but my written testimony focuses more broadly on the full set of options, natural and technological, that can remove carbon dioxide already in the atmosphere because it won't be feasible to eliminate all human-caused sources of greenhouse gases over the next few decades, we need to develop ways to pull carbon dioxide directly out of the atmosphere if we're going to successfully achieve net-zero emissions.

Of course, technologies that reduce or avoid further emissions, including renewables, nuclear and carbon capture and storage, must be advanced aggressively together with carbon dioxide removal options to make the net-zero goal possible. And there are numerous policies that are required today to bring these systems to scale. And on that score, I really want to commend this Committee for its leadership in bringing forward the bipartisan American Energy Innovation Act which is really an important piece of legislation that includes many critical programs that will benefit carbon management. BPC oversees several efforts, including the American Energy Innovation Council, the Direct Air Capture Advisory Council and our new Farm and Forest Carbon Solutions Initiative that are focused on these issues and on behalf of all of our partners, we look forward to working with this Committee to help advance the American Energy Innovation Act and any additional legislation you develop to advance these nascent industries.

I just also want to say that in addition to my work on energy policy at BPC, I spent the last decade in the private sector working first as a developer of carbon capture projects and then in the biomass energy industry. Through this experience I can offer a first-hand account, both of the challenges facing some of these approaches along with the enormous benefits that can come from deploying them at scale.

Turning next to natural climate solutions, I'd like to make the following points. When it comes to agriculture and forestry policy, we like to say that what's good for climate can also be good for our farms and our forests. While climate change has been a deeply polarizing issue, especially in rural America, forestry and agriculture provide a unique opportunity to protect the climate, support the health of American lands and contribute to the economic vitality of

rural communities. In fact, we can't solve this problem without the help of our farmers, our ranchers, our forest landowners and our public lands managers. Reaching net-zero by 2050 will require active participation from all of these stakeholders. In the U.S. forests already sequester the equivalent of about 15 percent of our national CO_2 emissions. Agriculture, while contributing about 10 percent of U.S. greenhouse gas emissions, has enormous opportunities to sequester carbon and crop lands and in grasslands. Importantly, these actions also come with environmental co-benefits. For example, they make the land more resilient to extreme weather, to wildfire and other climate-related impacts.

Policies on natural climate solutions should focus on incentives and on markets and on technical assistance. This should be done in ways that encourages the private sector to invest in these solutions. In addition to value in carbon storage, policies that bolster markets for sustainable wood products and provide pragmatic approaches to carbon accounting should be prioritized as they are critical enablers for capital to flow into the space. New research programs are important for developing the information systems and the technologies so that soils, crops and forests can enhance their carbon uptake. And finally, restoration and management of our public lands will be important as we address the risks of climate change. Reducing the threat of catastrophic wildfires, looking for opportunities to reforest burned areas and improving the health of our rangelands are all critical parts of the solution.

In closing, I want to thank this Committee, again, for its leadership and for the opportunity to testify and to lend the Bipartisan Policy Center's support to your efforts in developing large-scale carbon management technologies. Creating the industries of the future has always been America's superpower and will be especially critical here as we develop a strategy for addressing climate change. Carbon management is one of the best investments that we can make. Thank you.

[The prepared statement of Mr. Mackler follows:]

BIPARTISAN POLICY CENTER

Testimony on the Development and Deployment of Large-Scale Carbon Dioxide Management Technologies

United States Senate
Committee on Energy and Natural Resources

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Chairman Murkowski, Ranking Member Manchin, and members of the committee, thank you for convening this hearing on the development and deployment of large-scale carbon dioxide management technologies in the United States. BPC's Energy Project has a number of initiatives underway that relate directly to carbon dioxide management and I appreciate the opportunity to share our views on this important subject. My testimony today focuses specifically on options for removing carbon dioxide that is already in the atmosphere, but it is worth emphasizing at the outset that BPC subscribes to an "all of the above" approach to addressing climate change. Technologies that reduce or avoid further emissions, including low- and zero-carbon fuel and electric power alternatives, energy efficiency, and carbon capture, storage, and utilization systems for large point sources of emissions are obviously all part of the solution, together with the carbon dioxide removal options I'll be discussing here. In short, the scale of the challenge is so large, and the stakes are so high, that we simply must be able to draw on a large, diverse, and flexible toolset of policies and technologies to succeed.

For this hearing, I'd like to emphasize five key points:

- Carbon dioxide removal strategies, including both natural and technology-based strategies, will be needed along with emissions reduction strategies to meet national and international climate change goals. Because it won't be practically and economically feasible to eliminate all human-caused sources of greenhouse gases over the next few decades, we need ways to also pull carbon dioxide out of the atmosphere to achieve net-zero emissions.
- Effective carbon removal strategies are needed to diminish the economic disruption and dislocation that is inevitable as our nation makes the necessary transition to a net-zero emissions profile over the next three decades.
- Experience shows the constructive and often vital role that government support can play in spurring innovation and nurturing new industries. This support can take different forms, as appropriate, at different points in the innovation cycle, from funding research, development, and demonstration (RD&D) to providing a policy and market environment in which new technologies can gain a foothold and become commercially successfully.
- Congress and this committee can take a number of steps to meaningfully advance large-scale carbon dioxide management technologies and strategies. Doing so would deliver near-and long-term benefits in terms of economic competitiveness, flexibility to meet climate objectives, farm and forest productivity, and other environmental co-benefits (clean water, ecosystem protection, etc.).
- Different types of carbon dioxide removal strategies present different challenges. Direct air capture of carbon dioxide or "DAC" is a new technology that requires additional RD&D and financial support to achieve the cost reductions and performance improvements needed to enable large-scale deployment. By contrast, farm- and forest-based solutions are available and can be implemented now but are hampered by a lack of durable market and policy drivers to catalyze needed long-term investments in improved land management and carbon monitoring and accounting approaches.

1. Introduction

The Bipartisan Policy Center (BPC) is a Washington, D.C.-based think tank that actively fosters durable bipartisan solutions to critical public policy challenges by engaging with good ideas from across the political spectrum. BPC's Energy Project focuses on advancing policies and technologies that promote American prosperity, economic competitiveness, and energy security while also addressing the problem of climate change and accelerating the transition to low- and zero-carbon technologies. As detailed later in this testimony, three ongoing BPC Energy Project initiatives are especially relevant to this hearing: the American Energy Innovation Council, which was founded in 2010, consists of 11 corporate leaders and is dedicated to promoting clean energy innovation; our Direct Air Capture Advisory Council includes industry, business, and policy leaders and is working to advance DAC technology; and our recently launched Farm and Forest Carbon Solutions Initiative focuses on natural carbon removal through land-based strategies that also create new economic opportunities for rural and farm communities.

My testimony today begins by discussing the imperative to remove carbon dioxide from the atmosphere—in conjunction with concerted efforts to reduce and avoid new emissions—to achieve a net-zero-carbon economy. I'll then turn to the challenges and opportunities associated with two different approaches to carbon dioxide removal: direct air capture or DAC, in which mechanical and chemical processes are used to extract carbon dioxide from the air (once captured, the carbon dioxide can be used in other industrial processes or products or permanently stored in geological reservoirs), and farm- or forest-based strategies that increase the uptake and storage of carbon dioxide from the atmosphere in soils and biomass. The last part of my testimony suggests specific actions Congress and this committee can take to support the development and deployment of these "negative emissions" strategies and summarizes BPC's near-term plans for work in this area.

2. Carbon Dioxide Removal is Needed to Achieve "Net Zero" Greenhouse Gas Emissions

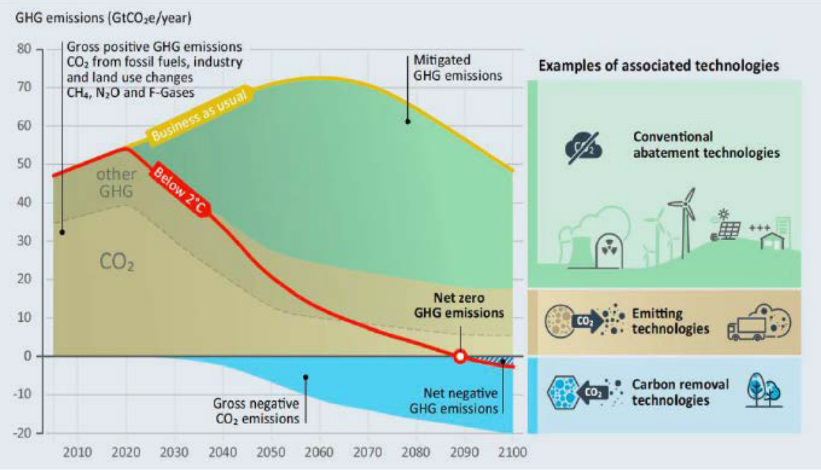
Recent years have brought the risks of climate change into clearer focus and strengthened the scientific case for urgent action to limit rising levels of greenhouse gases in the atmosphere. To meet internationally accepted climate goals, experts agree, net emissions globally will have to be reduced to nearly zero by roughly 2050—meaning that within a mid-century timeframe, remaining human-caused releases of carbon dioxide and other greenhouse gases into the atmosphere will have to be balanced by an equal quantity of carbon dioxide removed. The dimensions of this challenge are difficult to overstate given the scale of the energy systems involved and the variety of sources, from agriculture and industrial processes, to power plants and cars, that contribute to the problem.

While attention has long focused on technologies for reducing or avoiding new emissions, recent years have also seen increased interest in strategies for actively removing carbon dioxide from the atmosphere. This interest reflects a growing recognition that while commercially viable options for rapid decarbonization already exist in some sectors—the electric power industry, for example, has recently seen strong growth in the use of wind and solar technologies—low and zero-carbon options have yet to emerge or remain prohibitively expensive for other energy-use applications such as long-haul air travel and marine shipping. Adding to the overall challenge of getting to zero carbon are the various non-

energy sources that also produce greenhouse gases: some industrial processes, for example, generate carbon dioxide as a direct by-product of chemical reactions. According to a recent report released by the International Energy Agency, "key technologies the energy sector needs to reach net-zero emissions are known today, but not all of them are ready."[1]

Given that some level of dependence on fossil fuels is likely to continue well into the second half of this century, several expert organizations have concluded that active carbon dioxide removal (CDR) strategies—sometimes also called "negative emissions technologies" (NETs)—will be essential. For example, a synthesis report issued by the United Nations in 2019 highlighted the need for "immediate and all-inclusive action encompassing deep decarbonization complemented by ambitious policy measures, protection and enhancement of carbon sinks and biodiversity, and *effort to remove CO_2 from the atmosphere*" (emphasis added).[2] In 2018, a special report by the Intergovernmental Panel on Climate Change (IPCC) similarly noted that *all* modeled pathways for limiting warming this century to 1.5°C project the use of CDR.[3] And the National Academy of Sciences has concluded that negative emissions technologies will need to play "a significant role," for the simple reason that deploying such technologies "may be less expensive and less disruptive than reducing some emissions."[4]

Figure 1. The Role of CDR (or "negative emissions technologies") In Climate Mitigation[5]



Fortunately, several options exist for removing carbon dioxide from the atmosphere, some of which rely on natural processes (such as photosynthesis) while others make use of chemical and mechanical processes. Direct air capture is a technology-based approach for extracting carbon dioxide from the ambient air; once captured, the carbon dioxide can be used in other applications or permanently stored so it can't re-enter the atmosphere. Other strategies aim to increase carbon uptake by forests or soils, for example through afforestation (planting new forests) and reforestation (replanting previously forested lands), or by restoring degraded lands and changing agricultural practices. Bioenergy with

carbon capture and storage (BECCS) is another negative emissions option: In this approach, biomass energy plants are paired with systems for capturing the resulting carbon dioxide emissions at the point of discharge and permanently storing the carbon dioxide away from the biosphere. Other options that have been identified under the broad heading of CDR strategies include enhanced weathering to promote carbon mineralization (essentially, exposing reactive minerals in rock to bind with carbon dioxide in the atmosphere) and ocean alkalization.[6]

Known strategies for carbon dioxide removal, as the IPCC has pointed out, "differ widely in terms of maturity, potentials, costs, risks, co-benefits and trade-offs."[7] BPC's current work, and my testimony today, focus on two specific approaches to carbon dioxide removal—direct air capture (DAC) and land-based strategies—that we believe hold promise for widespread deployment in the timeframe needed to achieve current climate goals. Of these two options, DAC is less advanced but offers important potential advantages in terms of siting flexibility and scalability that justify near-term federal investment to accelerate the process of technology development, demonstration, and commercialization. Land-based CDR strategies, by contrast, have been studied for some time and could be deployed at scale almost immediately if the funding and interest were there. For these strategies, the salient challenges are not so much technological—rather a lack of market or policy drivers constitutes the chief obstacle to investment despite the substantial economic and environmental co-benefits such strategies often deliver.

The next sections of this testimony discuss the opportunities and challenges for DAC and farm- and forest-based carbon sequestration in more detail and suggest some areas where we would urge the committee and Congress to consider a more active federal role.

3. Direct Air Capture

The concept of capturing carbon dioxide in the ambient air has been around for some time, but DAC technology as a potentially important tool for addressing climate change has only recently come to the attention of policymakers, investors, and industry. The appeal of DAC is that it offers nearly unlimited carbon dioxide removal capability, provided costs can be sufficiently reduced and systems for transporting and storing captured carbon dioxide can be developed. Longer term, the United States has ample capacity to sequester large quantities of captured carbon dioxide in saline aquifers and other geological reservoirs. In the near-term, however, the economics may favor pairing DAC with existing markets for carbon dioxide in applications such as cement production and enhanced oil recovery.

A variety of DAC systems have been proposed and a few small operating DAC facilities have been constructed in the United States, Canada, and Europe.[8] All of these systems use fans to move large quantities of air through a filter or a liquid, which contains chemicals that bind to the carbon dioxide in the air. In some designs, the carbon dioxide is first turned into a solid that will release pure carbon dioxide gas when heated; in other designs the filter or sorbent is directly heated to produce a concentrated stream of carbon dioxide. Because of these steps, DAC systems require energy to operate; depending on the specific design, they typically also require inputs of chemicals and water.

Costs estimates for DAC vary widely. Costs for early systems were reported to be as high as $600 per ton of carbon dioxide captured; more recent reports from DAC developers claim costs as low as $100 to $200 per ton or less. The European company Climeworks, for example, aims to drive costs down to around $100 per ton within 10 years.[9] In the United States, several projects are at the pilot stage or under development. Carbon Engineering, a Canadian company, has one plant in British Columbia and aims to build another plant in partnership with Occidental Petroleum in the next couple of years in west Texas. An American company, Global Thermostat, has pilot plants in California and Alabama, a demonstration project under construction in Oklahoma, and plans to build a technology center in Colorado.

As a candidate to provide additional, large-scale CDR capability, DAC offers important advantages—particularly with respect to scalability and siting flexibility. DAC plants can be large or small, and because they rely on industrial processes, they can be controlled and adjusted as needed. DAC capacity can also be added in increments, using modular systems, which allows for flexible expansion as the need or opportunity arises. Siting flexibility makes it possible to locate DAC systems where low-cost and preferably low- or zero-carbon energy sources are available (e.g., waste heat or renewable energy) and where competition with other land uses is not a concern. And unlike systems that capture carbon dioxide from more concentrated exhaust gas streams, DAC plants need not be co-located with major emissions sources such as power plants.[10] Finally, siting flexibility means that DAC plants can be located in settings that are favorable for the permanent geological storage of captured carbon dioxide (e.g., atop saline aquifers) or where commercial opportunities exist to use the carbon dioxide.

Overall, a recent modeling assessment[11] put the global potential for carbon dioxide removal and storage using DAC at 16–30 billion metric tons per year in the 2070–2100 timeframe under different deep decarbonization scenarios and economic and technical assumptions. The study authors found that deploying DAC "significantly reduces mitigation costs" and "complements rather than substitutes other NETs." The authors also concluded that the key factor limiting DAC deployment is the rate at which the technology can be scaled up.

In light of this potential, extending America's record of leadership in innovation to DAC technology could have substantial benefits, not only in terms of achieving domestic climate mitigation goals but in tapping a large and growing global market for net-zero-carbon technologies. Other positive economic impacts would be more immediate: The Rhodium Group, for example, has estimated that the build out and operation of a single DAC plant with a carbon dioxide capture capacity of 1 million tons per year would create more than 3,400 jobs, including nearly 300 ongoing jobs to operate and maintain the completed facility.[12] A thriving DAC industry would also increase demand for high-quality jobs in steel, cement, chemicals, industrial equipment manufacturing, construction, engineering, and electric power, among others.

To realize these benefits, however, important cost, technology, and scale-up challenges still have to be overcome. Experience with a wide range of technologies, in energy and other sectors, suggests that rapid cost reductions and successful commercial deployment are possible if promising innovations can be nurtured through the early stages of technology development. (The striking cost reductions achieved by wind and solar energy technologies over the last two decades provide a dramatic illustration of this

point). Moreover, the U.S. government has often played a vital role in the innovation cycle, by funding basic research and development, sponsoring or supporting demonstration projects, and enacting policy changes that help create markets for new technologies. We therefore applaud recent efforts by Congress to provide funding and other support for DAC development, as discussed in Section 5 of this testimony.

4. Farm and Forest Natural Carbon Solutions

Farm- and forest-based strategies represent another important category of CDR options. Among their key advantages, these natural carbon solutions (1) employ technologies and land management practices that are ready for implementation today, (2) are comparatively low-cost options per ton of carbon removed from the atmosphere, and (3) provide important co-benefits to the local environment (e.g., improved water quality and wildlife habitat) and to local economies in predominately rural areas (e.g., sawmills, wood products manufacturing, farming). Farm- and forest-based strategies encompass a variety of land management practices that remove carbon dioxide from the atmosphere by plant photosynthesis and store it in soils and forest biomass. Many individual farmers, ranchers, and forest managers use carbon-storage-enhancing land management practices today, but primarily for other reasons such as soil erosion control, crop and forest productivity, and wildlife habitat. Stronger policy and program support is needed to scale up practices and to streamline and improve measurement and accounting of carbon removal benefits.

The National Academy of Sciences estimate that the U.S. can store an additional 500 million metric tons of carbon dioxide per year—or about 9 percent of the nation's annual greenhouse gas emissions—through a mix of carbon-enhancing practices on croplands, grasslands, and forests.[13] This is a central estimate with current practices that do not involve using protected forest areas or compromising food supply or biodiversity. Achieving this level of additional carbon storage will require the widespread participation of private land managers, but public land managers and the federal research enterprise will also be critical to scaling up natural carbon removal. BPC's recently launched Farm and Forest Carbon Solutions Initiative has identified an initial set of wide-ranging policy options that we urge Congress to consider. We believe these options have substantial potential to garner broad bipartisan support.

Specific policy priorities that fall within the purview of the Energy and Natural Resources Committee include:

- Scaling up carbon removal in federally managed forests. Reforestation, restoration, and improved forest management are key practices to sequester more carbon in trees. Reforestation is the re-planting of trees on land that was once forested. Restoration involves actions designed to recover lost or degraded forest structure, ecological functioning, and biodiversity. Restoration improves overall forest health and resilience to pests, diseases, and wildfire that can kill trees and cause carbon loss. Improved forest management involves a wide variety of practices that can increase the rate of carbon removal by forests, including thinning to promote growth, expanding harvest rotations to grow larger trees and maintain carbon removal rates, and treating areas affected by pests and diseases.
- Scaling up carbon removal in federally managed grasslands. Restoration of native grasslands can significantly improve soil health, increase soil carbon sequestration, and improve the resilience of the landscape to wildfire. Grassland buffers can also be used along streams to sequester

carbon in the soil. Support for sustainable grazing practices on federal lands can have significant carbon removal benefits. For example, rotational grazing (when animals are moved around to different pastures) encourages plants to send out more and deeper roots, which increases soil biomass and sequesters carbon from the atmosphere.

- Investing in improved soil monitoring and research. Soils represent a significant pool of stored carbon, but further research is required to understand the dynamics of soil carbon fluxes and to develop better carbon monitoring methods and land management practices for effectively increasing stored soil carbon. Further research, including field and lab trials, is also needed to investigate how working lands benefit from increased soil carbon and to estimate the economic value of implementing soil management practices that increase carbon sequestration. Genomic development of the root systems of biofuel crops is a key area for research into improving the economic value and carbon sequestration potential of specific types of crops.

Cost estimates for agricultural and grassland soil carbon storage practices are in the range of $30–$100 per metric ton of carbon dioxide removed, while forests fall in the range of $10–$100 per metric ton, depending on the specific practice and region of implementation.[14] These costs are comparatively low relative to other identified CDR options available today, and many measures to enhance carbon sequestration also align well with the goal of making U.S. farm and forestry operations more resilient to changing economic and climate conditions. Common co-benefits include increased productivity and yields, cleaner water, greater drought resilience, improved wildlife habitat, open space conservation, and increased rural economic opportunities.

Job creation in forestry and agriculture is an economic benefit of increased investment in enhanced carbon sequestration practices—one that may have particular appeal in the aftermath of the current COVID crisis. According to the Economic Policy Institute, a total of 13.4 direct, indirect and induced (DII) jobs are created for every million dollars of final demand in the forestry industry.[15] Direct jobs are jobs specifically related to an industry, indirect jobs support the industry, and induced jobs result from the increased spending of those employed in direct and indirect jobs. In agriculture, the estimate is 16.0 DII jobs and 14.4 DII jobs created per million dollars of final demand in crop agriculture and animal production, respectively. Further, support activities for agricultural production and forestry contribute 11.8 jobs for every $1 million in final demand. Agriculture and forestry are traditionally rural industries that create jobs and generate positive local economic impacts, including for many rural Native American, Alaska Native, and indigenous communities.

Despite their advantages, natural CDR strategies are not being widely implemented today due to a lack of consistent national demand for the climate benefits of forest and soil carbon sequestration. These climate benefits are typically valued based on their ability to compensate for, or offset, greenhouse gas emissions that occur elsewhere. A carbon offset is a unit representing the reduction or removal of one metric ton of carbon dioxide (or its equivalent). Governments and the private sector have created two systems to monetize and stimulate demand for carbon offsets: (1) regulatory programs that create compliance carbon markets, and (2) voluntary carbon markets that satisfy individual and corporate climate commitments. These markets have been instrumental in mobilizing private capital for natural CDR deployment, but they have had mixed success in creating steady demand for carbon offsets. The growth of compliance markets in the United States and internationally has been hindered by lengthy

and expensive project approval procedures and changing eligibility rules. Trading volumes in the voluntary market have been limited given that demand is created only by voluntary buyers (corporations, institutions, and individuals).

Beyond carbon markets for offsets, various government incentive programs at the state and federal levels provide financial compensation and technical assistance to private landowners and managers to improve forest, soil, and rangeland health. These programs have been successful in expanding implementation of forest and soil carbon-enhancing practices among participants, but they have enrolled only a small percentage of private farms and forests.

Natural CDR strategies also present methodological challenges related to data measurement, verification, and carbon accounting issues that have long been debated within the climate policy community. At the heart of the debate is the tension between two primary goals: (1) providing clear incentives and simple accounting approaches to support straightforward implementation and encourage widespread landowner participation, and (2) establishing the measurement, monitoring, and verification protocols needed to ensure that claimed sequestration benefits have actually occurred. Related to this second point are issues of permanence and how to address the risk that carbon sequestered by a project may be reversed (i.e., released back to the atmosphere). Forests and agricultural lands are vulnerable to carbon reversals from natural and human-caused disturbances including harvest, wildfire, and conversion to other land uses. Most carbon accounting protocols address the permanence issue by including mechanisms to account for potential carbon losses—for example, by requiring a buffer pool, which holds a portion of carbon credits from a project in reserve to draw from in the event of an unexpected disturbance.

5. Considerations for Federal Policy

A first priority for members of this Committee should be passing the American Energy Innovation Act, which contains a number of critical provisions addressing carbon capture and CDR strategies. We particularly commend Chairman Murkowski and Ranking Member Manchin for their work on this bill, which, among other provisions, expands research into carbon capture technologies and establishes a program for developing CDR technologies at scale. Strategies such as creating a DAC prize competition, test center, and pilot and demonstration program can all be effective in generating the breakthroughs needed to push this technology forward.

In fact, one of the reasons the European company Climeworks has been successful in developing DAC facilities despite the absence of a larger market driver is because it received considerable funding from the European Union (i.e., EU Horizon 2020 and incubators). By contrast, the United States still has no operating commercial DAC facility. In the coming months, BPC's own DAC advisory council, which includes former political leaders such as Mississippi Governor Haley Barbour and former Senator Byron Dorgan, will be exploring additional opportunities to close this gap by focusing on business models that can help jumpstart investment in DAC projects. projects

In addition, BPC recommends that Congress extend by five years the 45Q tax credit for geologic storage of carbon dioxide to account for delays by the IRS in issuing final guidance related to use of the credits. We also recommend the passage of direct pay tax provisions that apply to the 45Q tax credit to support

the deployment of commercial-scale carbon capture in the United States. Further, consideration should be given to 45Q expansion to incentivize direct air capture.

BPC applauds recent congressional efforts to fund nascent DAC research, development, and deployment programs at the Department of Energy (DOE) as part of FY 2020 appropriations. The provision of $35 million for DAC research and development across multiple DOE offices, specifically the Office of Fossil Energy, the Advanced Manufacturing Office and Bioenergy Technologies Office, and the Office of Science, is a welcome step and gives DOE flexibility to determine appropriate research priorities and collaboration strategies. In addition, provisions from the SEA FUEL Act that were included in the FY 2020 National Defense Authorization Act provide $8 million to the Department of Defense for R&D on direct air capture and ocean carbon capture. Together, these early investments can provide a foundation for expanded federal efforts to advance DAC technology in future years.

A more active federal role could also be decisive in expanding on-the-ground implementation of forest and soil carbon practices—particularly in public forests, grasslands, and rangelands managed by the U.S. Forest Service, Bureau of Land Management, National Park Service, and other agencies of the Department of Interior. Practices can be focused on areas that are in need of ecological restoration and that are near the wildland–urban interface, where certain forest and soil carbon practices have the added benefit of reducing the threat of wildfire to people and property. Expanding wildfire and hazardous fuels programs at federal land management agencies is also critical to reduce wildfire-induced carbon losses in forests and grasslands.

In addition, we urge Congress to continue supporting research programs related to forest and soil carbon at the U.S. Geological Survey, the DOE National Laboratories, and the Advanced Research Projects Agency–Energy. Priorities for further study and policy development include improving and simplifying measurement and verification protocols for natural carbon sequestration, particularly in soils, in order to streamline implementation, reduce transaction costs, and boost project participation.

Finally, BPC has developed a broad set of recommendations for leveraging U.S. agriculture and forest carbon opportunities in recovering from the economic fallout of the COVID crisis.[16] We specifically call the committee's attention to the below subset of BPC recommendations that particularly benefit rural industries and create jobs, many of which are outdoors and conducive to social distancing:

- Congress should provide an additional $35 to $50 million per year in funding over four years for the U.S. Forest Service's Collaborative Forest Landscape Restoration Program (CFLRP). The program provides grants that cover up to 50% of the cost of carrying out and monitoring restoration treatments on national forests. Many projects under the CFLRP have gone through National Environmental Policy Act review and could be initiated quickly with additional funding.
- Congress should provide additional funding for Interior Department hazardous fuels reduction programs on public lands managed by the National Park Service, U.S. Fish and Wildlife Service, Bureau of Land Management, and Bureau of Indian Affairs.
- BPC recommends lifting the cap on the Reforestation Trust Fund (RTF) to $60 million per year and funding the U.S. Forest Service at that full amount to implement reforestation projects in National Forests. This is similar to the Reforestation Act introduced this Congress. The RTF, which was established in 1980 to reforest public lands impacted by wildfire, pests, disease, or timber harvests, is funded by existing tariffs imposed on imported timber and wood products. Lifting the cap would not raise tariffs.

- Additional funding for the U.S. Forest Service Wood Innovation Grant Program and the Rural Revitalization Technologies Program would help diversify rural economies by fostering opportunities for innovative wood products, such as cross-laminated timber. These grants promote the use of wood in commercial building construction and broaden wood products markets. BPC recommends federal funding of $40 million over four years for the Community Wood Energy and Wood Innovation Program and $20 million over four years for the Rural Revitalization Technologies Program.
- BPC recommends additional funding for the U.S. Forest Service Jobs Corps Civilian Center Wildland Fire Program and the AmeriCorps National Civilian Community Corps to (1) increase the number of certified wildland firefighters and (2) increase the number of trained workers available for completing necessary conservation and resource management projects on public lands and in communities across the country. AmeriCorps members are shared among various agencies including the U.S. Forest Service and the U.S. Fish and Wildlife Service.

We believe a significant opportunity now exists to advance policies that drive greater development and deployment of natural carbon storage practices. This is why the BPC Energy Project recently launched a new Farm & Forest Carbon Solutions Initiative that will focus on developing bipartisan consensus around a more specific set of policy options. As part of that process, we aim to fill key information gaps by:

- Analyzing the efficacy of existing USDA and Interior Department programs and authorities with respect to promoting natural carbon solutions;
- Identifying best practices for tailoring farm- and forest-based carbon policies to public, private, and tribal lands;
- Examining the need for changes to existing statutory authorities;
- Evaluating policy options—including for nutrient and manure management and for methane capture and use—that maximize economic and environmental benefits; and
- Assessing potential funding and implementation mechanisms such as public-private partnerships, voluntary carbon and/or ecosystem services markets, and federal grant programs or incentive payments to landowners.

6. Conclusion

Today's hearing is a welcome indicator of growing bipartisan interest in pragmatic, cost-effective solutions that can make a meaningful difference on climate change and help safeguard American prosperity and energy security as our nation makes the necessary transition to net-zero emissions. The fact is that we do not yet possess the technological capacity to fully decarbonize our energy systems consistent with the demands of a modern economy. Globally, the situation is even more daunting given many countries' current resource constraints and development needs.

Against this backdrop, BPC's American Energy Innovation Council has consistently called for a tripling of federal energy innovation budgets and for increased efforts to deploy "first of a kind," breakthrough technologies here in the United States. Achieving net-zero carbon emissions in a mid-century timeframe clearly requires some combination of greatly expanded deployment of already available and cost-competitive low- and zero-carbon options, together with the accelerated development and implementation of new technologies such as advanced nuclear, zero-carbon fuels, long-duration

electricity storage, carbon capture and storage, and direct air capture. For many new technologies, targeted federal support can make the difference in the crucial leap from early-stage research and demonstration to commercial success.

Getting to net-zero carbon, however, also requires fresh thinking about how to unite diverse stakeholders around the multiple benefits that can flow from effective climate action. Among farm owners and forest managers, for example, there is growing interest in natural carbon removal opportunities. As in other industries, however, policies that are viewed as increasing cost or uncertainty are likely to continue to lack support. Finding new ways to encourage and reward practices that also deliver economic benefits to farmers and forest owners—and that position farmers, ranchers, and forest managers as valued contributors to climate solutions—will be instrumental. Similarly, positioning DAC as a mitigation option for industries that might have difficulty fully decarbonizing, and as a way to supply carbon dioxide for use in other applications while also delivering climate benefits, could help increase investor interest in this technology. In both cases, a diverse coalition in support of CDR solutions can be a powerful voice in the conversations that are occurring now around economic stimulus and recovery in the near term, and viable climate solutions in the longer run.

For too long, the debate over policy responses to climate change has been held hostage by extreme views: that there's either no problem, or in any case nothing to be done, on the one hand, or that solutions are easy and costless on the other. Now time is running short. The Committee's willingness to engage these issues with the seriousness and purpose they deserve is grounds for hope that a new consensus, and a new basis for real progress, is beginning to emerge.

13

Endnotes

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[8] The three companies currently active in DAC are U.S.-based Global Thermostat, with pilot plants in California and Alabama and plans to build a commercial demonstration plant in Oklahoma and a technology center in Colorado; Canada-based Carbon Engineering, with a pilot plant in British Columbia; and Switzerland-based Climeworks, with plants in Iceland, Switzerland, and Italy. (See BPC Fact Sheets. Available at: https://bipartisanpolicy.org/report/explaining-direct-air-capture)

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The CHAIRMAN. Thank you, Mr. Mackler.

We appreciate the contribution from each of you here this morning. Again, there is so much to talk about here, so I will just jump in. I will say though, as all of you have talked about the different areas that we can look to that are extraordinary opportunities for us, whether it is in the technologies or as you have ended with, Mr. Mackler, an emphasis or a recognition that our farms and forests can be these great carbon sinks as well. None of you have mentioned our oceans which, of course, occupy about, you know, I don't know what the percentage is, 70 percent of Planet Earth and this is an area, I know this is not jurisdictional to this Committee, but we have been looking into the opportunities that we find in seaweed and algae and kelp, particularly in Alaska. It is kind of exciting to think that we have available to us areas of—there is nothing innovative about kelp or sea grass, but to think that it can actually help us in how we are to sequester, accumulate, carbon is kind of exciting. So we are working on a blue carbon initiative with Senator Whitehouse, and again, an innovative, making things happen initiative out there.

I want to start with you, Assistant Secretary Winberg. When we talk about our ability to innovate our way forward, we recognize that there are oftentimes barriers that hold us back. One is opportunity for capital investment. It is just tough in these innovative areas. The other, and this is something that we can control a little bit more directly, are some of the regulatory matters that these innovators, those that are looking to make a difference here, that they encounter. Are there some regulatory reforms that you can think of that either you have been working on within the Department or that could stimulate more predictable and consistent investment in some of these technologies that we have been talking about?

Mr. WINBERG. Thank you for the question.

I think there are. In addition to the appropriations that we get that allow us to advance the R&D, and we are making great strides, the last time I talked to this Committee we were talking about a notional price of about $60 a ton for CO_2. We are seeing prices now in the $40 range, and we think we can get down to $30. With respect to policy, the 45Q is so very important and so making sure that the industry has the time needed to implement or to implement projects that can take advantage of 45Q, so extending out the sunset date for 45Q, I think, is very important.

And generally, the way I look at policy is carrots work much better than sticks, and 45Q is one of those carrots that will incent industry to move forward. Given the COVID–19 situation that we have, the need for an extension, I think, becomes more acute because companies' balance sheets are not as strong as they were. Their earning statements aren't as strong as they were. And so, as they're looking out at their capital investments, they may delay projects that they would otherwise do. And so, that's a good reason for extending out the 45Q.

The CHAIRMAN. Well, I appreciate you reiterating that. I think almost all of you have raised 45Q as one of those tools that we have. You have mentioned some of the good legislation that we have been working on, the EFFECT Act, we are looking at the

CREATE Act. So there are measures that are out there, but really highlighting 45Q, I think, is something for us all to be considering.

Let me ask a question to you, Mr. Hezir, and this is important for us to recognize that the work that is going on here is pretty critical, but we also want to know what others are doing in innovating in these areas. Senator Manchin and I had an opportunity, I guess it was now a couple years ago, maybe it was last year. We were at the University of Aberdeen and had an opportunity to go through a pretty exciting laboratory in terms of what they are doing to utilize the CO_2 into value-added products. And Assistant Secretary Winberg, you know, the thought that we are making decking and roofing. We saw sheetrock when we were there, building blocks. It is pretty exciting to see.

Mr. Hezir, can you share with us who—what other countries are really leading in this area that we are looking to for a little bit of inspiration or collaboration?

Mr. HEZIR. Yes, thank you, Senator, I'd be happy to do that.

In our report last year, we devoted an entire chapter to discussing international efforts on CDR research. You singled out Australia and that is, kind of, an interesting country because they're doing work on CDR mineralization. They're doing work on geologic sequestration, and they're also doing work on blue carbon and oceans-related CDR. So they do have a very broad-based program. But if you look around the world, in mineralization there's work going on in the Middle East in Oman, in Iceland, South Africa. A lot of work in DAC is going on right now in not only the project in Canada but in a number of European countries, and also in terrestrial and in the biological and the bioenergy with carbon capture area, the UK is engaged in a major project. And so, we see a lot of opportunities for international collaboration and I think, as Secretary Moniz said, Mission Innovation we see as a potential platform for expanding that into collaboration in CDR.

One final thing I would just mention. You brought up the concept of blue carbon, and the European Commission recently launched a four-year research initiative called OceanNETS involving six countries and, I think, 14 different institutions, including a few scientists in the U.S. that's going to be looking at a variety of oceans-related CDR and that would be just a wonderful opportunity for U.S. participation.

The CHAIRMAN. Great. I appreciate that. We will look into it.

Senator Manchin.

Senator MANCHIN. Well thank you so much and all of you for your expertise here.

A couple things that I was concerned about and this might be self-serving, but first of all, I was very disappointed about the Petra Nova plant in Texas. It stopped capturing carbon early this year due to the economic burden caused by plummeting oil prices. As we all know, the most common use for captured CO_2 is for enhanced oil recovery. Unfortunately, such as in my state, we are now seeing diversifications critical for longevity of the CCUS projects that we need to ensure that there are ways to create value from capturing CO_2 whether from power plants or from ambient air. So I would like to hear from the panel about other impacts of the pandemic on the deployment of CCUS and carbon removal

technologies and what other tools are needed to help foster innovative valuable carbon utilization methods?

Also, it would be helpful for more widescale deployment in states that don't have much oil to recover where we can put this, store this carbon. I am understanding with our saline and our mines that have been played out, there is a possibility of a tremendous amount of storage there that we can be putting CO_2 in. So if Mr. Winberg and any of the panelists want to respond to this.

Mr. WINBERG. One of the areas that, I think, we have a bit of a shortfall here in the United States is the necessary infrastructure to move CO_2. As you point out, not all areas are geographically or geologically suitable for CO_2 storage.

Senator MANCHIN. Well, especially those areas such as West Virginia that basically produce a lot of CO_2 because of the tremendous amount of power plants that we have and this is not feasible for it to work there unless we have some other use for it.

Mr. WINBERG. Yes, absolutely.

So two thoughts on that. One is building out a CO_2 infrastructure system. Pipelines are becoming increasingly difficult to build here in the United States, but that doesn't take away the very real need for a CO_2 infrastructure so that we can move this CO_2 to where it's needed to, in effect, commoditize it. And number two is the research that we have ongoing to find other uses for CO_2 beyond enhanced oil recovery, to turn CO_2 into a feedstock or a commodity to build out products whether it be fuel or other valuable products. So both of those are absolutely necessary if we're going to make significant reductions in CO_2 emissions.

Senator MANCHIN. One thing, if I can. The U.S. Geological Survey has estimated there is enough geological storage in the U.S. to store over 3,000 metric gigatons of carbon dioxide which is over 550 times the carbon dioxide that the U.S. emits in a year. But despite that vast resource for carbon storage, some of the regions of the country, like the majority of the East Coast, have little to no geological storage capability. We are looking for the most promising, existing solutions for this.

Yes, ma'am?

Ms. ANGIELSKI. Senator Manchin, you know, for those regions of the country that don't actually, like West Virginia, I mean, there is some storage potential, but it's a lot more expensive to store.

Senator MANCHIN. Yes. Correct.

Ms. ANGIELSKI. There's opportunities to look at, also, offshore opportunities. I know that the East Coast does have offshore potential, and I think that if we were doing more exploration there to understand how best to store CO_2 offshore, that would be one opportunity. The other, as mentioned, CO_2 you can convert into useable products already discussed, but I think that we, DOE's done a great job at financing projects to look at some of the research and developments needed. But I would recommend more increased funding for larger scale and testing at scale. Some of the challenges associated with CO_2 utilization or conversion is the amount of CO_2 that you produce from a power plant just overwhelms the amount of CO_2 that can be converted into the product. So we just need to be looking at broader scale storage opportunities there and funding those opportunities.

Senator MANCHIN. If——

Mr. MACKLER. Senator Manchin, if I might respond to your question?

Senator MANCHIN. Sure.

Mr. MACKLER. With respect to the impacts of COVID on all of this, it definitely has slowed things down. It has decreased the tax appetite for a lot of companies as Shannon had said earlier, this means that things like 45Q are not necessarily the only or best policy option. I would point you to other policy options like contracts for differences, rate recovery in the rate case. New York, for nuclear plants, has created a zero-emission crediting system, a ZECs, similar to the renewable RECs system. This is something that could also be done in the power sector. Interestingly, what we have also seen during COVID is that investment in CO_2 removal has grown. Investment in CO_2 reuse and recycling have grown. Investors see this as an important aspect of the future and there's a bit of a land rush into this space. Creating the policy, framework and the infrastructure, things like pipelines, to deliver this future is excellent and important work.

Senator MANCHIN. Let me just say one thing because my time has run out. My concern has been this, that basically the states that have been energy producers and the country has relied on for quite some time, that they are not left behind. These people who have done this tremendously hard work all these years, all they are asking for is an opportunity. So as we develop these new technologies, I would hope that the tax credits would be mandated to be used in the areas where the job loss has come from, from energy. If we are replacing energy technology, we are moving forward, then those people should have an opportunity for another life, if you will, and a good paying job. And there is where we can direct our tax credits to make sure they are used in areas that had the job losses in energy production. I would hope everyone would be conscious about that because it is very difficult, very challenging. Thank you.

The CHAIRMAN. Thank you, Senator Manchin.

Senator Barrasso.

Senator BARRASSO. Thank you, Madam Chairman and Ranking Member Manchin for holding this important hearing this morning. Thank you all for being here to testify.

The COVID–19 pandemic and economic slowdown has really offered all of us an opportunity to reflect on the future of our energy landscape. I would also like to thank the witnesses who are joining us today because your research and outreach efforts are critical to informing not just lawmakers but everyone as we work together to develop policies and strategies to tackle climate change. Wyoming is a leader in carbon management. We have the integrated test center in Gillette where they are holding the competition that, Madam Chairman, you mentioned the trip, along with Senator Manchin, to Aberdeen, Scotland, in which I was involved. One of those researchers we met is now part of the finalist group working in Gillette, Wyoming, on the prize related to finding better ways to capture carbon and use it. This is located next to Basin Electric's Dry Fork Station. Researchers can test scaled up versions of their carbon capture technology. The University of Wyoming is dedicated

to developing these technologies, educating the next generation of carbon management leaders and the Environment and Public Works Committee is going to be having a hearing in Gillette onsite on this coming up next month in August.

I have strongly advocated for the research, development and implementation of carbon capture, utilization and storage, and Madam Chairman, it makes me think about ten years ago, hard to believe, but it was ten years ago that you and I introduced the GEAR Act, 2010, which stood for Greenhouse Gas Emission Atmospheric Removal Act, to do just exactly what we are talking about. Then the Chairman of the Committee back at that time was Senator Jeff Bingaman from New Mexico who co-sponsored with us and worked on this legislation. So we have been at this for a while, as you have. Since then, we have worked hard to enact an expansion of the 45Q tax credit. All of you who have mentioned that today, my current bill, S. 383, the Utilizing Significant Emissions with Innovative Technologies Act, the USE IT Act, has now passed the Senate for the second time as part of the Fiscal Year 2021 National Defense Authorization Act. Senator Inhofe, he was a member and former Chairman of the Environment and Public Works Committee, made sure it was in the bill. So we look forward to having that as a policy for our nation soon.

It is good to see some old friends back. Secretary Moniz, good to see you again. You and I have discussed the scale of carbon capture removal when you testified before the Committee last year. I think you noted that we have to think about removing carbon dioxide on a gigaton scale. Mr. Hezir, how quickly can we scale up current projects to reach, as Dr. Moniz described, a gigaton level of removal of carbon dioxide?

Mr. HEZIR. Senator, thank you for the question.

In our report we had outlined a very rigorous, sort of, goal-oriented RD&D program that would really deliver the types of solutions that we need at scale within a ten-year period. And so, we would see the next decade as really being a decade of innovation leading into then a period of large-scale deployment. I think that the pace of the deployment ultimately will depend upon some combination of what future climate policy might be as well as future financial incentives. But right now what we see is the need to really develop the innovation agenda so that we have the types of solutions that we need that can be deployed at scale and can be not only that but also the range of solutions that not only include direct air capture, but also looking at other pathways like terrestrial and oceans and mineralization.

Senator BARRASSO. This is a question then for all or any of the witnesses because to achieve this kind of gigaton-scale, the world's largest CO_2 emitters—India, China—they need to actively engage in carbon removal. What should we be doing to make sure that China, India and other major, global economies are serious about using large-scale carbon removal technologies? And anyone who wants to jump in on that can do that.

Yes?

Mr. MACKLER. Thank you for the question, Senator.

What I would encourage the Committee to think about as we think about large-scale carbon removal is that there are a portfolio

of technologies available today, or in the pipeline, that will be available at some point in the future and the leadership of the United States in helping to advance all of that will really pay dividends to us as we look at the export market going forward. And there are things that we can do today, when, especially when it comes to natural sinks to enhance those natural sinks by developing technologies and creating markets so that the best practices and those advancements can go into the marketplace as we develop the more technological solutions like direct air capture and that will, and the scale will come from the innovation program being coupled with the right policy frameworks that can create the business models so that private capital can invest and actually deploy these technologies. And at that point, that's when we will have shown the technologies work and can then export them to the world.

Senator BARRASSO. Thank you.

Mr. Secretary, I see you have removed your mask.

Mr. WINBERG. I think there are a number of forums that we're working in already, the carbon sequestration leadership forum, the CEM and those are international organizations, some working with IEA, some that are separate from IEA, but those are the opportunities where we can promote the U.S. technology because again, Senator, the U.S. is leading in the carbon capture space. The Integrated Test Center is just a spectacular site for small-scale testing of these capture technologies where, again, we're on the path to reduce the cost down to $30 a ton, per metric ton. Nobody else in the world is where we are with respect to developing these capture technologies, getting them commercialized and especially getting the cost down.

So I think that there are a lot of opportunities for us to take that technology and export it to other countries, and we are doing that through these forums that I mentioned.

Senator BARRASSO. Thank you, Madam Chairman.

The CHAIRMAN. Thank you, Senator Barrasso.

Let's turn to Senator Heinrich.

Senator HEINRICH. Thank you, Chairman, and I want to thank you and the Ranking Member for having this hearing. It really is long overdue. A lot of work has been occurring in this space and now it is starting to really break into the news and into the popular imagination. I think we have an opportunity where there is a lot of interest on both sides of the aisle to really push this forward.

My first question is to Mr. Hezir. There is now a growing consensus that we are going to need to remove carbon dioxide from the atmosphere because of how long we have delayed addressing carbon pollution, and we know that there are chemical technologies today that are proven that do this but they are all relatively expensive, quite expensive, compared to where we need them to be. How do we balance that portfolio of potential chemical processes, make sure we treat them fairly, but at the same time provide tools to, as rapidly as possible, drive that proven science down the cost curve the way that we have seen technologies like solar, distributed generation driven down the cost curve?

Mr. HEZIR. Yes, Senator, you're absolutely right. There are a variety of chemical methods starting out with some of them being borrowed from, you know, long experience in the petrochemical industry. In our report one of the things that we identified as the very early on opportunity for DOE is to start off by really doing a comprehensive technoeconomic assessment of the various alternatives out there and by doing so by including funding some of the operating and data collection costs from some of the existing pilot scale projects, but then, as a principal research priority should be focused on the objective of cost reduction.

And there's three areas in our report that we identify that we thought were critical. One was the development of better sorbents, the second one was materials and structures for carbon capture systems, and then the third one is in manufacturing, being able to create engineered systems that can be manufactured at mass scale. And particularly in the first two areas, sorbents and materials, are areas where the national laboratories, in particular, can be extremely helpful in identifying innovative approaches for both of those.

Dr. FRIEDMANN. Senator, if I could add quickly to this?

The thing—there are companies out there that deliver carbon capture solutions, direct air capture, in particular. The thing they need is customers. More than anything else, to get down the cost curve, we need to deploy. And in this context the government has always been the first purchaser of clean energy. They bought solar panels.

Senator HEINRICH. Yes.

Dr. FRIEDMANN. They bought windmills. They bought fuel cells. They bought batteries for military applications, for aerospace applications, for federal buildings. I would encourage the Committee to consider the government directly procuring direct air capture services.

Senator HEINRICH. That is a great point.

I want to go on to hydrogen. We have heard a fair bit today about making hydrogen from fossil fuel sources, but if you look at the news right now and if you just follow the energy news, you are seeing an enormous amount of investment in renewable hydrogen, even though there is a cost increment. So you are seeing NextEra make an announcement in Florida for a $65 million pilot solared hydrogen plant. You sre seeing Iberdrola investing in Spain. You are seeing Air Products and Chemicals investing in a plant in Saudi Arabia. Why is there an apparent disconnect where making hydrogen from fossil sources is cheaper today but clearly industry thinks that it may not be tomorrow because we are seeing a really substantial amount of investment in renewable hydrogen, green hydrogen directly from renewable sources?

Mr. Winberg, you look like you want to answer that.

Mr. WINBERG. There is a lot of press these days about the so-called green hydrogen, but the fact of the matter is at about——

Senator HEINRICH. You said so-called. Why do you say so-called?

Mr. WINBERG. I say so-called because with steam methane reforming using natural gas and CCUS, you can get 95 percent carbon capture and that's been given the color code of blue, but it's pretty clean hydrogen. You can also use coal with biomass and

some waste plastics and municipal solid waste with CCUS and then you're not——

Senator HEINRICH. But obviously industry thinks that is not where we are going. I mean, if you just look at where the investment is headed. What do they know that you are missing?

Mr. WINBERG. I don't think——

Dr. FRIEDMANN. Senator?

Mr. WINBERG. I don't think that I'm missing anything, Senator. I think there's a lot of press coverage on the so-called green hydrogen, but again, the fact is that we are continuing to produce the vast majority of methane around the world with natural gas and there are opportunities——

Senator HEINRICH. You mean hydrogen, not——

Mr. WINBERG. I'm sorry, hydrogen from methane.

Senator HEINRICH. Yes. They do produce a lot of methane. That is what we are trying to get away from.

Mr. WINBERG. Well, I don't know if it was Freudian but it's methane produced, or hydrogen produced from methane. What we haven't attached to that is CCUS, but we have one project and it's Air Products and they are producing blue hydrogen.

Senator HEINRICH. Air Products is also investing in renewable hydrogen in Saudi Arabia, but my point is simply that I think we should have some of those voices at the table because they obviously are keyed into a trend that I think we should all be aware of.

The CHAIRMAN. Thank you, Senator Heinrich.

Let's now turn to Senator Daines.

Senator DAINES. Thank you, Chair Murkowski.

Montana is uniquely situated to lead the nation in carbon capture. We have the largest reserve of recoverable coal. We have large-scale coal plants like the Colstrip Power Plant. We have easy access to geological storage and the potential use of carbon for enhanced oil recovery. We really check all the boxes in Montana.

However, unfortunately and due to extreme litigation, Colstrip Units 1 and 2 were forced to close earlier than planned. We are also seeing an early closure of a coal plant in Sidney, Montana, on the eastern side of our state. Both sites could be perfect locations for DOE investment, specifically for a large-scale, DOE-funded CCUS demonstration project. The workforce is there. Transmission capacity, which is a very important component of all this, is there. It is already built, and the community is ready. All that is needed is for DOE to come out and work with Montanans to get this funding flowing.

Assistant Secretary Winberg, DOE has a number of different funding streams for CCUS from beginning stage feasibility and engineering studies to full-scale demonstration projects. As I mentioned earlier, Montana and, specifically, the Colstrip Power Plant are prime areas for DOE investment. Could you provide an update on what funding opportunities would be available and how we might get this money out to a place like Colstrip?

Mr. WINBERG. Yes, Senator, I'd be happy to and thank you.

So DOE did, we supported a CCUS study at the Colstrip Power Plant. We are also moving forward very quickly with our Coal FIRST program and so, I think there are opportunities for plants

like Colstrip to host a Coal FIRST power plant which may very well produce hydrogen, might produce electricity, might produce both. And I think there's also an opportunity for Colstrip to avail themselves of the much talked about 45Q. There are a lot of developers out there that are looking at a variety of facilities to install CCUS to avail themselves of the 45Q tax credit, and I think Colstrip is uniquely situated to avail themselves of that.

Senator DAINES. So it is a huge issue for us in Montana, not only as Colstrip providing a lot of good high-paying jobs, it is an incredible part of our tax base there for Montana to support our education systems and basic government services, not to mention it provides baseload for the grid, very, very important. My request would be, would you commit to working with me and Montanans to find ways that DOE could invest in communities like Colstrip?

Mr. WINBERG. Absolutely, yes, sir.

Senator DAINES. Secretary Winberg, you know the 45Q tax credit is essential for companies to invest in and build CCUS technology. However, we have been waiting for years, it has been years, for finalized guidance and rules from Treasury. DOE has been intimately involved with Treasury on this guidance but we need a finalized rule. On May 28th, Treasury and IRS released proposed regulations. That is an important step, increasing certainty for companies investing in this technology, but these are large investments into—they need this certainty. However, these rules are subject to change or being revoked until they are, this is the important word, finalized. Could you give me an update on the release of a final rule and can you commit to me that DOE will work to get all those involved to get this done this year?

Mr. WINBERG. I'd be happy to give you an update, sir.

The 45Q is out for comment. It closes on Monday and then I am quite confident that DOE will be working with the Internal Revenue Service as we have during this entire 2+-year period, working with them on the final rulemaking that will then provide the necessary guidance for the CCUS projects. And I can commit to you that we will do everything that we can to assist IRS not only to make sure that the rule accommodates projects, but does it as expeditiously as possible.

Senator DAINES. Yes, we need this finalized as quickly as possible. Thank you.

Mr. WINBERG. Yes, sir.

Senator DAINES. Last question, Mr. Winberg.

DOE also administers a number of loan and guarantee programs, including the Advanced Fossil Energy Program, the Renewable and Efficient Energy Program and the Tribal Energy Program. It is my understanding that a large amount of the lending potential still remains unused. These programs seem to be a perfect fit to help companies that want to invest in CCUS, but they are struggling for capital, particularly during this COVID–19 pandemic. What do we need to do to get more of these loans out the door?

Mr. WINBERG. Well, I think first and foremost they have to be financeable projects and then they have to go through the phase requirement. I can tell you that the Secretary of Energy, Secretary Brouillette, committed and asked for a formal review of the program requirements to see what could be done to expedite the pro-

gram. And sir, I know that that is underway. But we have been working with the Loan Program Office on a number of fossil energy projects and it is, a lot of times the hang-up is that they are not yet bankable projects and that creates some challenges.

Senator DAINES. Mr. Winberg, I am out of time. Thanks for your answer.

The CHAIRMAN. Thank you, Senator Daines.

Senator King.

Senator KING. Thank you, Madam Chair, and thank you for holding this hearing. I want to state at the outset that I think this is an incredibly important issue. We have these tremendous fossil fuel resources in this country, the problem is CO_2 and so, to the extent we can find solutions to that problem, it would be good for the society, good for the climate, good for the planet.

Mr. Hezir, the issue, it seems to me, is cost. As Senator Heinrich mentioned, solar and battery technology has diminished significantly in cost, dramatically in the case of solar over the last 15 or 20 years. The question I have is, is it realistic to expect that kind of downward cost curve in carbon capture or carbon removal? I am going to differentiate between those in a minute, but are we chasing something that is feasible and reasonable to chase or is this economically impossible?

Mr. HEZIR. Yes, Senator.

I think it varies across the technology so obviously we know from experience that some of the chemically-based technologies, there are opportunities for innovation there and there's also opportunities for learning by doing, deployment at scale that can help with the economics there. So we do think that there are opportunities to bring down the cost there. I do want to just quickly add a comment on Senator Heinrich's question with respect to hydrogen. And there, I think that, clearly, I think that the industry is looking at the combination of innovation in electrolyzer technology as being also an opportunity for significant cost reduction. And when you compare that with cheap electricity such as one cent per kilowatt-hour solar, you can ultimately drive down the cost—of green hydrogen.

Senator KING. The idea——

Dr. FRIEDMANN. Senator King?

Senator KING. Yes, yes.

Dr. FRIEDMANN. If I could add to your question, we have seen the cost of CCS drop 50 percent in the past ten years. We're going to see it drop again, 50 percent in the next five to ten years and again after that. We are nowhere close to the engineering or thermodynamic limits of cost reduction. And the best way to get it forward is to create incentives for deployment and to get learning by doing in the market.

Senator KING. And by continued support for research and innovation.

Dr. FRIEDMANN. Absolutely essential. That makes it faster. It accelerates our pathway to cost reduction and decarbonization.

Senator KING. As an old energy guy in the energy business, I think in terms of cost per kilowatt-hour. Can anybody give me a figure on what $30 per ton of CC equals in per kilowatt-hour?

Dr. FRIEDMANN. I can give you those answers, but it varies a lot by plant type, by heat rate, by all these other kinds of things.

Senator KING. Sure.

Dr. FRIEDMANN. A good way to think about it is on the order of one and a half cents per kilowatt-hour for a coal—for a kilowatt-hour that's about what it would be on a gas plant. Retrofitted would be closer to two cents for a coal plant retrofit.

Senator KING. And that is at current cost, not projected hoped-for cost, is that correct?

Dr. FRIEDMANN. No, that's at $30 which is what you said, so at $30 cost. Sixty-dollar cost it's more like two and a half cents, which is what it is today.

Senator KING. Okay.

Dr. FRIEDMANN. But I would recommend that you think about this not just from the power sector. If you think about it in terms of dollars per ton steel made, or petrochemical production or hydrogen, it is way, way cheaper than every other option.

Senator KING. Other than that one cent solar power you mentioned.

Dr. FRIEDMANN. Even at one cent solar power, you're talking about a 25 percent capacity factor. In order for green hydrogen in the United States to be the same cost as blue hydrogen in the United States, it needs to be a half cent per kilowatt-hour at 25 percent capacity factor or it needs to be three cents a kilowatt-hour, 90 percent of the time.

Senator KING. So the tradeoff would be the capital cost to develop excess solar capacity that could be used for hydrogen production——

Dr. FRIEDMANN. That's an important part of it, yes.

Senator KING. ——as a kind of battery.

Dr. FRIEDMANN. That's one way to go, yes. And if you're thinking about power markets, that's a good thing to do. If you're thinking, though, about the infrastructure required for that, just providing U.S. steel with hydrogen made from green hydrogen, you'd need a 50 percent increase in the U.S. grid. There's just a lot that needs to be done.

Senator KING. I understand.

Give me an idea of the cost differential between carbon removal and air capture. It is significant, is it not?

Dr. FRIEDMANN. Right. So today direct air capture is about $450 a ton. That's the cheapest plant that's operating. In 2025, we expect the first million-ton-per-year plant to be operating. I expect that will come in below $200 a ton, and by 2030, I expect it will be cheaper than $150 a ton.

Senator KING. And what is the price of capture?

Dr. FRIEDMANN. That's the all-in cost capture, transportation and storage from direct air capture. By comparison——

Senator KING. I am sorry, what is removal?

Dr. FRIEDMANN. That is removal.

Senator KING. I am looking for the differential between removal and capture.

Dr. FRIEDMANN. So the costs that I just gave you were for direct air capture. So that would be by 2030, maybe $150 a ton. For point-source capture, probably on the order of $30 a ton.

Senator KING. That is a 2030 estimate, that $30 a ton? That is the goal.

Dr. FRIEDMANN. Correct.

I would say though that cash for clunkers is $400 a ton. What we pay for ethanol today is $500 a ton. The EV subsidies are $600 to $1,400 a ton. We already pay for this stuff.

Senator KING. Got it.

Thank you. If you could follow up with the Committee with some of that analysis, the financial analysis, now, 2025, 2030 estimated, I think that would be very helpful.

Thank you.

Dr. FRIEDMANN. I would be eager to do so.

Senator KING. Thank you.

[Information regarding financial analysis of carbon removal and direct air capture follow.]

Response from Dr. Friedmann to Senator King:

Regarding Sen. King's request, here are the key references I used to answer his questions:

On the cost of prior policies:
Gillingham & Stock, 2018 (PDF attached)

On the costs of point-source capture today:
NPC Dual Challenge Report (https://dualchallenge.npc.org/)

On the cost of DAC for the first 1 million ton/y plant and the potential costs in 2030:
Rhodium Group (PDF attached – https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/)

All of these are captured in a new figure from a new report by our Center (I'm principal author). The link to the full report is located at: https://www.energypolicy.columbia.edu/research/report/net-zero-and-geospheric-return-actions-today-2030-and-beyond. The key figure is Figure 8 (page 40), but I've attached an image of the key figure regarding Sen. King's questions.

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The Cost of Reducing Greenhouse Gas Emissions

Kenneth Gillingham and James H. Stock

What is the most economically efficient way to reduce greenhouse gas emissions? The principles of economics deliver a crisp answer: reduce emissions to the point that the marginal benefits of the reduction equal its marginal costs. This answer can be implemented by a Pigouvian tax, for example a carbon tax where the tax rate is the marginal benefit of the emissions reduction or, equivalently, the monetized damages from emitting an additional ton of carbon dioxide (CO_2). The carbon externality will then be internalized and the market will find cost-effective ways to reduce emissions up to the amount of the carbon tax.

However, most countries, including the United States, do not place an economy-wide tax on carbon, and instead have an array of greenhouse gas mitigation policies that provide subsidies or restrictions typically aimed at specific technologies or sectors. Such climate policies range from automobile fuel economy standards, to gasoline taxes, to mandating that a certain amount of electricity in a state comes from renewables, to subsidizing solar and wind electrical generation, to mandates requiring the blending of biofuels into the surface transportation fuel supply, to supply-side restrictions on fossil fuel extraction. In the world of a Pigouvian tax, markets sort out the most cost-effective ways to reduce emissions, but in the world

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we live in, economists need to weigh in on the costs of specific technologies or narrow interventions.

This paper reviews the costs of various technologies and actions aimed at reducing greenhouse gas emissions. Our aim is twofold. First, we seek to provide an up-to-date summary of costs of actions that can be taken now using currently available technology. These costs focus on expenditures and emissions reductions over the life of a project compared to some business-as-usual benchmark—for example, replacing coal-fired electricity generation with wind or weatherizing a home. We refer to these costs as static because they are costs over the life of a specific project undertaken now, and they ignore spillovers. In the environmental economics literature, these static costs are an element in creating what is called a marginal abatement cost (MAC) curve, which plots out the marginal costs of achieving a cumulative level of emissions abatement in order from the lowest- to highest-cost technology or measure.

To economists not in the energy-environment field, these marginal abatement costs might contain some surprises. Although we are skeptical of most "free lunch" static estimates, for some technologies the cost of emissions reductions is remarkably low. For example, blending corn ethanol into gasoline up to a 10 percent ratio provides essentially costless emissions reductions (our point estimate is in the "free lunch" range) in the United States because ethanol is a less-expensive octane booster than alternatives derived from petroleum. Another low or negative static cost source of emissions reductions is replacing coal-fired electricity generation with natural gas, a switch that has been widely adopted by power generators located where gas prices are low because of the fracking revolution. On the other hand, some actions that might seem green are, from a static perspective, anything but. For example, driving a Ford Focus electric vehicle in a region in which electricity is generated by coal has approximately the same CO_2 footprint as a Ford Explorer sport utility vehicle that averages 25 miles per gallon, and costs nearly as much. We find a wide range of costs for interventions currently being employed, both across and within different types of interventions. This heterogeneity in costs implies that we could achieve the same amount of greenhouse gas emissions reductions that we are achieving now at a much lower static cost, or greater emissions reductions for the same cost. Possible reasons for the use of more expensive policies include the chosen policies having less transparent costs, individual policies having justifications beyond just climate policy, differences in the marginal costs across locations, and lobbying by businesses that could potentially be affected by lower-cost policies. In some cases, especially policies aimed at developing nascent technologies, the policies are developed with a longer-term vision in mind.

These estimates of static costs help to inform discussions about climate policy, but they miss the critical consideration that climate change is a long-term problem. As a result, the proper answer to our opening question is not necessarily what is the least expensive mitigation strategy among options available today, but what are the actions if, taken today, will minimize the cost of mitigation both today *and* into the future, recognizing that actions taken today can influence future costs. We refer to such costs as dynamic, because they outlive the life of a specific project.

Our second aim is to distinguish between dynamic and static costs and to argue that some actions taken today with seemingly high static costs can have low dynamic costs, and vice versa. We make this argument at a general level and through two case studies, of solar panels and of electric vehicles. The cost of both technologies has fallen sharply, arguably driven in part by demand-side incentives that in turn stimulated learning-by-doing and technological improvements, the benefits of which are only partially captured by the manufacturing firm. In addition, purchasing an electric vehicle today drives the demand for charging stations, which in effect reduces the cost (here, the cost of time and worry) to potential future purchasers. Under the right circumstances, such dynamic effects can offer a justification for policies that a myopic calculation suggests have high costs.

Estimates of Static Abatement Costs

Before we begin, we briefly digress on units. The standard units of emissions costs and benefits are dollars per metric ton (1,000 kilograms) of CO_2 emissions avoided. As a point of comparison, the social cost of carbon is an estimate of the net present value of monetized social damages from emission of an additional metric ton of CO_2; under the Obama administration, the US government estimated the social cost of carbon to be approximately $46 in 2017 dollars for a ton of emissions in 2017 (IWG 2016).[1] Burning one gallon of petroleum gasoline produces roughly nine kilograms of CO_2, so a social cost of carbon value of $46/metric ton CO_2 corresponds to $0.41 per gallon. Also, carbon dioxide is only one of many greenhouse gases; others include methane, nitrous oxide, and hydrofluorocarbons. To facilitate comparisons, it is conventional to convert costs for reducing non-CO_2 greenhouse gases into CO_2-equivalent units, and we adopt that convention here.[2]

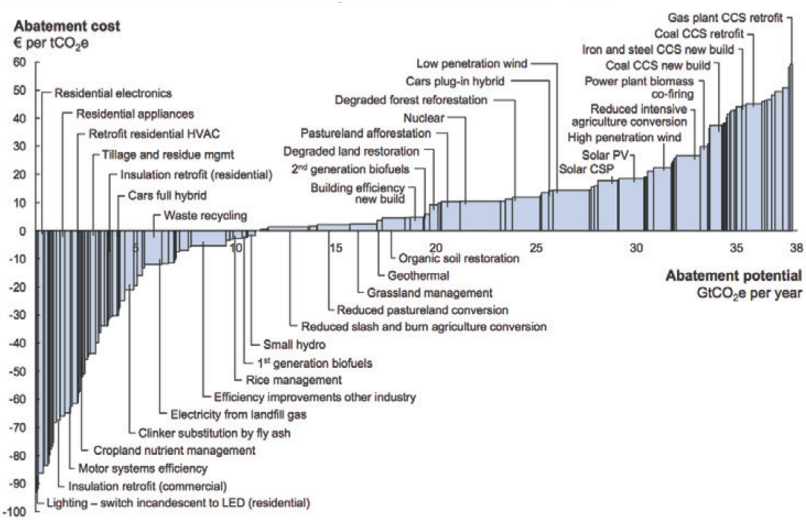
Brief Background on Marginal Abatement Cost Curves

The marginal abatement cost (MAC) curve plots measures to abate emissions in order from the least to most expensive. For each, there is a cost per ton of emissions reduced and a quantity of emissions reductions available at that cost. The

[1] The Trump administration withdrew this estimate by executive order and forbid agencies from using the underlying research for regulatory purposes; as of this writing, the Environmental Protection Agency is using two estimates, $1 and $6 per ton, depending on the discount rate (3 or 7 percent) (Newell 2017). The estimate of $46/ton is in the range of the academic literature, although some estimates are much higher (as one example, see Gillingham et al. 2018). There is currently a cross-institutional interdisciplinary effort to provide a comprehensive update to the social cost of carbon based on recommendations made by the National Academy of Sciences (2017), which is discussed on the Resources for the Future website at http://www.rff.org/research/collection/rffs-social-cost-carbon-initiative.

[2] A complication in developing CO_2-equivalent estimates is that the atmospheric residence time of greenhouse gases varies. The most common approach, the global warming potential approach, is only an approximation when used to calculate the social cost of non-CO_2 greenhouse gases. See Marten and Newbold (2012) for a more comprehensive approach to calculating the social cost of non-CO_2 greenhouse gases.

Figure 1
The McKinsey (2009) Marginal Abatement Cost Curve: "Global GHG Abatement Cost Curve Beyond Business-As-Usual-2030"



Source: Global GHG Abatement Cost Curve v2.0. Figure and notes reproduced with permission from McKinsey (2009).
Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO_2e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

use of MAC curves to support climate policy analysis dates back at least a quarter century (for an early review, see Grubb, Edmonds, ten Brink, and Morrison 1993). All models that estimate the mitigation costs of climate policy either implicitly or explicitly use a MAC curve.

The most prominent attempt at developing a comprehensive marginal abatement cost curve is the well-known McKinsey curve, which is constructed using engineering estimates of the cost of implementing new technologies or other measures.

Figure 1 displays the global version of the McKinsey curve (McKinsey & Company 2009). A striking feature of the McKinsey curve, which is shared by MAC curves more generally (for example, see figure 2 in Grubb et al. 1993), is that some interventions have negative abatement costs: that is, emissions can be reduced, and money saved, at the same time. Economists, including ourselves, are often skeptical of these "free lunch" estimates, unless they are supported by convincing evidence and explanations. Negative costs require institutional entities, such as firms, not to be optimizing, or require the existence of behavioral failures in consumer decision-making (like consumers acting myopically). In some cases, entities such as

Table 1

New Source Generation Costs when Compared to Existing Coal Generation

(ordered from lowest to highest)

Technology	*Cost estimate ($2017/ton CO_2)*
Onshore wind	24
Natural gas combined cycle	24
Utility-scale solar photovoltaic	28
Natural gas with carbon capture and storage	42
Advanced nuclear	58
Coal retrofit with carbon capture and storage	84
New coal with carbon capture and storage	95
Offshore wind	105
Solar thermal	132

Source: Author's calculations updating methodology from Clean Air Task Force (2013) based on Energy Information Administration estimates from the 2018 Annual Energy Outlook. Costs are projected for facilities that come online in 2022. Costs do not incorporate federal renewable tax credits.

governments are institutionally complex and/or not minimizing costs, so these free-lunch savings are potentially valid but institutionally difficult to realize. When these negative costs are for energy efficiency programs, this is often called the "energy efficiency gap" and there is a continued debate in the literature on whether there is a real gap or whether the gap can be explained by unaccounted-for costs (Gerarden, Newell, and Stavins 2017; Gillingham and Palmer 2014; in this journal, Allcott and Greenstone 2012).

The concern over negative costs highlights a limitation of marginal abatement curves like the McKinsey curve in Figure 1: specifically, that they are based on engineering estimates, which have their own assumptions and typically do not include behavioral considerations. An example of such a behavioral effect is turning the heat up because the cost of doing so has declined because of weatherization. Economists are typically interested in the combined effect of behavioral responses and the engineering costs.

Static Cost Comparisons

In addition to these and other methodological concerns, the cost estimates in the McKinsey curve in Figure 1 are out of date. We therefore turn to more current estimates of marginal costs. These estimates are drawn from the economics and trade literatures, supplemented by our own calculations.

To fix orders of magnitude, we begin with some "bottom-up" or engineering cost estimates for the power sector, presented in Table 1. These estimates compare the cost per ton of CO_2 abated by replacing electricity generated by an existing coal-fired power plant with electricity generated by a cleaner alternative. The estimates are based on the US Energy Information Administration's (2018) so-called

"levelized" cost of electricity for the different sources, which combines discounted capital, operating, and maintenance expenses to produce a cost of energy per megawatt-hour, given the typical utilization rate or capacity factor for each generation type. These estimates are similar to private sector estimates, such as those by Lazard (2017).

According to these estimates, the least expensive technologies to reduce emissions relative to existing coal are onshore wind, natural gas combined cycle, utility-scale solar photovoltaics, and natural gas with carbon capture and storage technology. Advanced nuclear technologies are more expensive, followed by other carbon capture and storage technologies, offshore wind, and solar thermal. The technologies in this set of estimates that are less expensive (when replacing existing coal) than the Obama administration's social cost of carbon estimate of $46 per ton of CO_2 are onshore wind, natural gas combined cycle, utility scale photovoltaic, and natural gas with 90 percent carbon capture and storage. In comparison, offshore wind and solar thermal are currently quite expensive ways to reduce emissions (although offshore wind costs are falling). These estimates only consider climate benefits of switching from coal, not any other health co-benefits arising from reductions in local air pollutants.

From a policy perspective, engineering cost estimates such as those in Table 1 have important limitations. Some of these technologies are in wide current use, so cost estimates are reasonably reliable (onshore wind, natural gas combined cycle), whereas other technologies have demonstrated technical feasibility but current projects are subject to large cost overruns, so the engineering costs could be underestimates (for example, advanced nuclear, carbon capture and storage). Another limitation is that these are national averages, and costs vary regionally depending on local conditions (for example, local fuel prices, wind conditions, and insolation). In addition, these are costs of switching technologies, which differ from the costs of a policy designed to encourage technology switching. These engineering estimates do not incorporate behavioral responses or any indirect emissions such as fugitive methane emissions from the production and transport of natural gas.

We therefore turn to a systematic review of costs of interventions—typically policies—aimed at reducing greenhouse gas emissions. This review draws on more than 50 recent articles in the economics literature. We selected papers based on a few criteria. First, the paper must be an economic analysis, so we draw most heavily from papers published in economics journals and economics working paper series. Second, the paper must either have enough information so that we can calculate a cost per ton of emissions reduction or include an explicit estimate of this cost. Most papers we review have an explicit estimate in dollars per ton CO_2. Third, we focus on papers published in the past decade, and nearly all of the papers included in our review are published after 2006. In some cases, we have supplemented the estimates from the economics literature with studies from the trade literature and/or our own calculations.

The results are summarized in Table 2. The table presents ranges of estimates whenever there are multiple estimates from either the same study or multiple studies; the online Appendix available with this paper at http://e-jep.org provides

Table 2

Static Costs of Policies based on a Compilation of Economic Studies

(ordered from lowest to highest cost)

Policy	*Estimate ($2017/ton CO_{2e})*
Behavioral energy efficiency	−190
Corn starch ethanol (US)	−18 to +310
Renewable Portfolio Standards	0–190
Reforestation	1–10
Wind energy subsidies	2–260
Clean Power Plan	11
Gasoline tax	18–47
Methane flaring regulation	20
Reducing federal coal leasing	33–68
CAFE Standards	48–310
Agricultural emissions policies	50–65
National Clean Energy Standard	51–110
Soil management	57
Livestock management policies	71
Concentrating solar power expansion (China & India)	100
Renewable fuel subsidies	100
Low carbon fuel standard	100–2,900
Solar photovoltaics subsidies	140–2,100
Biodiesel	150–250
Energy efficiency programs (China)	250–300
Cash for Clunkers	270–420
Weatherization assistance program	350
Dedicated battery electric vehicle subsidy	350–640

Note: Figures are rounded to two significant digits. We have converted all estimates to 2017 dollars for comparability. See Appendix Table A-1 for sources and methods. CO_{2e} denotes conversion of tons of non-CO_2 greenhouse gases to their CO_2 equivalent based on their global warming potential.

an expanded version of Table 2 with sources and methods. As in a marginal abatement cost curve, we have ordered the estimates in Table 2 from lowest to highest cost.

We highlight seven features of Table 2.

First, the range of costs of these interventions is extremely wide, from less than $10 per ton to over $1,000 per ton. What is striking about this range is that all the interventions in Table 2 are either policy steps that have been implemented, at least in some jurisdiction, or have been actively proposed and considered. Most of the costs are relatively expensive, in the sense that they exceed $46/ton. Evidently, static cost is only one consideration when a policy is proposed or considered. This heterogeneity likely stems from multiple sources, including the carbon intensity of the displaced fuel (for example, is the electricity on the grid coming from coal or hydropower?) and the other policies in place.

Second, there is a wide range of costs *within* a type of intervention. For example, subsidies to wind generation, such as the wind production tax credit in the United States, have estimated carbon abatement costs ranging from $2 to more than $260

per ton of reduced CO_2. For wind power, one reason for the large range is that there is large variation across sites in wind potential. The range is even wider for subsidies for solar photovoltaics, in part because there is wide variation in solar potential across locations (the solar power potential in southwestern Arizona is roughly twice that in upstate New York[3]), in part because of the timing of the programs (for example, earlier programs faced higher solar panel costs than later programs), and in part because of differences in scale (utility-scale arrays cost much less to install per kilowatt than rooftop arrays) (Baker, Fowlie, Lemoine, and Reynolds 2013). The wide ranges of estimates in Table 2 underscore that policies may have very different costs per ton of CO_2 depending on the empirical setting and/or the methodology of the study. The ranges of the estimates should not necessarily be taken as a proxy for uncertainty, for they simply show how estimates vary across studies. Due to within-study uncertainty, values above and below the ranges are likely to occur with some probability.

Third, some of the interventions that have negative economic costs in the McKinsey curve (and in other marginal abatement cost curves) have positive costs here. For example, engineering estimates of weatherization programs often suggest that they have negative costs. So why have such changes not already been undertaken? This is the energy efficiency paradox. In a randomized controlled trial, however, Fowlie, Greenstone, and Wolfram (2018) found that the actual costs of the weatherization exceeded the savings, leading to the $350/ton estimate of the mitigation cost reported in Table 2. They attribute the difference between the negative engineering costs and the actual positive costs for the homes in their study primarily to flaws in the engineering models.

Fourth, some of the costs in Table 2 *are* negative. A striking estimate arises from behavioral economics studies of how small nudges can get consumers to reduce their energy consumption, thereby saving money while reducing emissions; the estimate in Table 2 is taken from Allcott and Mullainathan's (2010) meta-analysis of behavioral interventions. An example of such a nudge is the OPOWER program, in which an insert in the residential electricity bill compares the homeowner's usage to that of neighbors, costing the utility very little and leading to consumer savings. One concern, which we share, is that while the cost of such reductions is negative, the total emissions reductions from such nudges are likely to be relatively small and partially transitory. The other negative estimate in Table 2 is for corn ethanol, which some might find surprising.

In the United States, petroleum gasoline blend stock must be blended with an octane booster to bring it up to the 87 octane standard of regular unleaded gasoline. Ethanol is a lower-cost octane booster than its petroleum alternatives (Irwin and Good 2017). In 2012—a year in which there were no direct federal subsidies and the federal ethanol mandate under the Renewable Fuel Standard was not binding—ethanol comprised just under 10 percent of the US retail gasoline supply.

[3]See the National Renewable Energy Laboratory (NREL) National Solar Radiation Database (NSRDB) Data Vewer at https://maps.nrel.gov/nsrdb-viewer/.

The California Air Resources Board (2018) estimates that ethanol from new corn ethanol plants has roughly 70 percent of the life-cycle CO_2 emissions of petroleum, including the carbon effects of induced land use change. Thus, for blends up to 10 percent, ethanol has negative greenhouse gas emissions reductions costs, and indeed is the market choice. Blending ethanol up to approximately 30 percent continues to enhance octane. The US fueling infrastructure, however, generally cannot handle blends above 10 percent, nor are engines designed to harness those octane advantages to improve energy efficiency, a situation known as the "E10 blend wall." As a result, subsidies are needed to incentivize ethanol consumption in blends higher than E10, and those costs increase quickly when measured in dollars per ton of CO_2 avoided.

Fifth, a few of the interventions have very low costs. Some, like the Clean Power Plan—the Obama administration's rulemaking for CO_2 emissions standards in the power sector—and regulations to reduce methane flaring from fracked oil wells that coproduce natural gas, are examples in which the regulation intensity was chosen with cost in mind. The Clean Power Plan is notable for its low cost per ton of emissions reductions (this estimate is taken from the *Regulatory Impact Analysis for the Clean Power Plan*, US Environmental Protection Agency 2015). This cost per ton is less than any of the engineering costs in Table 1, for two reasons. First, some of the emissions reduction comes from switching generation from existing coal-fired plants to existing gas-fired plants, and so does not require building a new plant as in Table 1. Second, because the Clean Power Plan allowed interstate trading of emissions permits, new low-greenhouse gas generating facilities would be built where it is most economically efficient to do so, yielding lower costs than the generic plant replacement costs in Table 1. The Clean Power Plan is also notable because its projected CO_2 emissions reductions are the largest, or nearly so, among the interventions in Table 2.

Sixth, some of the interventions have very high static costs. The United States and Europe have programs that require blending biodiesel into the diesel fuel supply. Biodiesel can be made from many oil feedstocks, including waste grease, but on the margin it is made from food-competing feedstocks such as soybean oil. These food oils are expensive and production of soy biodiesel requires a large subsidy, which is provided in the United States primarily through a tax credit and through the Renewable Fuel Standard. In other cases, the high costs are a result of inefficiencies in program design. For example, the temporary Cash for Clunkers program was installed at the depth of the recession in 2009 to provide an infusion of demand for new cars to support the auto industry and to provide countercyclical fiscal stimulus. Because the program exchanged old vehicles for more efficient new ones, it boosted fleet fuel economy. However, it had substantial temporary inframarginal transfers that were not a problem for its primary purpose—to pull forward auto demand—but made it a costly way to reduce emissions.

Seventh, the literature suggests that the cost of reducing carbon is low for some land use policies (see "Reforestation" on Table 2). In a randomized controlled experiment that lasted two years, Jayachandran et al. (2017) found that cash payments

for forest conservation in Uganda substantially reduced deforestation and cost $1 per ton of carbon sequestered. They do not, however, provide evidence on what happened after the payments stopped, and a natural concern is that there would be a reversion to the deforestation baseline. If so, the emissions reduction would be temporary, that is, the emissions would simply be postponed, not eliminated.[4] This distinction between permanent and temporary sequestration, along with the difficulty of ascertaining whether the payments actually induce incremental carbon retention in practice (something that was in fact found in Jayachandran et al.'s experiment), are at the heart of the controversy over the use of carbon offsets (for example, van Benthem and Kerr 2013; Bento, Kanbur, and Leard 2016).

One sobering insight from the estimates in Table 2 is that many of the least-expensive interventions cover a small amount of CO_2 reductions, whereas the scalable technologies that that are at the center of discussions about a transformation to a low-carbon economy—electric vehicles, solar photovoltaic panels, and offshore wind turbines—are among the most expensive on the list. Behavioral nudges are a very small step towards deep decarbonization. In contrast, the more expensive scalable technologies have a much greater potential for substantial emissions reductions. For these technologies, what matters most are not the static costs today, but the costs and consequences of these interventions over time, that is, the dynamic costs of the intervention. It is informative to know what are the cheapest interventions to do today, but we would argue that it is even more important to know what interventions might most effectively drive down the price of large-scale reductions in emissions in the future.

Dynamic Costs

The long residence time of CO_2 in the atmosphere makes climate change a long-term problem, in which (to a first approximation) what matters is the total number of tons emitted over some long horizon. As a result, the key to reducing emissions in the future is to have low-cost alternatives to fossil fuels that are zero- or low-carbon. The true total cost of investments or interventions today therefore must include both their static or face-value cost, and any spillovers those investments have for future costs of emissions reduction. The importance of a dynamic perspective is hardly new—see Popp, Newell, and Jaffe (2010) for a review—but it is often neglected both in the public debate and in the literature on costs of abatement. Yet, the welfare benefits of even small growth rates in the efficiency of clean technologies may be large, as suggested by simulations in Hassler, Krussel, Olovsson, and Reiter (2018).

[4]The distinction between temporary and permanent forest sequestration is important. Temporary rainforest sequestration is equivalent to storing emissions then releasing them later. In a manner analogous to how generating electricity from wind displaces retired coal-fired electricity, permanent sequestration permanently keeps the CO_2 in question out of the atmosphere.

Conceptual Framework

The static cost estimates of the previous section focus on direct reductions in emissions in the relatively short-run. However, expenditures on certain kinds of short-run reductions in emissions today can also affect emissions in the future, above and beyond direct emissions from the project. There are at least four reasons why this second component of emissions reduction could be nonzero and possibly large for some green technologies. Three of these stem from externalities, while the fourth is the difference between myopic and dynamic cost minimization.

First, many of these low-carbon technologies are nascent, and there could be substantial gains in production efficiency as more units are produced. Such gains can arise from engineering and managerial improvements made as production increases, a channel referred to as learning by doing, and from scale economies. To the extent that such gains are only partially appropriable by the firm, an expenditure today provides a positive externality that reduces costs in the future. The first case study that we discuss in the next subsection—solar panels—focuses on this learning-by-doing effect.

Second, a related externality arises from research and development spillovers because research results are only partially appropriable. These spillovers also represent a market failure, and economists have argued that the spillovers are likely to be particularly large for emerging clean technologies (Nordhaus 2011). To the extent that purchases today spur additional research, which then reduces costs, expenditures today reduce emissions tomorrow. It can often be difficult to separate the effects of research and development spillovers from learning-by-doing spillovers, for as a firm ramps up production, it also may ramp up research. For this reason, economists have often encouraged caution in relying too heavily on learning-by-doing to model technological change (Nordhaus 2014).

Third, a separate externality that is present for some technologies is a network or "chicken and egg" externality, in which an expenditure today influences the options that are available to others in the future. For example, purchases of electric vehicles today will, on the margin, stimulate demand for charging stations, which once installed will lower the effective cost for future potential purchasers of electric vehicles. Our second case study, of electric vehicles, in principle includes both learning-by-doing and network externalities.

Fourth, energy investments typically have substantial irreversible components, which in general implies state dependence so that the dynamically optimal path may differ from a sequence of myopic optimizations each chosen at a point in time. This potential for lock-in is at the heart of the debate about the merits of natural gas as a bridge fuel towards decarbonizing the power sector, in which renewable proponents argue that natural gas is cheaper only if one optimizes myopically and fails to recognize that the power sector will eventually need to be decarbonized. This intuition underlies Vogt-Schilb, Meunier, and Hallegatte (2018), who show that if abatement is achieved through investment in long-lived capital, it can be optimal to begin emissions abatement with expensive abatement investments that have large emissions reduction potential because they crowd-out dirtier long-lived investments. Irreversibility (state

dependence) also underlies the results of Fischer and Newall (2008), Acemoglu, Aghion, Bursztyn, and Hemous (2012), and Acemoglu, Akcigit, Hanley, and Kerr (2016), who show that a carbon price combined with research subsidies for low-greenhouse-gas technologies may be desirable to attain dynamically efficient outcomes.

Of course, long-term considerations may not always lower the cost of emissions reductions. For example, nuclear power has long had major federal research subsidies but its cost has gone up, not down (Davis and Hausman 2016). Additionally, as the marginal ton of displaced electricity becomes cleaner (for example, displacing natural gas instead of coal), the cost per ton abated by low-carbon renewables will tend to increase. One major reason why dynamic considerations are often ignored is that they tend to be highly uncertain. But that uncertainty should be viewed as a research challenge rather than an excuse to ignore dynamic considerations. And there is some evidence from the recent literature.

Dynamic Cost Case Study 1: Solar Panels

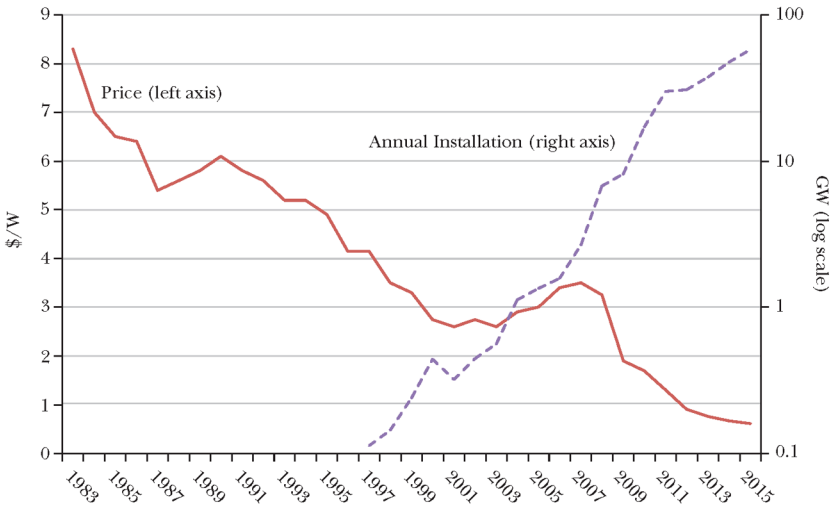
From 2010 to 2015, the price of solar photovoltaic panels fell by two-thirds, while annual global panel installations grew by 250 percent, as shown in Figure 2. The fact that panel sales increased when their price fell is hardly surprising, but more intriguing is that the steepest decline in panel prices after about 2007 post-dated the initial growth in panel sales, which began around 2002. The growth in sales in the mid-2000s was associated with policies that provided aggressive financial support for installing rooftop photovoltaic arrays through the German Energiewende, which provided a substantial feed-in tariff that allowed solar installations to be compensated at a very high rate for electricity fed into the grid, and the California Solar Initiative, which provided generous upfront subsidies for solar installations.[5] These early panel purchases were very expensive and account for some of the high photovoltaic cost estimates in Table 2. As stressed by a number of researchers (for example, Borenstein 2017), the static cost per ton of CO_2 reduced from policies to encourage solar installations tends to be high. Our literature review finds costs ranging from more than $100 per ton of CO_2 to in the thousands per ton of CO_2. On the lower end, Hughes and Podolefsky (2015) estimate costs of the California Solar Initiative at between $130 and $196 per ton. On the high end, Abrell, Kosch, and Rausch (2017) find a static cost per ton of €500–1300 (roughly $574–$1,492 in 2017 dollars) for solar feed-in tariffs in Germany and Spain (a solar feed-in tariff is a long-term fixed price contract for purchasing electricity from a solar array).

However, both the timing shown in Figure 2 and recent research suggests that the early push in demand, stimulated by deep government subsidies, did in fact help to drive down the price of solar panels. One channel is that current subsidies may

[5] Many US states have generous net metering policies that act as implicit subsidies by compensating solar fed into the grid at the retail rate. Some states have Renewable Portfolio Standards that require utilities to procure certain amounts of renewable power (sometimes with a solar carve-out) by certain dates. At the federal level, since 2008, there has been a 30 percent investment tax credit for the installation of a residential solar system.

Figure 2

Solar Panel Price Indexes Excluding Subsidies and Cumulative Worldwide Installed Capacity, 1983–2015



Source: International Energy Agency (2017), Navigant Consulting (2009), and Gerarden (2018).

encourage firms to innovate to reduce their future costs. Gerarden (2018) estimates that this induced innovation effect, which does not include learning-by-doing, contributed to the decline in solar array prices and increased the long-run external social benefits from global government subsidies to solar adoption by at least 22 percent. His results further suggest an important spillover from any single country that subsidizes solar to the rest of the world due to the investment in innovation by international firms. In this sense, the German Energiewende subsidized lower-cost solar for the rest of the world.

Other channels for cost reduction in the production of solar panels include learning-by-doing and economies of scale. Nemet (2006) decomposes the reduction in cost into the manufacturing plant size, module efficiency, and cost of silicon, finding that between 1980 and 2001, economies of scale from larger manufacturing plant sizes accounted for 43 percent of the cost reduction. Most of the remaining cost reduction could be attributed to improvements in module efficiency due to research and development investment. The substantial cost declines in solar module prices over the past decade are often attributed to economies of scale (Carvalho, Dechezleprêtre, and Glachant 2017). Economies of scale and learning-by-doing can in many cases be appropriable by the firms making decisions to scale up (this appears to be the case for learning-by-doing among rooftop solar installers, as Bollinger and Gillingham 2018 explain), so that learning-by-doing and scale economies do not by

themselves necessarily constitute reasons for policy intervention. Absent a carbon price, however, the demand for solar panels will be less than it would be were there a carbon price. As a result, second-best policies that are initially expensive (like the German Energiewende) can in principle stimulate production that would not normally happen because fossil fuels are cheaper than they would be, were their externality priced. For solar panels, at least, all this seems to have been the case.

Going forward, we might continue to see policy-induced cost reductions for solar technology. As the penetration of solar rises, and as the rest of the electricity system decarbonizes, such cost reductions will have to continue to be substantial to offset the higher potential costs of additional storage needed because of solar intermittency.

Dynamic Cost Case Study 2: Electric Vehicles

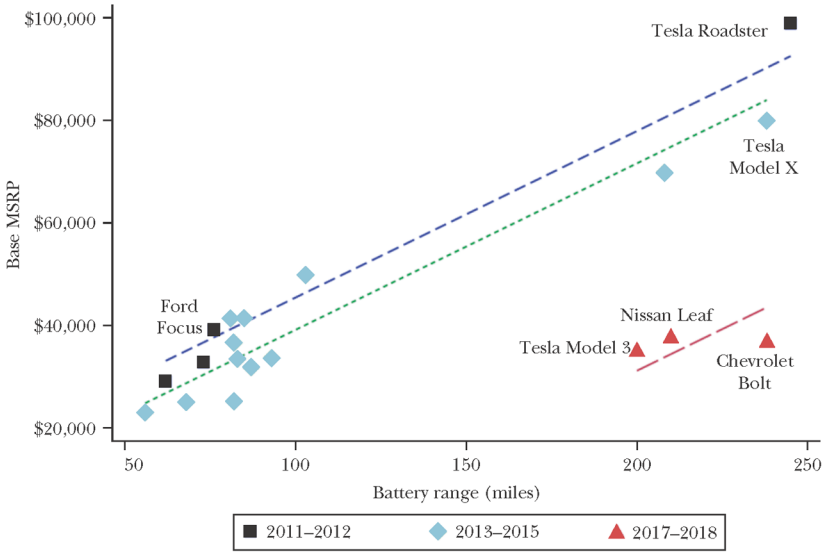
Like solar panels, the static costs of CO_2 reductions obtained by using electric vehicles is high in Table 2 (the last row). Today, many electric vehicles in the United States are charged using electricity that on the margin is produced by fossil fuels. Holland, Mansur, Muller, and Yates (2016) use the method of Graff Zivin, Kotchen, and Mansur (2014) for computing marginal emissions to examine the static optimal second-best purchase subsidy on electric vehicles accounting for both greenhouse gases and local air pollution. Holland, Mansur, Muller, and Yates (2016) find that the subsidy ranges from a subsidy of $2,785 in California (with relatively clean electricity on the margin) to a *penalty* of $4,964 in North Dakota, where electricity is generated from coal. Archsmith, Kendall, and Rapson (2015) perform similar calculations that additionally include life-cycle considerations, and find that on average electric vehicles currently only slightly reduce greenhouse gases relative to gasoline-powered vehicles.

From a dynamic perspective, however, the case against programs to support electric vehicle purchases is far less clear. The static calculations ignore the fact that the grid is evolving and becoming cleaner. Moreover, the general issues raised for solar panels—induced innovation, learning by doing, and economies of scale that would not otherwise be achieved because carbon is not priced—apply to electric vehicles as well. Unlike the case of solar panels, however, we are not aware of any research that investigates drivers of price dynamics for electric vehicles, perhaps because the cost declines and sales growth are so recent. The available data are, however, suggestive that the analogy to demand-pull effects for solar panels also applies to electric vehicles.

Figure 3 plots electric vehicles that entered the market from model years 2011 to 2018 based on their suggested retail price (y-axis) and battery range (x-axis). The price-range frontier has strikingly shifted out: more recent market entrants have greater battery range at lower cost, underscoring this rapid improvement in technology.

The large declines in price for vehicles with the same range is mainly due to the ongoing decline in battery prices. From 2009 to 2015, the price of batteries for electric vehicles fell by 75 percent (US Department of Energy 2016). Like solar

Figure 3
Electric Vehicle Manufacturers Suggested Retail Price (MSRP) Plotted against the Battery Range Shows Impressive Technology Improvements within a Short Time



Source: J. Li (2017) and authors' calculations.
Note: Dates indicate year the model is introduced. Regression lines are fit with a common slope and different intercept for each group of model years.

photovoltaic arrays, electric vehicles have been a target of demand-pull subsidy programs. Since the Energy Policy Act of 2005, there has been a US federal income tax credit of $7,500 (which phases out with production by any given manufacturer). Many states have additional incentives, such as a $3,000 rebate in Connecticut, eligibility for driving in a high-occupancy lane with only a single occupant in California, and a zero-emissions vehicle mandate in 10 states that requires automakers to sell a certain number of zero tailpipe emission vehicles (including electric vehicles) for every non-zero-emissions vehicle sold. Numerous papers in the transportation literature have provided evidence suggesting that electric vehicle subsidies increase demand for electric vehicles, as one would expect (reviewed in Zhou, Levin, and Plotkin 2016). The general pattern of demand-pull policies combined with subsequent sharp declines in costs is similar to that found for solar panels. We note that it is consistent with learning-by-doing and scale economy effects, and that confirming or refuting this hypothesis is an important area for future research by economists.

Electric vehicles also exhibit network effects, whereby the purchase of an additional electric vehicles makes the installation of a charging station more profitable. Thus, a positive feedback can exist, leading to multiple equilibria. For example, there may be one equilibrium with few charging stations and few or no electric vehicles, and another with many charging stations and electric vehicles. There is a growing literature on electric vehicles and network effects. Zhou and S. Li (2017) point out the possibility of multiple equilibria in electric vehicles and argue that a subsidy targeted at the marginal electric vehicle purchaser can be much more efficient than a policy that provides large inframarginal gains to those who would purchase an electric vehicle anyway. Yu, S. Li, and Tong (2016) discuss how network effects can lead the market solution to underinvest in electric vehicles compared to what is socially optimal. J. Li (2017) develops a structural model of two-sided market estimated with vehicle registration data from the United States and finds that mandating compatibility in charging stations would benefit consumers, enhance network effects, and increase the size of the electric vehicle market. Springel (2018) uses vehicle registration data from Norway—the country with the highest penetration of electric vehicles—to estimate a structural model showing that subsidies for charging stations are more effective for increasing electric vehicles uptake than are purchase subsidies for electric vehicles, but their effectiveness tapers off with increased subsidy.

The findings of these papers on network effects point to how a static perspective on policies to encourage technologies such as electric vehicles miss important aspects germane to the long-term cost-effectiveness of different policy approaches.

Static versus Dynamic Costs: Other Examples

Our two case studies present the sanguine view that seemingly expensive investments today result in lower costs in the future, a finding broadly akin to the theoretical work of Vogt-Schilb, Meunier, and Hallegatte (2018), Newbery (2018), Acemoglu et al. (2012), and Acemoglu et al. (2016). This happy result, however, is not preordained. For example, taking the dynamic approach may lead one to invest *less* in a carbon abatement technology if costs are expected to increase, rather than decrease, over time. Nuclear technology may fall into this category as construction costs of nuclear energy have risen, not fallen (Davis and Hausman 2016). Increasing costs of integrating renewable electricity into the electric grid can also work in this direction. In other cases, the static approach is perfectly appropriate. Consider policies to reduce methane leaks from the natural gas distribution system: the costs of sealing these leaks is likely to be similar in the near future as it is today because the process of sealing leaks is well understood but costly (digging up pavement and replacing pipes). Still other cases are less clear. Policies that would promote fuel switching to natural gas may reduce emissions in the short-run, but have potential to lead to investments in long-lived capital assets, and possibly even technological lock-in (Gillingham and Huang 2018).

Challenges

The costs of reducing carbon emissions discussed in this paper pose several challenges. One of these challenges is that some politically appealing programs, such as support for biodiesel or subsidies for energy efficiency programs, can be quite costly either for technological reasons or because of behavioral responses. Because the costs for these programs are often masked and only apparent upon scrutiny by economists, they appear low-cost—but are not.

A second challenge is the reverse, where highly visible programs are perceived as high-cost, but are not. A prominent example is the Clean Power Plan, which would have resulted in large emissions reductions for a cost far below that of many other programs already in place.

A third challenge is that the static costs provide at best an incomplete picture of the true costs of a particular action, which must include the dynamic consequences. The sign of those dynamic consequences in general depends on the intervention. If the intervention is replacing coal electricity generation by natural gas, low short-term costs might lead to higher longer-term costs if the result is long-lived natural gas infrastructure that is locked in and costly to abandon as the price of renewables drops. In contrast, if the intervention is providing subsidies for purchasing electric vehicles, the demand-pull effects of induced learning by doing and economies of scale can make dynamic costs much lower than a myopic static calculation would suggest. Because climate change is a long-term problem and the changes ultimately needed to reduce emissions are vast, the dynamic costs are far more important than the static ones.

A fourth challenge is to the economic research community, and it stems from the previous observation. As is clear from our review, most of the empirical studies of costs by economists focus on static costs, typically static costs of programs that have already been in place. This is natural because there is data on these programs, and understanding the costs of previous programs is a helpful guide to designing future programs. But particularly in the field of climate change research, more attention is needed on the determinants of dynamic costs. This exciting field of research merges environmental and energy economics with the extant literature on productivity, diffusion, and learning-by-doing. We have highlighted two areas—solar photovoltaics and electric vehicles—in which demand-pull policies appear to have induced cost reductions; however, that need not always happen and magnitudes surely vary from one case to the next.

Climate change is a long-term problem, and the focus of policy must be on long-term solutions. To make major progress on climate goals, like 80 percent decarbonization by 2050 in the United States, will require new technology deployed on a vast scale. Even if each technological step is evolutionary—cheaper electric vehicle batteries, connecting the grid to harness the wind potential in the Midwest, reducing the cost of offshore wind, developing and commercializing low-carbon fuels for air transport—the overall change will be revolutionary. If a price on carbon is not politically feasible—and arguably even if it is—these long-term considerations

need to be incorporated into our short-term policy tradeoffs. From the perspective of the cost calculations in this paper, one clear implication is that choosing low-cost interventions without a future, including ones that lock in fossil fuel infrastructure, can result in too much emphasis being placed on what is cheapest to do today. We are always surprised by the specifics of technological progress, but as economists, we are not surprised that it is more likely to occur when the right incentives are in place.

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Capturing Leadership

Policies for the US to Advance Direct Air Capture Technology

May 2019

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May 2019

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Peter Marsters, Rhodium Group, LLC

Prepared for Carbon180 with financial support from The Linden Trust for Conservation and the ClimateWorks Foundation

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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.

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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.

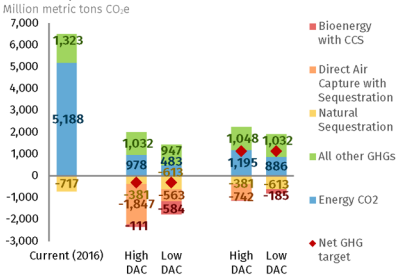
This report focuses on one of these emerging carbon removal technologies: Direct Air Capture (DAC). DAC safely removes CO_2 from the air using chemical filters and produces a concentrated stream of CO_2 for use in products like concrete and fuels or for permanent geologic storage. Carbon180, the Linden 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.

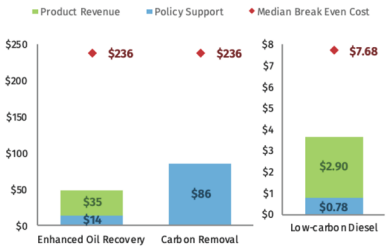
Even under a less ambitious US target of 83% below 2005 levels in 2050 (our "83by50" scenarios), carbon removal technology remains necessary to offset stubborn sources of CO_2 such as long-haul aviation and shipping, and energy-intensive industrial activities. There is growing scientific evidence that 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.

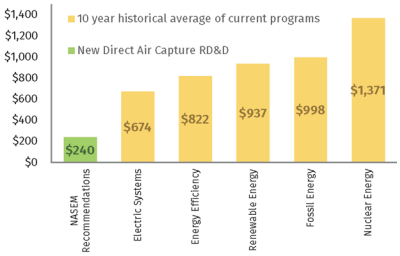
Federal Action Is Needed to Push and Pull DAC Into the Marketplace

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]

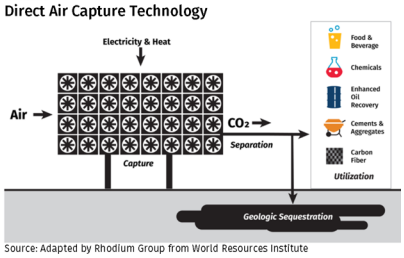
Scientists estimate that to limit global temperature increases to 2°C, global greenhouse gas (GHG) emissions will by 2030 need to decline 10% to 30% below 2010 levels and between 2065 and 2080 fall to net negative.[iv] To limit global temperature increases to 1.5°C, emissions need to by 2030 decline 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]

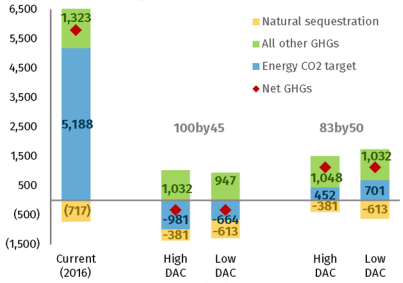
One CDR approach not explicitly represented in our modeling platform is natural sequestration of carbon in forests and soils. Every year CO2 is removed from the atmosphere by plants and other organisms through photosynthesis and other biological processes. The carbon can stay in soil, trees and roots 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

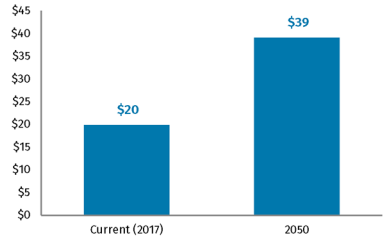


Source: US Environmental Protection Agency (EPA), US Mid-century Strategy, Rhodium Group analysis

Unprecedented Mitigation Action on All Fronts

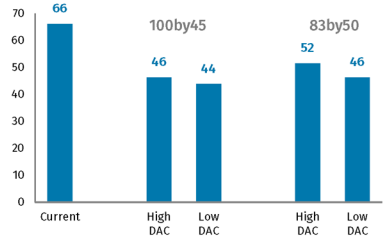
In our bounding scenarios, the pace of electrification and energy efficiency in buildings, vehicles and other end-uses is assumed to scale with the ambition of GHG reductions as part of a broad portfolio of climate policy action. Across all four scenarios, we assume the US economy continues to grow while 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.

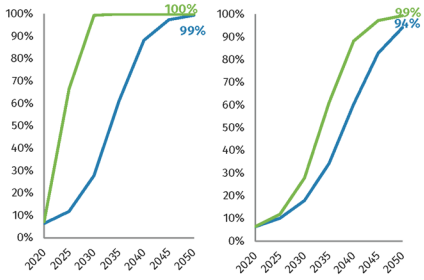
FIGURE 2.3.
Initial US final energy demand, current and 2050
Quads



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]

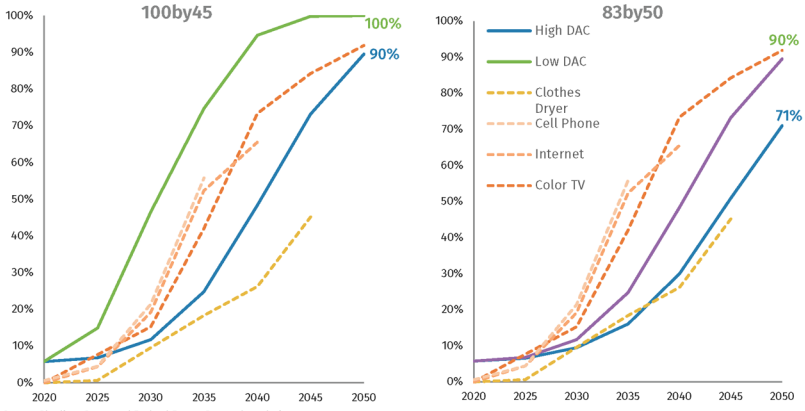
FIGURE 2.4.
Electric vehicle share of light-duty vehicle sales
% of sales



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.

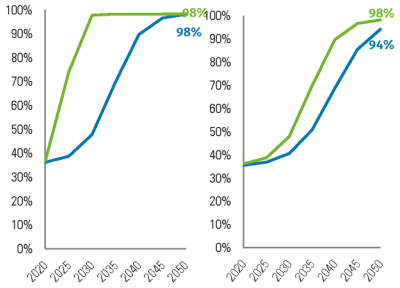
FIGURE 2.5.
Electric vehicle share of light-duty vehicle stock and penetration of other technologies
% of stock



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).

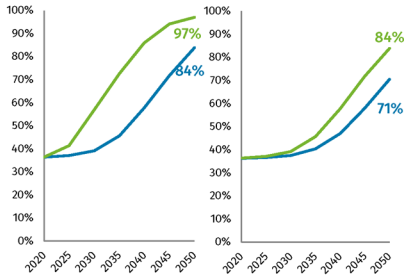
FIGURE 2.6.
Electric share of new residential heaters
% of sales



Source: Rhodium Group and Evolved Energy Research analysis.

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 2.7.
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

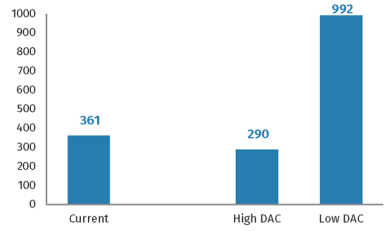
In all of our scenarios, an array of electric power generation technologies compete to serve conventional and newly-electrified loads, as well as any additional demand from the operation of DACS facilities, hydrogen, and other fuel production. Available options to decarbonize the electric system in the 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).

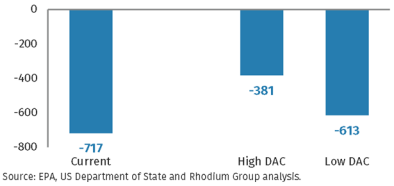
FIGURE 2.9.
US biomass supply, current and 2050
Million dry tons per year



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



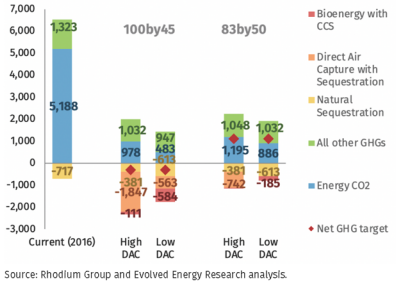
Source: EPA, US Department of State and Rhodium Group analysis.

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.

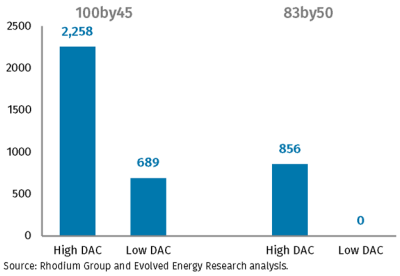
FIGURE 2.11.
US GHG emissions under DAC bounding scenarios, current and 2050
Million metric tons CO_2e



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.

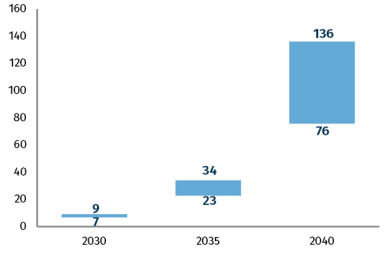
If any one component of a multipronged approach to meeting GHG reductions targets fails, technological CDR, especially DACS will be required as backup. Electrification could be slower than projected, for instance, or energy efficiency improvements could continue at current rates rather than the step 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 CO_2, 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.

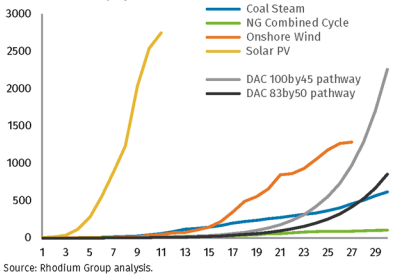
The US has scaled up industrial technologies like DAC before. The expansion of the nation's electric power system and associated generating technologies shows that the goal of building 850 to 2,250 DAC plants over 30 years is achievable. We tallied the cumulative amount of capacity deployed over time 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.

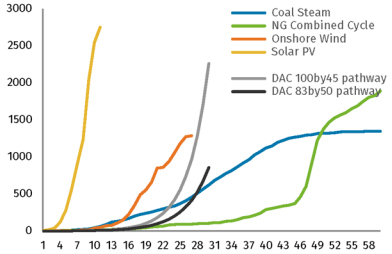
Another lesson from the electric power sector comes from the historical deployment of NGCC units. Over the first 30 years, NGCC units experienced much slower deployment compared to other technologies (Figure 2.14). In part to blame was the complicated nature of the technology as compared to a steam boiler. 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 CO_2 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.

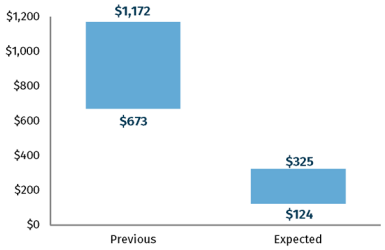
DAC Cost Estimates Have Declined, but More Innovation Is Needed

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 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 carbon 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]

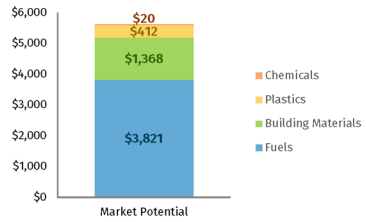
Current Market and Policy Opportunities for DAC

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

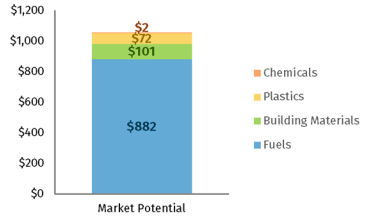


Source: Carbon180

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

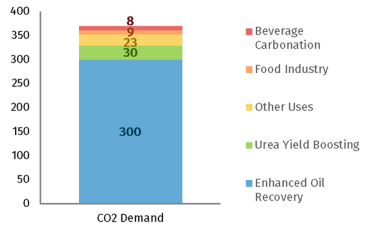
heat used in the production process are from low- or zero-emitting sources. Several companies are developing methods to compete in these markets using DAC or recycled CO_2.[lvii] The potential US market for these products is over $1 trillion per year (Figure 3.3).[lviii] Beyond the markets for products 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.

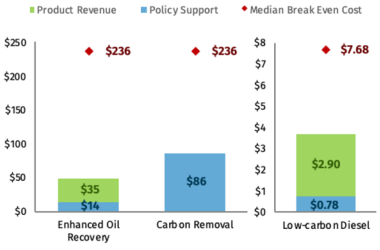
Current Policy and Market Opportunities Can't Get DAC on Track to Scale

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.

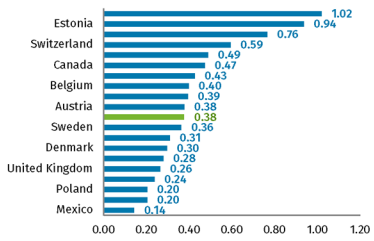
Research, Development, and Demonstration for DAC

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.[bxxiii] 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.[bxxiv] Over $4.8 billion has been spent each year, on average, over the past ten years.[bxxv] 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).[bxxvi] 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.[bxxvii] 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.[bxxviii] Still, the US has a long way to go. DAC technology presents a crucial opportunity for US leadership in technology innovation.[bxxix]

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

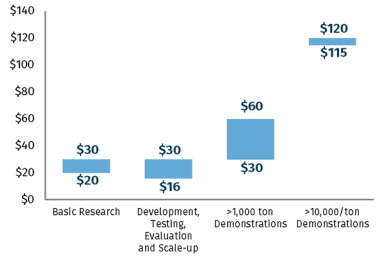
While the exact design of such a DAC RD&D program is outside the scope of this paper, the NASEM provides comprehensive recommendations on key activities and funding levels for a 10-year program supporting basic and applied RD&D.[bxxx] Each component plays an important role in fostering breakthroughs 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.[bcxxi] 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.[bcxxii] 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



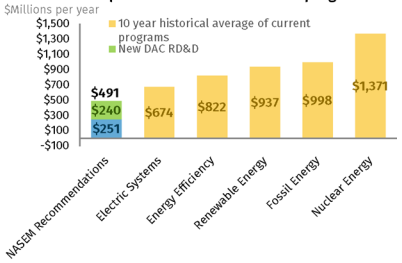
Source: NASEM

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).[bcxxiii] The recommended sum also represents less than 36% of DOE's spending on nuclear energy research.[bcxxiv] 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

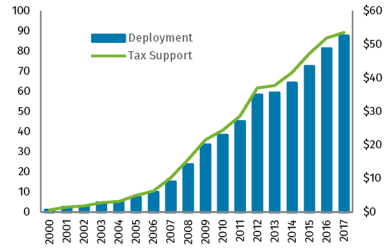
goals once an RD&D program is in place. The challenge DAC faces is similar to that of other technologies that have crossed the valley of death. Consider the experience of wind and solar, the two fastest-growing clean technologies today in the US. As we demonstrated in Chapter 2, both these technologies 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

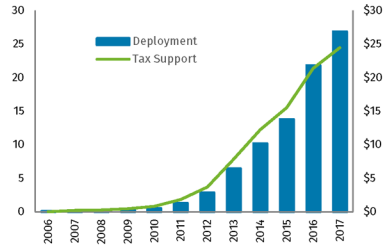
Congress passed a Production Tax Credit (PTC) for wind in 1992 and an Investment Tax Credit (ITC) for solar in 2006. With the tax credits, plus other more modest federal tax advantages and state policies in place, wind and solar deployment began to take off and attract large amounts of private investment (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.

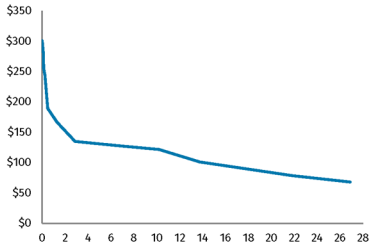
FIGURE 4.5.
Federal policy support and solar deployment
Cumulative solar capacity, GW (LHS); Cumulative tax support, $2017 billions (RHS)



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)

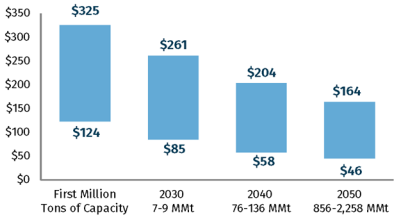


Source: Lawrence Berkeley National Lab, EIA, Rhodium analysis.

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.[bxxvi]

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.[bxxvii] 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.[bxxviii] 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.[xciii] 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.

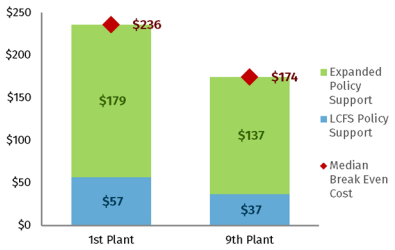
Extending the tax credit payout from 12 years to 30 years is also necessary. DAC plants are likely to have a useful lifetime of 30 years and they are unlikely to be built or operate without revenue certainty over that timeframe.[5] This is three times longer than the PTC payout for wind and represents 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

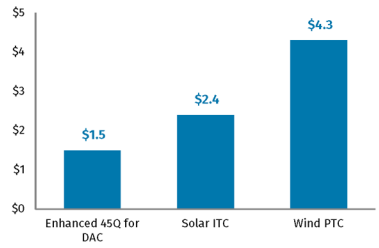


Source: Rhodium Group analysis.

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.

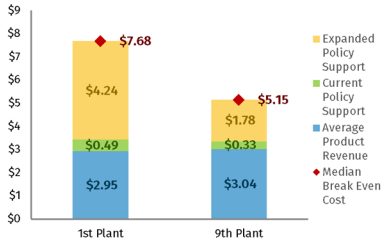
A federal fuels mandate that supports multi-million ton DAC deployment could either set a target specifically for DAC-derived fuels or set a carbon intensity requirement low enough that DAC fuels would be competitive. If the latter path is pursued, a 90% reduction in carbon intensity relative to gasoline 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]

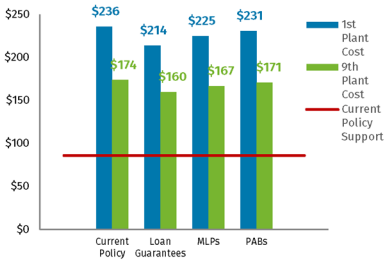
Master Limited Partnerships: An MLP is a partnership business structure with publicly traded units, hence it combines the benefits of being exempt from corporate taxes (like any other partnership), while still being able to access public investment by listing its units on stock exchanges (like any other 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.

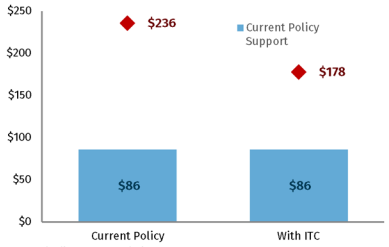
Accelerated Depreciation

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.

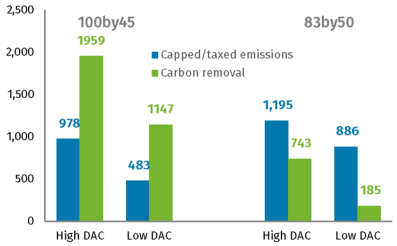
As noted previously, policymakers can establish a price by applying a tax on CO_2 emissions or through a cap-and-trade program that limits the quantity of emissions allowed in a given year and requires emitters to hold permits for every ton emitted. A carbon tax sets a known price for emissions into 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.

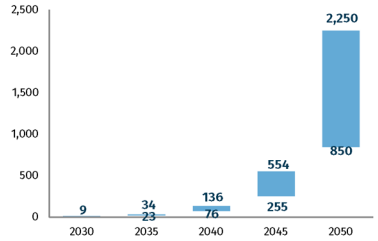
[7] Alternatively, the federal government could grant CDR monopoly power to a private utility with sufficient regulation and oversight.

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.

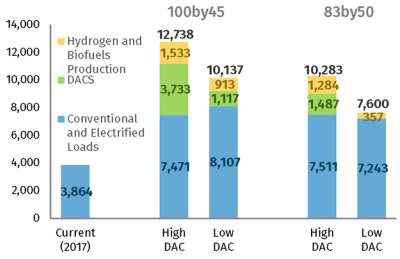
DACS Energy Requirements

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



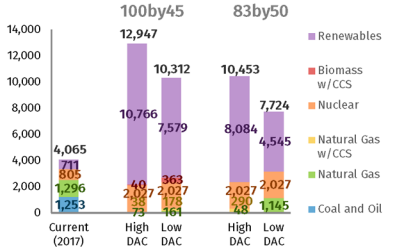
Source: Rhodium Group and Evolved Energy Research analysis.

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.

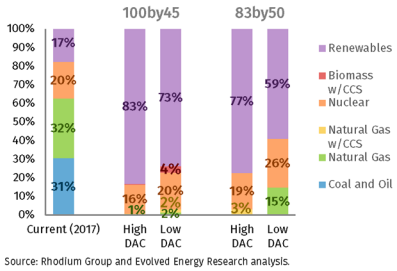
With the cost and performance assumptions used in our modeling, renewable generation increases by a factor of 6 to 11 over today's levels to meet an 83by50 target in 2050, providing 59% to 77% of all electricity (Figure 5.5). To meet a 100by45 target, renewables need to scale by a factor of 11 to 15 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



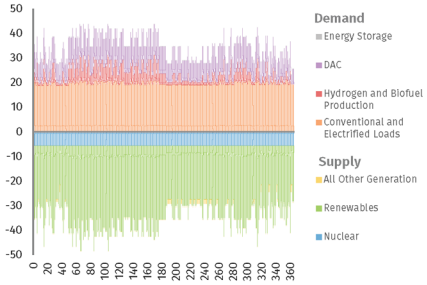
Source: Rhodium Group and Evolved Energy Research analysis.

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

system to accommodate the high penetrations of renewable generation we see in our scenarios. In our scenarios, we find that on most days of the year the amount of generation on the system far exceeds demand from conventional and electrified loads. If not for demand DACS as well as the production of biofuels and hydrogen this surplus generation would be curtailed, or long duration storage technologies 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

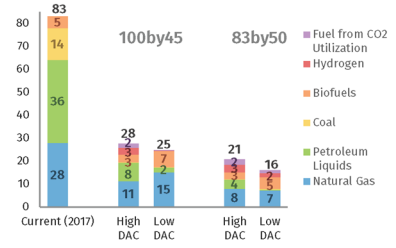


Source: Rhodium Group and Evolved Energy Research analysis. Note: All other generation includes natural gas and biomass with CCS.

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.

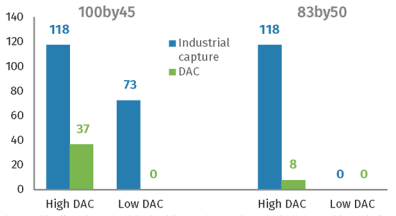
FIGURE 5.7.
US non-electric energy demand, 2050
Quads



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.

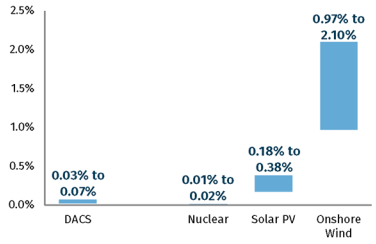
The Land Requirements for DAC and Associated Energy Supply

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 9th plant. The costs of the 9th 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 9th 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

	Liquid-solvent technology			Solid-sorbent technology		
Energy cost scenario	Low	Mid	High	Low	Mid	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.

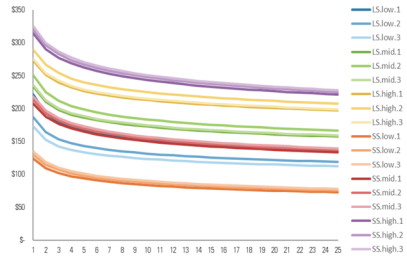
In our cost model, we assume all capital costs and energy requirement improves at the learning rate. We assume the

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

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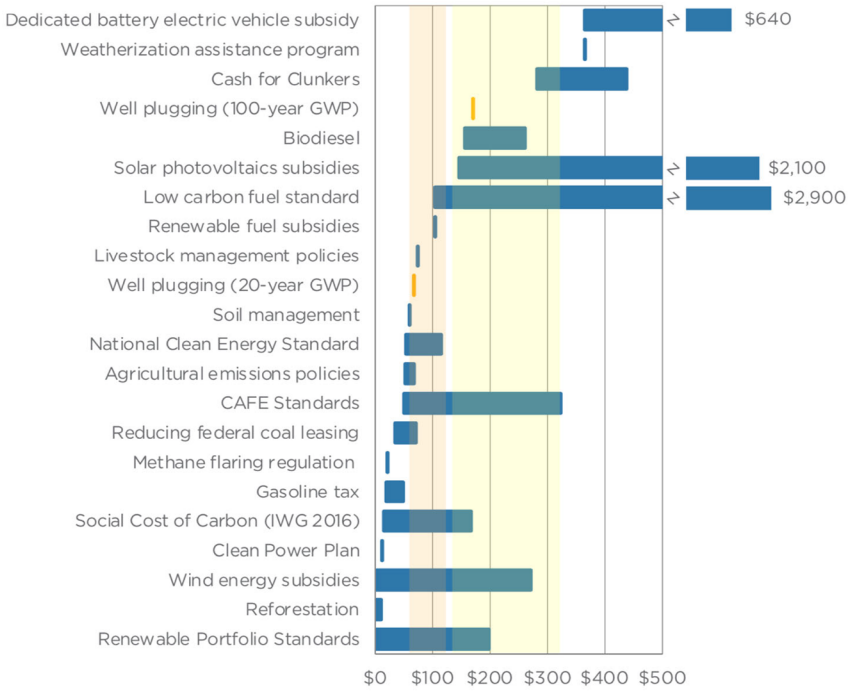
Figure 8: Estimated CO_2 abatement costs from selected US policies. Most of these policy options cost much more than the cost of carbon capture (orange shading) or even direct-air capture (yellow shading). Data from Gillingham and Stock, 2018. CCS cost data from GCCSI 2019 and NPC 2019. DAC costs from Rhodium Group, 2019.



Source: Bordoff et al., 2020.

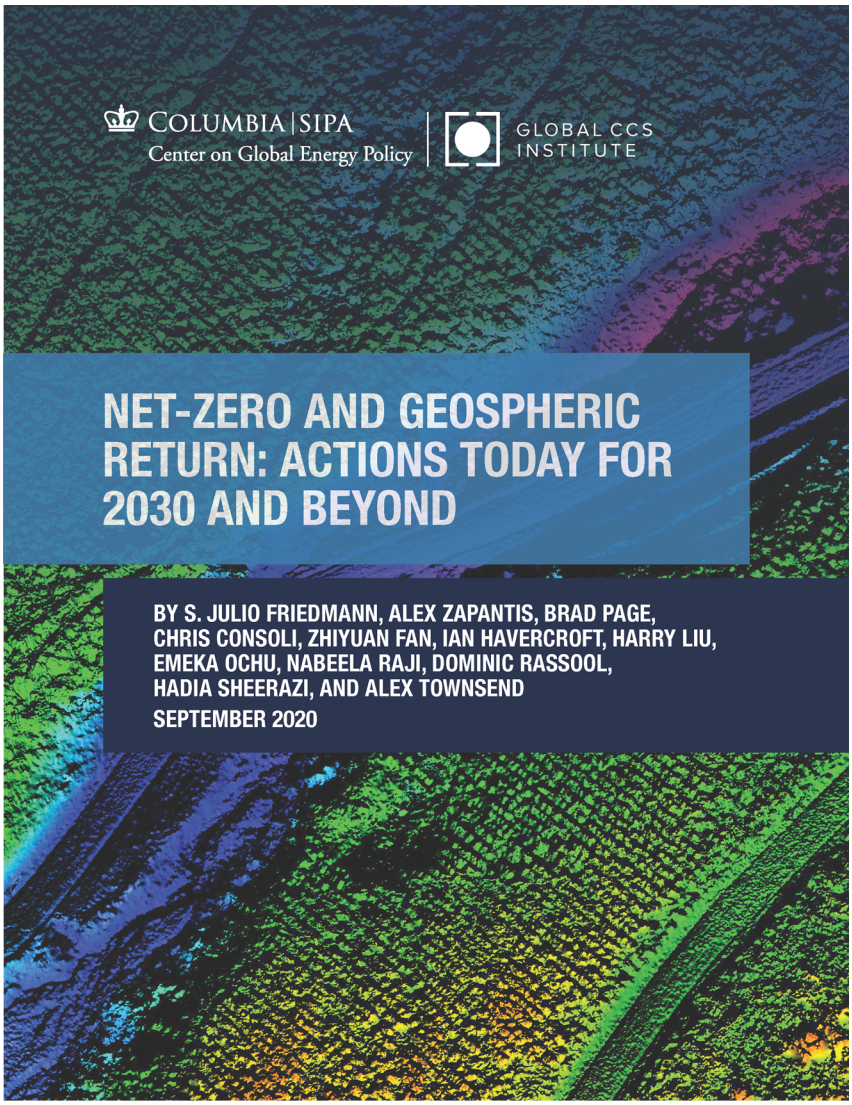

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TABLE OF CONTENTS

Executive Summary — **09**
- Infrastructure 09
- Projects 09
- Market-Alignment Through Policy 10

Introduction — **11**

The Arithmetic of Net-Zero — **13**

Centrality of Carbon Capture — **17**
- CO_2 Reduction and Mitigation 17
- CO_2 removal 20

The Role of the Geosphere in Establishing Carbon Balance — **25**
- 2030 Goal, Arithmetic and Requirements 25
- Time to Build 27
- Storage Resource Development 31
- Role of Law and Regulation 32

Projects: The Core Measure of Progress and Policy-Finance Focus — **34**
- Role of Institutional Investors 35

Policy Options — **37**
- Valorizing CO_2 37
- Costs and Avoided Costs 39
- Ecosystem Support 41
- Beyond 2030 44

Summary - It's About Time — **46**

References — **47**

Notes — **53**

EXECUTIVE SUMMARY

The case for rapid and profound decarbonization has never been more obvious or more urgent, and immediate action must match growing global ambition and need. An important new component of this discussion is the necessity of achieving net-zero global greenhouse gas emissions for any climate stabilization target. Until net-zero emissions are achieved, greenhouse gas will accumulate in the atmosphere and oceans, and concentrations will grow, even with deep and profound emissions reduction, mitigation, and adaptation measures. This places a severe constraint on human enterprise: any carbon removed from the earth must be returned to the earth.

To manage this aspect of the global carbon budget, carbon capture and storage (CCS) must play a central role. In particular, CCS will be important in two major roles:

- To manage emissions from existing, long-lived capital stock. This is especially true for rapid emissions reduction from three kinds of facilities: heavy industrial sector (i.e., cement, steel, and chemicals); production of near–zero-C hydrogen in abundance; and recently built power plants, in particular coal and gas facilities in Asia.
- To enable large-scale rapid carbon dioxide (CO_2) removal through engineered systems. This will include approaches like direct-air capture with storage (DACS), bioenergy with CCS (BECCS), and carbon mineralization.

Due to the intense urgency of the climate crisis, global emissions must drop 50 percent by 2030 and reduce a further 50 percent from that level by 2040 to achieve net-zero by midcentury—this is the science-based target of the Intergovernmental Panel on Climate Change (IPCC) 1.5°C report and the "well below 2°C" scenario ratified in the Paris Accord. Thus, reducing global emissions rapidly and profoundly, plus gigatonne-scale CO_2 removal, are the only ways to achieve these climate goals. The demands of 2030 place additional urgency on laying the foundations for growing deployment of CCS to achieve net-zero global emissions at lowest cost and greatest speed. A set of actions are essential:

Infrastructure

CO_2 transportation and storage networks today help illustrate the scale of what is required. Estimates suggest that the 8,000 kilometers (5,000 mi) of existing CO_2 pipelines in North America must be expanded by an additional 35,000 kilometers (21,000 mi) to maximize emissions reduction. Similarly, industrial hubs and clusters, now under development in Europe, China, and the Middle East, can accelerate the deployment of CCS at reduced cost. More storage sites must be assessed and approved, and options like CO_2 shipping must be explored for costs, opportunities, and technology requirements.

Projects

Large capital projects like CCS projects and related infrastructure require 6–10 years from

conception to commissioning. Currently, there are 19 large-scale industrial and two large-scale CCS power facilities operating, with combined capacity of about 40 million tonnes of CO_2 per annum, and an additional 20 projects under development. The International Energy Agency (IEA), IPCC, and many other groups estimate CCS projects must mitigate 1.5 Gigatonnes per annum (Gtpa) by 2030 to stay on a 1.5°C increase climate trajectory—an increase by a factor of 35 from today. This places urgency on commencing construction and completing infrastructure to serve the volume of CCS projects needed, and it is likely that additional human capital is needed to serve this essential market.

Market-Alignment Through Policy

Durable policies that align market dynamics and attract private capital will be essential—most importantly, policies that enable project finance. These can include tax credits, feed-in tariffs, rate recovery, construction or procurement mandates, grants, projects of common interest, carbon pricing, contracts for differences, regulatory emissions caps, or combinations of these policies. Some additional modest policy measures (e.g., modification of the London Protocol; innovation policy and Research, Development, and Deployment, or RD&D, support; clarification of long-term liability requirements) could play important roles in facilitating market adoption.

By focusing on 2030 targets as a stepping-stone to midcentury net-zero targets, governments can select what actions, investments, and policies can best serve domestic and global needs. Similarly, investments and policies made over the next decade will lay the foundation for continued decarbonization to achieve global net-zero emissions by midcentury.

INTRODUCTION

The case for rapid and profound decarbonization has never been more obvious or more urgent. The consequences of unrestricted greenhouse gas emissions continue to manifest. As the atmospheric concentration of CO_2 exceeds 415 parts per million (ppm) and the atmospheric load of CO_2 approaches 1 trillion tonnes, the hottest decade on record is closing with the second-hottest year on record. Other chronic concerns, including wildfires, hurricanes, flooding, and extreme heat, are leading to widespread ecosystem damage and economic loss. Scientists predicted much of this over 30 years ago with surprising accuracy. The devastating wildfires in Australia, the bleaching of coral reefs, and the flooding associated with major storms and continued sea-level rise offer the starkest representation of what is at stake.

Against this backdrop, it is increasingly clear how profoundly the world has failed to meet this challenge. Carbon emissions continue to rise, despite enormous progress on efficiency and clean energy generation, especially in wind and solar. The global climate agreement made in Paris and signed in Marrakesh is far from sufficient, placing the world on a trajectory well above 3°C of warming (UNEP, 2019). While it was meant to be a first step leading to more ambitious targets, most countries are failing to meet their Nationally Determined Contributions (NDCs), and it is unclear how they will achieve even these modest initial goals (FEU-US, 2019). While some nations, notably in Europe, find that politics supports higher ambition, the same politics can run counter to achieving environmental goals, as evidenced by the EU's recent climate deal with Poland (Strupczewski and Baczynska, 2019), retrenchment in Brazil with President Jair Bolsonaro (Diaz, 2019), continued investment in coal in India (Rathi, 2019; Bordoff, 2020), and other examples. Since the consequences of climate change are tied to the cumulative emissions in the atmosphere, every year of delay adds to our problem, making time the scarcest resource of all.

The IPCC 1.5°C report has highlighted the risks of further failure and made clear that we must achieve two specific, arithmetically binding targets to avoid the worst outcomes of climate change:

- Global net-zero emissions by midcentury, and
- Global net CO_2 removal afterwards at the multi-gigaton scale.

The framework embodied by both of these targets is relatively new but now widely accepted. It also helps clarify a fundamental axiom of a successful energy transition and climate counterstrike: **managing carbon emissions requires actually managing carbon emissions**.

Above all, one thesis remains central to both CO_2 reduction and climate restoration: **withdrawals from the geosphere must be balanced by returns to the geosphere**. Carbon stocks removed from Earth (the geosphere), past, present, and future, must be returned to the earth to balance the carbon and climate books for good. Said differently, the 2 trillion tonnes of CO_2 pulled from underground will not fit into the biosphere, which was in balance before the Industrial Revolution.

With this straightforward point in mind, the technologies and tools of carbon management have special relevance. Carbon capture and storage, deployed in many sectors, is a tool for CO_2 reduction. Approaches like direct-air capture, CO_2 mineralization, and bioenergy with CCS (BECCS)—technologies and approaches described in this report— are tools for CO_2 removal.

Despite decades of economic and technical findings underscoring the importance of these approaches, they remain misunderstood and are often misrepresented as "experimental."

- ***The core technology is mature***: Industrial-scale CO_2 capture has operated successfully since 1938, and geological storage of CO_2 since 1972.
- ***The technology works on existing stock and new facilities***: Carbon capture has already retrofitted steel, power, hydrogen, and other large facilities. This can accelerate decarbonization without premature retirement delay and takes advantage of existing capital stock. It also can serve to accelerate deployment of low-carbon hydrogen, low-carbon biofuels, and CO_2 removal technologies.
- ***Some supply chains are ready, while others require more support***: Industrial-scale CO_2 capture units are commercially available from multiple vendors. Commercial geological storage expertise and systems operate around the globe. However, scaling up these systems will involve deployment of infrastructure, cultivation of human capital, and expanding operating systems through investment.
- ***Policy support is required***: In some parts of the globe, regulatory systems operate well. Other parts of the globe require improved regulation. However, policies that align markets and help finance projects are inadequate for the task of global deployment.

The arithmetic requirements and technical opportunities of a net-zero global energy system are clearest when considering the road to a midcentury goal. In this, 2030 stands out as a specific milestone on that journey, in part due to the framework of the Paris Accord and the opportunities and limits to managing new and existing capital stocks. Ten years is sufficient time to create and modify policy, plan large-scale capital investments, and build infrastructure necessary to achieve midcentury decarbonization. This next decade will be central to any successful climate strategy, and respecting the primacy of carbon management is essential for success.

THE ARITHMETIC OF NET-ZERO

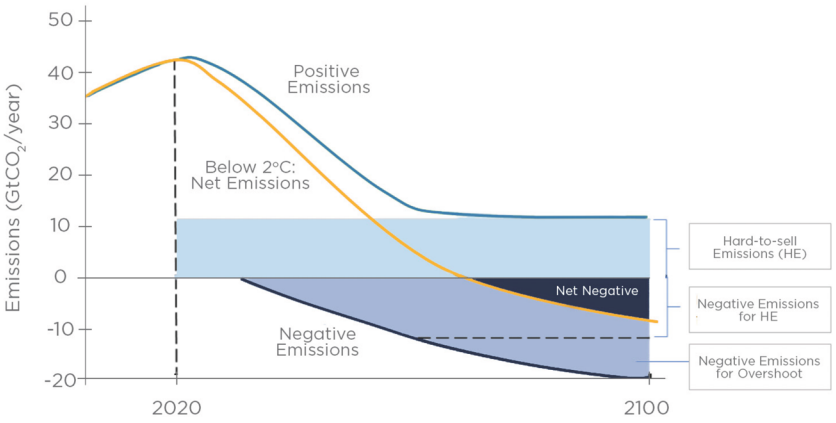
First and foremost, atmospheric concentrations of CO_2 will continue to grow and global warming will increase until the world achieves net-zero emissions. By definition, achieving net-zero emissions requires that any emissions that are not *reduced* must be *removed*. Emissions reduction and removal are distinct in nature and are different from emissions avoided:

- *Avoided emissions* are those that might have occurred but do not (for example, by not building a steel mill due to overcapacity or by building a solar PV power station instead of a natural gas power plant).
- *Reduced emissions* are existing emissions that no longer occur. Emissions may be reduced by many means, including conservation, efficiency, CCS, or shutting down or displacing existing emissions sources.
- *Removed emissions* are those that were emitted and are retrieved from the air and oceans. These can be from natural processes (e.g., mineral weathering), managed ecosystems (e.g., afforestation) or engineered systems (e.g., BECCS).

To achieve net-zero emissions, all emissions trajectories must decrease (Figure 1). However, if there are any residual emissions that are not reduced or mitigated, net-zero requires an equal mass of CO_2 removal. In many scenarios and descriptions, residual emissions are considered "hard-to-abate," meaning either the cost is extremely high (e.g., for aviation) or the technology does not exist (e.g., application of fertilizer). This is the core arithmetic of a net-zero emissions plan: ***any residual CO_2 emissions must be balanced by an equal amount of CO_2 removal***.

$$CO_2 \text{emissions} - CO_2 \text{removals} = 0$$

Figure 1: Representative pathway to net-zero and net-negative emissions. Orange line represents the emissions trajectory as the sum of the green and blue trajectories.



Source: J. Wilcox et al. 2020.

However, most analysis finds that it is not possible to achieve zero emissions soon enough to stabilize global average temperature below 2°C through reduction alone (e.g., Rogelj, 2018). In particular, the IPCC found that to achieve emissions consistent with a 2°C limit to human-caused warming, would likely require 85 percent emissions reduction by 2050 and annual removal of gigatonnes CO_2 before 2100 (IPCC, 2014a). Another important scenario is to aim at limiting human-caused warming to 1.5°C, and this requires that 100 percent emissions reduction and annual removal of 5–10 gigatonnes of CO_2 must occur around midcentury (IPCC, 2018).

By 2050: CO_2emissions(residual) - CO_2removal < 0

After 2050: CO_2emissions(residual) - CO_2removal = (-5 to -10 Gt/a)

The Scale of the Problem

When it comes to climate change arithmetic, the numbers are staggering and hard to understand or internalize. To help understand the numbers, it is useful to understand the nature of a gigatonne (Gt).

- **All the people on Earth combined weight roughly 1/2 a gigatonne.**
- **The global annual production of plastic is about 1 gigatonne.**
- **Global consumption of meat is approximately 1/3 a gigatonne.**

Unsurprisingly, managing many gigatonnes of emissions is extremely daunting. For example, the global oil market is roughly 5 Gt of material. Removing 5 Gt of CO_2 from the air and oceans requires an industry the size of the oil and gas industry operating in reverse.

This core arithmetic produces difficult corollaries. For example, the hard-to-abate sectors commonly are expressed as an irreducible annual sum of 8–10 Gt CO_2 equivalence (IPCC, 2014; ETC, 2018). The persistence of residual emissions is founded on the lack of alternatives, especially for land-use emissions, shipping, and aviation. Although some analysis has laid the foundation for innovation and progress in these arenas (ETC, 2018), the lack of realistic plans for deployment means that these emissions persist stubbornly across almost all analyses. Other difficult corollaries include:

- Achieving an 85 percent reduction in greenhouse gas emissions by midcentury requires a 50 percent emissions reduction each decade between now and 2050 (e.g., Rogelj et al., 2018). Given the long capital lives of existing infrastructure and facility stock, it is not clear how this might be achieved.
- A 1.5°C trajectory requires 5–10 Gt removal of CO_2 by 2050 and greater volumes thereafter. The National Academies (NASEM, 2018) find that this is not possible through reforestation alone given the limits of land and current technology.
- Any failure to reduce emissions must be balanced by CO_2 removal. For example, a failure to scale-up renewables, efficiency improvements, or electric vehicles will lead to a larger removal burden (FEU-US, 2019).

The core arithmetic produces an uncomfortable finding: existing capital stocks will overwhelm a 1.5°C or 2°C carbon budget. The IEA (2018) analyzed the global energy infrastructure either built or under construction. Assuming a natural capital life for facilities, just the existing capital stocks would emit 95 percent of the CO_2 emissions allowable under their sustainable development scenario, which is roughly 2°C of warming, and a 1.5°C budget was not possible without 100–1,000 Gt of CO_2 removal by 2100.

This leads to a straightforward arithmetic truth: achieving climate goals requires (a) premature retirement of existing facilities at an enormous scale, (b) many gigatonnes of annual abatement using CCS, or (c) both.

It is important to note that this is not a new or recent finding. On the contrary, the simple arithmetic of climate change makes CCS a central plank of abatement, like efficiency or renewables. In 2004, two very different sources reached this conclusion, both in Science. Socolow and Pacala (2004) argued that climate change impacts could be avoided through deployment of many "wedges" of technology. In their analysis, CCS featured prominently as a key pathway. The same year, then-US Secretary of Energy Spencer Abraham wrote that the costs of achieving climate targets were very sensitive to the presence or absence of CCS in analysis and that the costs of achieving the same goals without CCS were enormous. The IPCC reached the same finding in 2014, indicating that without CCS, the costs of achieving 2o C stabilization would be roughly 140 percent higher than without. The IEA reached the same conclusion in 2016 and 2018.

CENTRALITY OF CARBON CAPTURE

Given net-zero arithmetic and the urgency of climate change, two central roles emerge for CCS: CO_2 reduction and CO_2 removal. Reduction is a climate mitigation measure and involves preventing emissions from entering the atmosphere associated with existing systems. Removal is an additional set of measures that withdraws CO_2 from the air and oceans directly as a way to balance residual emissions and ultimately to un-emit legacy carbon in the air and oceans and restore climate. The versatility of carbon capture and the functionally limitless carbon storage capacity of the geosphere allows CCS to play these key roles immediately, growing toward the 2030 timeframe.

CO_2 Reduction and Mitigation

Heavy Industry—heat and process emissions

Reducing emissions in industry is one of the greatest challenges of reaching net-zero emissions. Industry is the basis of our modern society and is an essential source of economic growth, bringing financial benefits and job opportunities to communities around the world. While creating this wealth, industry produces nearly one-third of global greenhouse gases. The cement, iron and steel, and chemical sectors are the largest sources of industrial emissions. These industries provide a range of products that are vital to everyday life. Demand for the goods produced by industry is expected to grow in the future, driven by a growing population, increased living standards and economic growth.

Around one-quarter of industry CO_2 emissions are process emissions that are inherent to production processes. For example, in cement production, 65 percent of emissions come from the calcination of limestone, a chemical process underlying cement production (ICEF, 2019). In addition, one-third of industry energy demand is for high-temperature heat, for which there are few mature alternatives to the direct use of fossil fuels (Friedmann et al., 2019).

Many regions of the world are planning to grow their industrial sectors, which will likely contribute to a rise in industry emissions without additional policy action. For example, the Indian government has set an ambition in its National Steel Policy 2017 to increase steel production from 122 million tonnes in 2015–16, to 300 million tonnes in 2030–31. The steel sector is central to economic development in India, contributing 2 percent to India's GDP, and employing 0.5 million people directly and two million indirectly through supply chains. In Qatar, plans are in place to increase LNG production capacity from 77 million tonnes per annum today to 126 million tonnes per annum by 2027. The construction of coal-fired power plants continues, mostly in Asia, with nearly 600GW new capacity expected to be added by 2030 (Cui et al., 2019). The IEA estimates industry CO_2 emissions will rise by 11 percent, to 6.7 gigatonnes of CO_2 per year, without further climate mitigation policies (IEA, 2019).

CCS provides one of the most mature and cost-effective options for reducing emissions from industrial processes and high-temperature heat. Several reports, including from the Energy Transition Commission and the IEA, have concluded that achieving net-zero emissions in hard-

to-abate industry without CCS may be impossible and at best is much more expensive.

CCS in the Power Sector

Achieving net-zero emissions by midcentury would not be possible without decarbonizing the power sector, which accounts for one-third of global CO_2 emissions (IEA, 2019). The rapid deployment of renewable energy, associated with strong policies (like renewable portfolio standards and construction mandates in China and India) and dramatic cost reductions are positive contributors to success in reducing electricity emissions. That progress is grossly insufficient to achieve net zero by 2050, and existing coal and gas power systems continue to be built and are expected to operate through 2050 and beyond. Analysis shows that CCS provides both the fastest and cheapest pathway to deep decarbonization for these plants (IEA, 2020b). In many deep decarbonization scenarios, coal use reduces rapidly (Table 1).

Table 1: Coal utilization reductions assumed in IPCC Illustrative Pathways

IPCC Illustrative Pathway to 1.5°C	Pathway 1	Pathway 2	Pathway 3	Pathway 4
Reduction in primary energy from coal in 2030 compared to 2010	-78%	-61%	-75%	-59%
Reduction in primary energy from coal in 2050 compared to 2010	-97%	-77%	-73%	-97%

Source: IPCC, 2018.

Actual trends are very different from those required by these scenarios. Although investment in fossil fuel power generation has fallen over the past decade, it received USD $120 billion in 2018 (IEA WEI, 2019) and the global coal and gas fleets continue to grow, **more rapidly since the COVID-19 pandemic began** (IEA, 2020a). These facilities have economic lives of decades and a large global fleet of coal- and gas-fired power stations are expected to remain in operation well past the middle of this century (IEA, 2020b). Most gas power plants operate for about 30 years, while coal-fired generation plants operate for 40–50 years, and this newly installed capacity will remain in operation through to 2060 without premature closure—CO_2 emissions from the global coal fleet are expected to approach 10GtCO_2 in 2030 and exceed 7GtCO_2 in 2050 (Cui et al., 2019). If they operate, around 90 percent of those emissions must be captured and stored in 2030, and effectively all emissions must be captured and stored in 2050 to achieve net-zero. If power production from the global coal fleet is only half what has been assumed in this simple illustrative analysis, approximately 85Gt of CO_2 must be captured and stored from coal-fired power generation alone between 2030 and 2050 to be consistent with a 1.5°C climate outcome.

Clean Hydrogen

Hydrogen, as a fuel and feedstock, can play a significant role in the decarbonization of hard-to-abate sectors, provided production is clean and with a low-carbon footprint. Hydrogen can be burned in turbines or be used in fuel cells to generate electricity and can fuel both

light and heavy-duty vehicles. Hydrogen can provide a source of domestic and industrial heat and is a feedstock for industrial processes and synthetic fuels (like ammonia). The virtue of hydrogen is that it produces zero carbon emissions at point of use.

A clean hydrogen network of the future is quite different from today's system in volume, emissions, and use. In 2018, around 70 Mt per annum of pure hydrogen was used, almost entirely for refining (38 Mt) and the production of ammonia (31 Mt). Less than 0.01 Mt of pure hydrogen was used in fuel cell electric vehicles.

- Currently, 97 percent of global hydrogen production is from unabated fossil fuels, around three-quarters from reforming natural gas and the rest from gasification of coal (IEA, 2019; GCCSI, 2020). This is sometimes called "gray" hydrogen, which currently emits 830 Mtpa.
- When fossil fuel emissions from hydrogen production are abated through CCS, there are either reduced or zero associated greenhouse gas (GHG) emissions. This is sometimes called "blue" hydrogen.
- The remaining 2 percent of hydrogen is produced using water with electrolysis (IEA, 2019). When the electricity supply comes from zero-emissions power sources (e.g., hydro, solar, wind, or nuclear) it is sometimes called "green" hydrogen.

According to the IEA (2019), less than 0.7 percent of hydrogen production today is from fossil plants equipped with CCS (blue hydrogen) or renewable energy via electrolysis (green hydrogen).

For net-zero progress by 2030 and net-zero targets by 2030, rapid scale-up of clean hydrogen production will prove critical. ***The "Mission Possible" report (ETC, 2018) stated that global hydrogen production needs to grow by between 80 to 95 percent per annum by 2050 to reach net-zero emissions.*** The Hydrogen Council identified near-zero hydrogen could deliver around 6 Gt of annual abatement in 2050. (Hydrogen Council, 2017). In this respect, scaling up production of clean hydrogen from fossil fuels with CCS is simple and cost advantaged. Low-carbon hydrogen has been produced at commercial scale through gas reforming or coal gasification with CCS since 1982 (Table 2). Five large-scale "blue" hydrogen facilities with CCS produce low-carbon hydrogen today and three are under construction, with a total annual capacity of 1.5 Mtpa hydrogen, capturing over 7 Mtpa CO_2 (GCCSI, 2020).

Table 2: Hydrogen production facilities with CCS

Facility	H_2 Production Capacity (tonnes/day)	H_2 Production Process	Operational Commencement
Enid Fertilizer	200 (in syngas)	Methane reformation	1982
Great Plains Synfuel	1,300 (in syngas)	Coal gasification	2000
Air Products	500	Methane reformation	2013
Coffeyville	200	Petroleum coke gasification	2013
Quest	900	Methane reformation	2015
Alberta Carbon Trunk Line - Sturgeon	240	Asphaltene residue gasification	2020
Alberta Carbon Trunk Line - Agrium	800	Methane reformation	2020
Sinopec Qilu	100 (estimated)	Coal/Coke gasification	2021 (planned)

In comparison, the largest operating renewable powered electrolyzer in Fukushima Japan can produce ~2.4 tons/day of clean hydrogen.[1] The largest announced "green" hydrogen project to date, the Air Products-NEOM project in Saudi Arabia, would produce 650 tonnes of clean hydrogen using a combination of solar and wind (Air products, 2020) and shows both the promise and limits of "green" hydrogen production. The $7 billion project would supply 0.9 percent of global demand today. Meeting potential future global clean hydrogen demand of 530 million tonnes per year using electrolysis would require more than 26,000 TWh[2] of electricity—approximately equal to the total global combined electricity demand from all sectors in 2018 (IEA, 2019).

In this context, CCS-enabled blue hydrogen adds speed and saves money. For the price of the Air Products-NEOM project, roughly 300 Mt CO_2 could be captured and stored every year. Low-carbon hydrogen from fossil fuel with CCS is distinctly cost advantaged. Hydrogen made from fossil with CCS cost USD $1.50 –2.40/kg, compared to USD $4.00–7.45 for "green" hydrogen (IEA, 2019). Finally, when combined with biomass conversion, hydrogen production with CCS can remove CO_2 from the atmosphere.

CO_2 removal

As discussed, arithmetic demands that to achieve net-zero any residual annual emissions must be matched by an equal volume of CO_2 removal. There are many approaches to CO_2 removal, each of which has challenges (UNEP 2017, ICEF 2018). Three of those approaches require geological storage and return of CO_2 to the geosphere: DACS, bioenergy with CCS (BECCS), and carbon mineralization (CMin). The National Academies (2018) estimate that ~75 percent of CO_2 removal demanded of the carbon budgets requires these three approaches. Similarly, a recent report by Lawrence Livermore National Lab (2020) indicates that 80 percent of the

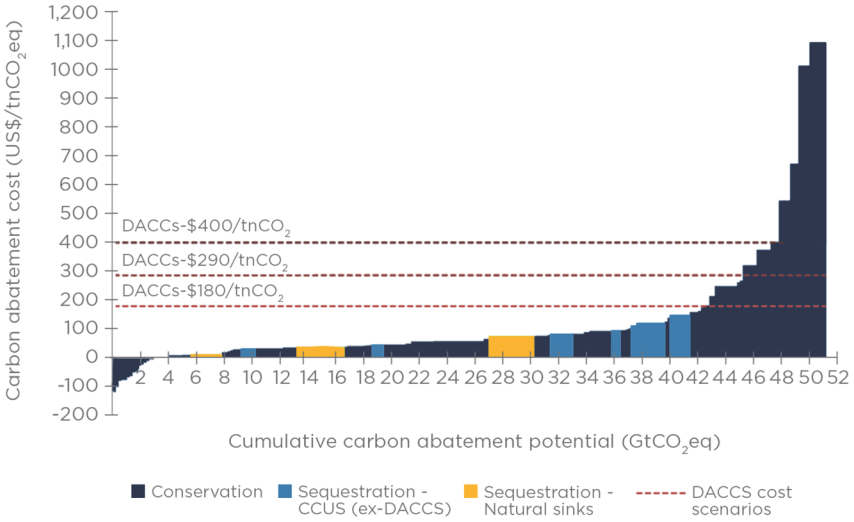
residual emissions identified by the state of California require geospheric return paired with CO_2 removal (BECCS and DACS).

Direct-Air Capture with storage (DACS)

Although many consider DACS technology to be new, the core technology is not. Devices that scrub CO_2 from air have operated since world-war II in submarines and since the 1960's in spacecraft—as dramatized in the iconic scene from Apollo 13 (ICEF, 2018). Capturing CO_2 from the air has become a climate mitigation strategy only recently, in part driven by increased urgency and prior failure to reduce emissions. Today, several companies operate DAC facilities and more provide options for CO_2 removal services.

Deployment of DACS requires the process itself to have near-zero emissions. However, if these conditions are met, then large-scale DACS can avoid enormous costs associated with our climate targets and provide a pathway to climate restoration (Figure 2; Goldman Sachs, 2020). NOTE: Arithmetic demands that failure in *any other mitigation pathway*, including efficiency, renewables, CCS, or reforestation, requires more DACS to balance the carbon budget. On this basis, and because DACS appears to have few technical, resource, or geographic limits, it can be considered a "backstop" technology to achieve climate goals.

Figure 2: Global marginal abatement cost curve for all greenhouse-gas emissions Dark-blue bars (conservation) represent substitution of emitting sources with non-emitting sources or efficiency measures. Pale-blue represents CCS on point sources. Green represent CO_2 uptake from managed ecosystems.



Source: Goldman Sachs, 2020.

A critical limitation of DAC is that the low concentration of CO_2 in air (~410 ppm) requires both lots of energy and large contacting systems, which today result in high costs. It is clear that these costs can come down (NASEM 2018) and are likely to drop dramatically over the next 30 years given appropriate policy support for deployment and innovation (EFI, 2019; Rhodium Group, 2019) with many experts agreeing on a total system cost of <$150/t sometime beyond 2030.

Biomass Energy with Carbon Capture and Storage (BECCS)

Biomass is the oldest energy supply used by humankind. The fundamental premise of BECCS is to combine CCS with bioenergy, in which biomass systems gather CO_2 from the air and oceans, people harvest the energy through conversion, and the carbon is permanently returned to the geosphere. The core technology options, such as biomass gasification, are available today and used widely (e.g., wood-based biomass gasification under the German

Energiewende). One large BECCS facility, the ADM corn-ethanol project in Decatur, Illinois, currently removes ~1 Mt/year through fermentation and geological storage. The "Getting to Neutral" report on California's emissions reduction strategy (LLNL, 2020) finds that ~100 Mt/y of BECCS is the cost-preferred pathway for CO_2 removal to achieve their state goals, representing ~70 percent of the state's needs.[3]

The core limitations to BECCS deployment today are cost and scale. Most biofuels and biomass-based power systems enter markets well above commercially competitive prices, even without the additional cost and energy requirements of CCS. In addition, the land required to grow large volumes of bioenergy crops places limits on what can be realistically considered for the upper limits of deployment (Reid et al., 2019), and also place additional costs on future deployment. Finally, BECCS will necessarily compete with agriculture for land, water, and energy, which presents challenges of governance and balancing policy needs.

An intrinsic concern regarding BECCS deployment is overall sustainability. Land-use changes (LUC) associated with biomass have led locally to severe environmental damage, affecting biodiversity, water quality, and environmental justice for indigenous peoples. Moreover, risks of carbon leakage and ecosystem carbon release from LUC can completely void the carbon and climate benefits of BECCS if executed using poor life-cycle pathways or systems with substantial LUC emissions. Conversely, with the appropriate focus on sustainable forestry and agriculture, including issues of equity and governance, BECCS could be scaled up quickly to good effect (Reid et al., 2019).

Mineralization

Over very long timescales, CO_2 reacts with silicate minerals at Earth's surface to make carbonate minerals. This is how nature removes large volumes of CO_2 over geologic time and is one of the processes that leads to ice-ages (Chamberlain, 1900). Recently, it has become clear that humans can accelerate this process, either by adding heat and energy or by combining air with the most reactive mineral fractions (IPCC, 2005; Keleman et al., 2020). This binds CO_2 in mineral form, making a highly stable pathway for geospheric return.

The enormous volumes of reactive minerals at Earth's surface and near subsurface make the volume potential for carbon mineralization effectively limitless (NASEM 2018), although the practical limits are a function of mineral kinetics, reactive surface area, and the quality of the mineral resource. As with any other mineral resource, the geographic distribution of high-quality carbon-mineralization resources are uneven. However, recent work has identified locations where mineral resources, low-carbon energy, and existing infrastructure are available to support carbon-mineralization projects. It would be generous to say this pathway and approach has received very little scientific and policy attention (EFI, 2019).

CO_2 utilization (CO_2U)

For good reasons, many see the value in turning CO_2 into goods for scale—that will be essential at some point for a circular carbon economy (CCE). The main types of valuable products made from CO_2 in a CCE are cement and aggregate, fuels and chemicals, and durable carbon. (ICEF, 2018) The products (and mid-products) of CO_2-to-fuels conversion include: CO, syngas (H_2 and CO mixture), methanol (CH_3OH), and eventually to long-chain hydrocarbons—which are more challenging but also of greater value (Hu et al., 2013).

- CO_2-based cement and aggregates are thermodynamically favored, and many companies exist today that sell these products.
- CO_2-derived fuels can be carbon neutral or even carbon negative and can be used as alternative drop-in fuels, especially for hard-to-abate sectors (e.g., aviation and shipping). They require substantial input energy to synthesize.
- Durable CO_2-based-products, including carbon fiber/tubes, plastics, and composites, etc., can last longer and keep carbon away from the atmosphere.

Unfortunately, even the largest applications are unlikely to use more than 1–2 Gtpa. Even that will require enormous energy requirements. The largest market, cement and aggregates, is unlikely to exceed more than 1–2 Gt (ICEF 2018). All other CO_2 utilization pathways identified, especially fuels and chemicals, are expensive and require more energy input than originally produced in combustion. For other durable carbon products (e.g., carbon fiber and carbon nanotubes), the value is high but the total market value is very small and cannot absorb large CO_2 volumes. For example, the global carbon fiber market is of the order of 100,000 tons. (Das et al., ORNL, 2016). Similarly, plastics cannot provide a large-enough market either (e.g., Epoxide, DOE's testing plant products, has ~20 Mt/y production and can take 40 percent CO_2 by weight [DOE, 2013; Rebstadt and Meyer, 2001]). Finally, if CO_2 utilization consumes energy or feedstocks with substantial carbon footprints, the life-cycle emissions could be very high. **For these and other reasons, geospheric return of CO_2 is essential to balance the climate books, even with a lot of CO_2U.**

THE ROLE OF THE GEOSPHERE IN ESTABLISHING CARBON BALANCE

Before the Industrial Revolution, the carbon cycle was effectively in balance. Since 1800, humans have perturbed that balance by adding 2 trillion tonnes of CO_2 to the air, much of which was taken up by the ocean and the rest into soils and forests (IPCC, 2014a). The rates at which soils and forests gained and lost carbon were fixed by evolution and the natural carrying capacity of ecosystems and further reduced by other human activities (e.g., deforestation). Today, the global economy (energy and land use) emits roughly 40 gigatonnes of CO_2 and other non-CO_2 greenhouse gases equal to 13–16 gigatonnes more CO_2.

Almost all of this CO_2 is taken from the geosphere in the form of coal, oil, and natural gas. Earth's crust effectively held this material in solid, liquid, and gaseous forms for many hundreds of millions of years. This demonstrates an important opportunity in net-zero accounting: Earth's crust is well-configured to hold carbon indefinitely (IPCC, 2005). In fact, natural occurrences of CO_2, produced today for enhanced oil recovery, had accumulated and remained in Earth's crust for as long as 280 million years.

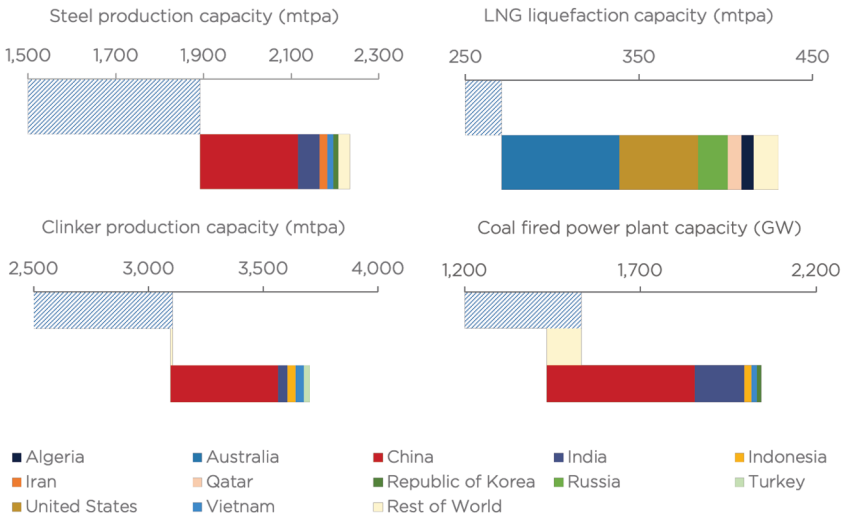
The capacity of Earth's crust to store CO_2 is effectively limitless (NASEM, 2018). Conventional geological storage systems like saline formations have an estimated storage volume of 10–20 trillion tonnes—far more than either annual emissions or our historic emissions. Unconventional systems, such as basalts and ultramafic rocks, are many orders of magnitude larger still. This capacity can serve in the coming decades to deeply curtail today's existing facilities as a strategy to halve today's emissions by 2030 and assist deep decarbonization by 2050. This capacity also can serve to balance any residual emissions and beyond that serve as the permanent repository of human legacy emissions. ***In a net-zero framework, the withdrawal of carbon from the geosphere can be balanced by return to the geosphere***—safe and permanent, both more durable and less risky than temporary carbon banking in the biosphere (e.g., Anderegg et al., 2020).

2030 Goal, Arithmetic and Requirements

Achieving net zero by midcentury will require a 45 percent reduction in CO_2 emissions worldwide by 2030 relative to 2010 levels—to get on track, CO_2 emissions would need to fall at a rate of roughly 5 percent per year between now and 2030 (e.g., Rogelj et al., 2018). In contrast, global CO_2 emissions have continued to rise since 2010.

A significant proportion of emissions are already locked into the system, making the transition ever-more challenging (IEA, 2019; Tong et al., 2019). Industrial and power plants have long lifetimes, typically around 30 to 50 years. Over the past decade there has been a significant increase in capacity of emissions-intensive infrastructure that under conventional assumptions will remain in place in 2050. For example, steel, clinker, and coal-fired power plant capacities have increased by between 18 and 34 percent since 2010, primarily driven by expansion in China and India (Figure 3). Plans are in place to increase unabated capacity further in many of these markets, accentuating the challenge of transitioning to a net-zero emissions economy.

Figure 3: Net capacity additions for three industrial sectors (steel, LNG, and cement) and coal-fired power in the world's five highest growth markets and the rest of the world.



Source: IEA WEI 2019.

Most models indicate CO_2 emissions will need to peak globally in the next few years (e.g., IPCC 2014; 2018; IEA 2019). Even in 1.5°C-consistent scenarios that initially overshoot temperature rises of 1.5°C, emissions peak by or shortly after 2030 (e.g., Fuss et al., 2018; Rogelj et al., 2018). Achieving this peak in emissions will require widespread climate mitigation action in a range of sectors. Across the 90 1.5°C-consistent scenarios in the *IPCC Special Report on Global Warming of 1.5°C*, CO_2 sequestration reaches 1.5 gigatonnes per annum on average by 2030, 35 times higher than the mass of CO_2 captured today. Other common themes include the continued growth in the deployment of solar and wind, the rapid phase-out of coal and the growth in low-carbon hydrogen as an energy carrier.

CCS has a critical role to play in achieving cheaper, easier, and rapid deep decarbonization of the hard-to-abate sectors, such as the power and industrial sector (mostly from cement, steel, and chemical subsectors). The IEA Clean Technology Scenario (2020) confirms that CCS is expected to contribute almost one-fifth of the emissions reductions needed across the industry sector (38 percent in the chemical subsector and 15 percent in both cement and iron and steel) to achieve the midcentury climate goals. One-third of industrial sector

energy demand is for high-temperature steam heat, which has only few renewable alternative sources. Further, process emissions inherent in some industrial production as a result of chemical reactions account for one-quarter of industrial emissions and cannot be easily avoided by switching to alternative fuels.

Thus, it is unrealistic to expect the achievement of net-zero emissions by 2050 without CCS. Even if all economically viable energy efficiency pathways are pursued, energy intensity will only be able to improve by 3.6 percent year-on-year from 2018 to 2040, without CCS (IEA, 2019).

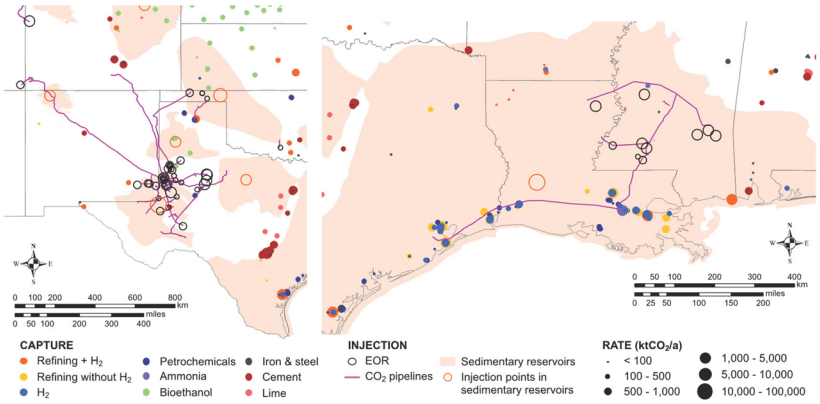
Time to Build

The life cycle of any large industrial project includes several feasibility and engineering studies prior to the investment decision followed by more detailed engineering design and finally, construction. This life cycle takes between 6–10 years, depending on logistical constraints and speed of approval (GCCSI, 2019b). Construction alone takes an average of 3–4 years. For example, the 1 Mtpa Boundary Dam project (Saskatchewan) and the 1.2 Mtpa Quest project (Alberta) took four years to progress from being identified to entering construction, and PetraNova (Texas) took three years. The Alberta Carbon Trunk Line project took eight years from inception to commissioning. Considering that CCS projects, like all infrastructure take time to develop, installing sufficient capacity to deliver 2.8 Gtpa CO_2 capture required to achieve the 2050 emissions target requires actions now.

Industrial CCS hubs offer significant cost and risk reductions compared to single sink-source CCS projects. Each segment of the CCS value chain requires investment in infrastructure such as CO_2 capture equipment, pipelines, and injection wells. These investments can only be made if they provide an appropriate risk-weighted return, so reducing cost and risk is key to rapid deployment of CCS. Hubs significantly reduce the unit cost of CO_2 transport and storage through economies of scale and provide multiple sources of CO_2 with access to shared infrastructure (see the later discussion of infrastructure). Hubs also reduce market risk by creating multiple customers and service providers for each actor in a CCS value chain. They have already become the dominant setting for CCS investments. For example, in the US the 10 large-scale CCS facilities, capturing 24.9 Mtpa of CO_2, utilize approximately 2,000 kilometers (1,182 mi) of shared pipeline connection to transport captured CO_2 (GCCSI, 2019a; NPC, 2019). In Canada, the Alberta Carbon Trunk Line brought two CCS projects online simultaneously, with more projects planned.

The US offers many additional opportunities for CCS hubs. A recent National Petroleum Council's report (2019) that examined the central United States identified 115 sites, with total annual emissions of 477 million tonnes, would be suitable for CCS retrofit based on their location, size, age, fuel efficiency, criteria pollutant emissions, and competitive status in local power markets. Many of these potential sites could be served by proximal storage sites, including along the Gulf of Mexico and in the Permian Basin of Texas (Figure 4).

Figure 4: Demonstrated "carbon hub" potential with CO_2 capture and neighboring sink opportunities surrounding existing CO_2 pipelines in the Permian Basin (left) and Gulf Coast (right) regions.



Source: Pilorgé et al., 2020.

In Europe, a majority of all proposed CCS projects are similarly part of an industrial cluster. Examples of some planned CCS hub development in industrial regions include:

- Port of Rotterdam and Port of Amsterdam, Netherlands
- Port of Antwerp, Belgium
- Humber and Teesside, United Kingdom
- Northern Lights, Norway
- Ravenna Hub, Italy
- The Acorn Hydrogen and CCUS project in Scotland, United Kingdom

Interestingly, five countries are required to access funding for projects of common interest under the European Commission (EC) rules. As the number of EU countries considering hubs has reached five, this could be material and provide a policy window for infrastructure development and support. The UK government plans to develop the first net-zero carbon cluster by 2040, and the heavy industry of the Ruhr Valley in Germany could take advantage of emerging hubs in the Netherlands. The government of Denmark is also considering CCS infrastructure. Such hubs in the EU and US can serve as a policy and development model for

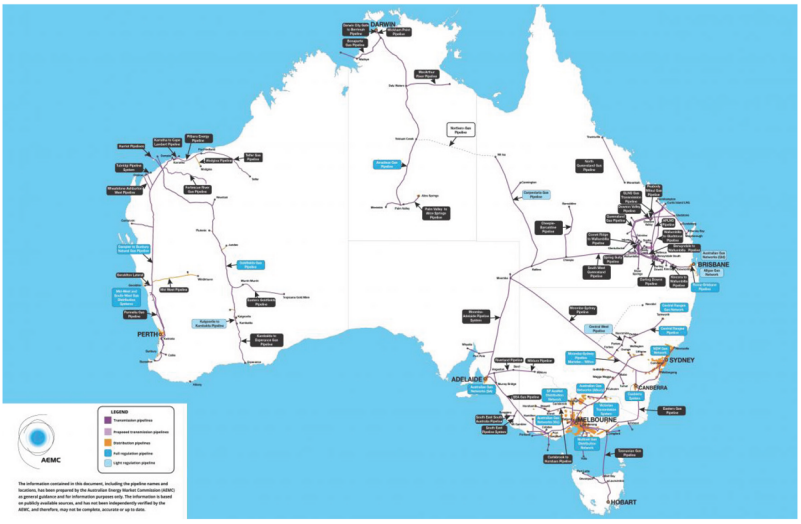
other industrialized regions (e.g., Tianjin/Hubei/Dalian in China or Cambay/Ahmedabad in India).

The development of individual hubs requires significant capital investment, including hundreds of kilometers of pipelines and proven storage infrastructure and requiring many billions of dollars. This is well within the range of typical industrial development. In 2019, there were more than 8,000 kilometers (5,000 mi) of CO_2 pipelines transporting more than 70 Mtpa of CO_2 from both natural and anthropogenic sources. Wallace, et al., (2015) and GPI (2020) independently estimate that roughly 28,000–35,000 kilometers (17,000–21,000 mi) of new pipeline would be needed to connect nearly 500 Mtpa of plant emissions to storage sites—roughly four times longer than today's network size and substantially smaller than the 4 million kilometers (2.5 million mi) of existing natural gas and oil pipeline networks. GPI (2020) also argues that this network could serve future CO_2 removal through direct-air capture.

Infrastructure Development Model: Australian LNG

Development of the Australian LNG industry demonstrates how similar infrastructure can be rapidly developed where there is a business case. In 2018, Australia was able to scale its export capacity to overtake Qatar's capacity, in part as a result of the infrastructure support of the Gorgon CO_2 storage project (required for operation of and export from the LNG facility there). Even more companies are investing in infrastructure throughout the region, turning Western Australia into a global LNG hub. Australia has more than 39,000 kilometers (24,000 mi) of natural gas transmission pipelines that efficiently transport gas under high pressure from where it is produced to the outskirts of cities both large and small. Transmission pipelines in the Northern Territory take gas from fields near Alice Springs in the center of the country to Darwin for use and LNG export. It is likely that the CO_2 storage infrastructure for the Australian continent will be substantially smaller and cheaper than the natural gas and LNG infrastructure.

Figure 5: Existing and Proposed Gas Transmission and Distribution Pipelines in Australia



Source: Australian Energy Market Commission 2020

Storage Resource Development

A worldwide portfolio of strategic, viable geological storage sites is essential to enable the planning and the development of CCS for net-zero. To reach 2030 and 2050 targets, a global stock-take of known storage capacity is critical, especially in key countries.

For decades, experts have known the global storage resources are more than enough to reach these climate targets (IPCC, 2005; Dooley et al., 2009; USGS, 2013; NETL, 2015). Their conclusion is based on a fundamental understanding—***rocks suitable for storing CO_2 are common and abundant around the world***. All global estimates greatly exceed 5 trillion tons of capacity (Table 3) and can accept CO_2 at a rate much larger than most nations' total emissions (e.g., Crippa et al., 2019).

Table 3: Global CO_2 capacity estimates

Geography	Low estimate (P10) in Gt	High estimate (P90) in Gt	Source
Global	8,000	53,000	Kearns et al., 2017
Global	6,000	40,000	Consoli and Wingust, 2017
North America	2,400	22,000	NETL, 2015; USGS 2013
China	1,100	3,600	Li et al., 2009; Consoli and Wingust, 2017

This high level of confidence in those storage resources is based in part on the natural occurrence of CO_2 storage systems, some holding CO_2 for over 250 million years (IPCC, 2005; IEAGHG, 2006). Mostly, this confidence rests on the well-understood physics, chemistry, and operational experience of oil and gas fields and the detailed characterization of rocks above, below, and adjacent to them. Although global gas and oil fields have substantial CO_2 storage potential (the US alone hosts between 185–230 billion tonnes of storage capacity in oil and gas fields) (NETL, 2015), they make up only a small percentage of the total resource available for CO_2. However, experience gained from hydrogeology and the oil and gas industry provides high confidence in an overabundance of CO_2 storage capacity.

A significant gap remains in key jurisdictions between available resources and known, commercially viable storage capacity (similar to the distinction between resource and proven reserves in oil and gas). The CO_2 Storage Resource Catalogue reviewed about 500 sites around the world (OGCI, 2020). The Catalogue reviewed over 12,000 $GtCO_2$ of storage resources using the industry-adopted classification system for CO_2 storage, the *Storage Resource Management System* (SPE, 2017). Only 400 $GtCO_2$ is "Discovered"; that is, having sufficient data that confirms the storage resource. Only 0.001 percent (100 $MtCO_2$) is considered qualified today and commercially ready.

Today, the majority of those well-assessed storage resources are in nations with advanced CCS

enterprises, including Norway, UK, US, Canada, and Australia. By 2030, a global portfolio of storage capacities in additional nations (especially China, India, Gulf Coast nations, and those in Southeast Asia) must match the required CCS capture rate. Such sites must commercially de-risked, technically feasible, environmentally sustainable, and locally accepted.

As a climate policy objective, injection and storage rate of individual storage sites must be confirmed and prepared, a process known as characterization and appraisal. Characterization and appraisal are time consuming and labor intensive, but well understood. A number of standards and best practice manuals exist, including the NETL best practice manual and DNV GL Recommended Practice (DNV GL, 2012). The International Standards Organization is also developing standards on site selection and appraisal. Characterization and appraisal of specific sites carry significant risk and uncertainty. Given the time it takes to develop storage sites and manage uncertainties, a focus should be on key sites (e.g., near industrial clusters) in key nations. Additional characterization work would help prepare potential sites for CO_2 removal projects, which today may be too far from emissions sources for conventional CCS projects.

Role of Law and Regulation

Transparent and predictable law and regulation are essential prerequisites for CCS investment. National governments and intergovernmental organizations emphasize the need to clarify CCS's position within international and domestic law and develop frameworks to support its deployment (e.g., Faure, 2016). Uncertainty surrounding existing law and regulation is frequently highlighted as major concern by investors, industry, and the wider public alike. Key uncertainties include:

- Access to and ownership of pore-space, especially in the US
- Operational requirements, including monitoring, reporting, and verification (MRV)
- Liability issues, including long-term liability requirements and transfer of liability to the state.

For several early-mover governments, addressing the issue was a priority when formalizing early policy commitments to the technology's deployment. In the past decade, the removal of legal barriers and the development of regulatory pathways within national regimes has become a defining aspect of national CCS activity.

Emergence of CCS-Specific Legislation

Although core elements of the CCS process have been practiced for many years as part of wider oil and gas industry operations, its role as a climate mitigation technology has challenged policymakers and regulators to adopt new approaches to its regulation. The result has been the development of new legal and regulatory frameworks aimed at regulating the entirety or discrete aspects of the CCS process. The past 10 years have seen amendments to international and regional agreements that explicitly include CCS activities within their scope, as well as the development of CCS-specific legislation in jurisdictions across Europe, North America, Asia, and Australia.

In all but one instance, one of two approaches has been adopted by policymakers and regulators: either enhance existing regulatory frameworks with CCS-specific provisions or enact standalone CCS-specific legal frameworks. The exception has been the development of "project-specific" legislation that regulates the operations of a single project; an example of which is the Barrow Island Act, which regulates Western Australia's Gorgon CO_2 injection project (Government of Western Australia, 2003).

The European Union's Directive 2009/31/EC offers an early example of a CCS-specific legal framework that deals with all aspects of the technology, throughout the project life cycle and within the context of climate change (European Parliament, 2009). The directive removes several potential legal barriers to CCS and clarifies the status of the technology under wider EU directives and regulations, including waste and water legislation. The European Commission chose to focus the directive upon the storage aspect of the CCS process and utilized several pre-existing legal instruments to manage some of the risks associated with the capture and transport aspects of the process. The resulting directive is a comprehensive CCS-specific regime, which includes requirements for the permitting of exploration and storage activities, monitoring and reporting obligations, liability and financial security provisions, and a process enabling the closure and long-term stewardship of storage sites.

In Canada, where regulatory competence for developing legislation is shared between national entities and provincial or territory bodies, the design and implementation of CCS-specific regulatory frameworks has principally occurred at the provincial level. Alberta's legal and regulatory regime is perhaps the most comprehensive CCS-specific model developed within the country to date (Legislative Assembly of Alberta, 2010). Similarly, in the United States, both federal and state authorities have undertaken development of CCS-specific law and regulation (e.g., EPA, 2010 a and b). These approaches serve as templates for other nations or regions considering how to provide clarity to project developers and investors.

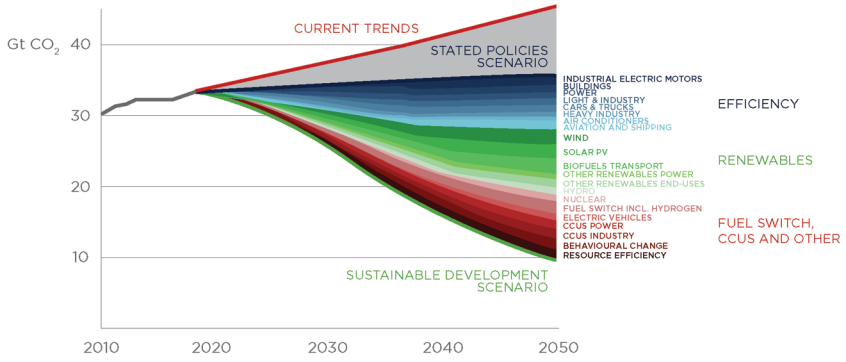
Because of these and related legislative developments, it is now possible for policymakers and regulators to reflect upon the critical legal challenges and intricacies involved in regulating the CCS process. While the ambition and complexity of the legislation developed to date varies greatly, several common areas stand out, and core legal and regulatory elements ("building blocks") will be required if regulatory regimes are to address concerns of investors and public stakeholders.

Only a small number of jurisdictions worldwide have well-defined and comprehensive CCS-specific frameworks. This will be insufficient to achieve net zero by midcentury and requires cultivation of regulatory frameworks. These jurisdictions and their regulatory models offer excellent examples of the challenges to be faced in designing and implementing CCS-specific legislation. For global deployment targets to be met, many more jurisdictions will need to develop their regulatory response to the technology, and the time required to undertake the process must not be underestimated. The urgency of this activity will prove increasingly acute in view of the timeframes contemplated to meet global climate change commitments and net-zero ambitions, including 2030 targets.

PROJECTS: THE CORE MEASURE OF PROGRESS AND POLICY-FINANCE FOCUS

To address climate change, climate models have generally recommended a combination of measures with greater contributions from CCS technology in scenarios that have more ambitious carbon targets, especially those which target net-zero emissions by 2050. For example, the IEA's Sustainable Development Scenario estimates 9 percent of the emissions reductions will come from CCS. While this figure may appear relatively small, the challenge of deploying CCS to meet it is significant. ***The 9 percent figure represents roughly 4 Gt CO_2 and a build rate of between 70 and 100 capture facilities per year***, in parallel with necessary transportation and storage infrastructure.

Figure 6: Energy-related CO_2 emissions & reductions in the Sustainable Development Scenario



Source: IEA World Energy Outlook (2019).

This means finance. CCS facilities are capital intensive, requiring hundreds of millions to billions of US dollars. Between now and 2030, capital support from governments will prove necessary to attract private capital. However, the sheer volume of capital required to achieve wide-scale deployment means private funding, both debt and equity. This is commonly the case for early deployment of clean energy technology deployment (see the offshore wind example later).

To date, CCS projects have not been able to attract private funding to meet high deployment rates. Most parts of the world lack solid, market-aligned policies for CCS, which limits financial viability. Most CCS projects are funded in public-private agreements involving a single corporation (or a fully owned subsidiary) that develops the project and places all financial

costs (and risks) on its balance sheets. While this makes the entire process of corporate finance attractive in terms of cost of capital and speed of implementation, too few companies are large enough to develop projects in this way, and corporate finance cannot deliver the projects needed to meet the targeted number of CCS projects for 1.5°C or 2°C scenarios.

The alternative, and more scalable funding model, is project finance. Capital for the project is raised on the basis of future cash flows with multiple investors in a single project, so both equity and debt investors are exposed to any uncertainty in performance of the project.[4] Unlike corporate finance, project financiers have no recourse to the assets of project owners and need stable, predictable returns to place their capital risk. This is particularly true of institutional investors (e.g., pension funds and sovereign wealth), which commonly accept low rates of return for low-risk investments, and to attract small- and medium-size investors (i.e., companies that lack large balance sheets). Reducing risks also reduces costs of capital, which will enable participation of smaller companies in the CCS sector.

The Role of Institutional Investors

Institutional investors—those that invest on behalf of third parties, such as mutual funds, pension funds, and insurance companies—will play an important role as CCS deployment ramps up. Institutional investors are attracted to investment in infrastructure projects because these provide secure, long-term cash flow while also providing a yield pickup (an investment strategy whereby bonds with lower yields are traded for bonds with higher yields) on the low returns available from government bonds.

Like all large-scale infrastructure projects, CCS projects will have a varying risk profile across the different phases of construction and operation. Once a project is commissioned, its risk profile falls because risks are highest during the construction phase and lower during operation. This drop in the risk profile of a project can lead to the refinancing of a project's debt with more favorable terms of lending being applied, which reduces project cost, bringing institutional investors to refinance or acquire projects that have entered operation.

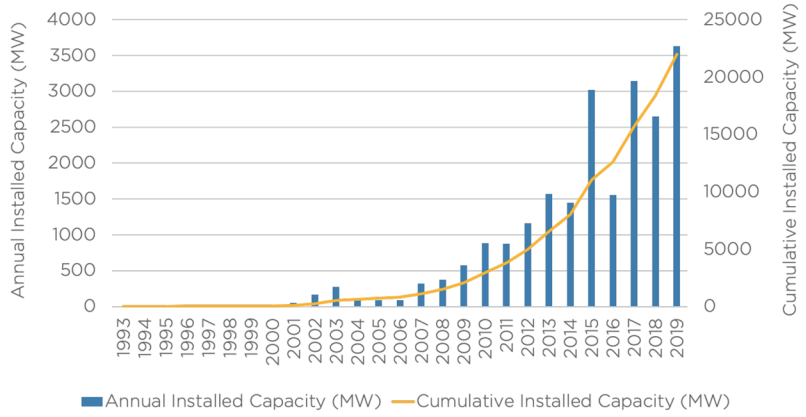
Lessons from European Offshore Wind

The European offshore wind sector is the most advanced in the world, and its recent development provides insights as to how project financing can be leveraged for large-scale CCS projects to increase the rate of deployment.

During the early 2000s, there were very few offshore wind projects in operation, similar to the status of CCS projects today. Once the EU confirmed offshore wind as a critical technology to meet the bloc's emission reduction targets, it implemented multiple policies to accelerate the rate of deployment of offshore wind farms. Private investors received a range of government subsidies in conjunction with other financing policies from the EC, including feed-in tariffs, green certificates, contracts for difference, and other "offtake agreements."

Each of these served the purpose of delivering a sufficiently high and stable revenue stream to offset project risks and generate acceptable returns. These incentives together de-risked investments in offshore wind overall and established a learning curve for the technology, creating more opportunities for smaller investors. As the offshore wind sector has evolved, investors have become more comfortable with project risks, so the participation of financiers has diversified, with commercial lenders playing a more prominent role than during the early stages of deployment. This had led to dramatic increases in the number of projects (Figure 6). Today, investments in offshore wind consist predominantly of conventional project finance.

Figure 7: Cumulative offshore wind installations from the early nineties until 2019



Source: Wind Europe

Although there are significant differences between offshore wind and CCS projects, there are important similarities, including novel, bespoke infrastructure and large corporate first-movers that fund projects on their books. With proper market-aligned policies, CCS could follow a similar trajectory.

POLICY OPTIONS

Without strong and predictable policies, market failures translate to market risks. If the cost of capture, transportation, and storage of CO_2 is greater than the value provided by climate policies, there is no incentive for investing in CCS. The value must be both stable and relatively predictable, and that predictability must ultimately be long-lived.

There are, however, additional challenges that require government intervention to get projects built, given the early stage of CCS ecosystems and networks:

- **Interdependency or cross-chain risk**: CCS facilities may involve one source, one sink, and one pipeline. These engender higher costs as well as a significant interdependency risk for disaggregated business models. This risk manifests as a higher cost of capital for potential financiers and represents a significant barrier to project investment.
- **Long-term liability risk**: While the risk of leakage from an appropriately selected storage resource is extremely low, unlimited or long-duration liability obligations make it very difficult for private sector investors to accept, particularly in jurisdictions where experience or access to geological data is limited. If these questions are not clarified through policy, even very low-risk projects may be difficult to launch.

Overcoming these risks will be essential to achieving 2030 rates of deployment. Thankfully, well-understood options are available as means to better manage or mitigate these risks so as to create an enabling environment for the private sector to invest in CCS.

Valorizing CO_2

Applying CCS at points of emission rapidly and profoundly reduces emissions. CCS does not, however, make products like steel or electricity, create revenues, or reduce energy consumption. In fact, capturing, transporting, and injecting CO_2 commonly adds costs and energy requirements. To merit investment, policies must place a sufficiently high value on the emissions reduction to incentivize investments. To date, the chief way this has occurred has been through the sale of human-made CO_2 for Enhanced Oil Recovery (EOR) rather than through environmental or clean energy policy mechanisms. Of the 21 projects currently in operation, 16 sell CO_2 for EOR (CO_2-EOR), a process whereby CO_2 is injected into oil reservoirs.

Widespread deployment of CCS will require a sufficiently high value to be placed on CO_2 emissions reduction independent of (and possibly as substitutes for) CO_2-EOR opportunities. This can only be achieved through market-aligning policies. Many options are available, and many examples exist supporting CCS deployment. Each jurisdiction determines the policy mix that best suits the local market.

- **Cap and trade**: These policies work by placing a limit on the total emissions—a regulatory cap—allowed for a given industry or the whole economy. The cap is split into transferable allowances, so companies can decide whether to contain their emissions or purchase additional allowances from others. Over time, governments may

reduce the cap so that there are less allowances available, thereby increasing demand for low-carbon interventions. By their nature, cap-and-trade schemes reward the most cost-effective forms of mitigation first. The European Emissions Trading Scheme (ETS) is one example, and a variation on cap and trade (baseline accreditation), the California low-carbon fuel standard, is a second (GCCSI, 2019). While cap-and-trade schemes provide a great deal of certainty over emissions reductions, they may carry significant uncertainty regarding the commercial value of these reductions. For example, the ETS value remains below the investment threshold for CCS investment and is not projected to meet it before 2030 (European Commission, 2018; CarbonTracker, 2018).

- **Carbon tax**: A carbon tax is a fixed cost imposed on CO_2 emissions. The pricing of the tax can be optimized to achieve reductions in line with targets for specific areas of the economy, and it can be increased over time to drive down emissions. For CCS, such taxes can be directed at large emitters and priced higher than the cost of capture. Like all taxes, however, their effectiveness is subject to their longevity. The Norwegian government introduced a carbon tax in 1991, which incentivized the development of the Sleipner and Snøhvit CCS projects. At the time, \$17/t CO_2, the cost of injecting and storing CO_2 for the Sleipner project, was much less than the \$50/t CO_2 tax penalty for CO_2 vented to the atmosphere (Massachusetts Institute of Technology, 2016; Herzog, 2016).
- **Tax credits and other incentives**: Governments may grant incentives such as tax credits to promote investment in a low-carbon technology. Credits can be investment-based (investment tax credits), performance-based (e.g., production tax credits), or both in combination. Tax credits have the benefit of being well-established climate change policies, having been used to drive significant investment in renewables over the past two decades. The US has used tax credits to stimulate renewable investments, including the wind production tax credit and the solar investment tax credit. In 2018, the US amended a performance-based tax credit for CCUS, 45Q (EFI, 2018; GCCSI, 2019). A similar mechanism, contract for differences (CfD), provides additional revenues for low-emissions production of electricity and acts as a production credit. The UK CfD for low-carbon electric power generation is an example that would support CCS deployment there (BEIS, 2020).
- **Green bonds**: One promising investment vehicle, sustainable bonds, allows investors to attach purpose to their investments, reconnecting finance with hard assets in the economy. In recent years, there has been significant growth in sustainable bond investments, particularly those issued to raise financing for climate-friendly investments. In terms of financing sources, there may prove to be substantial potential if projects are structured correctly. To this end, specialist funding sources (i.e., multilateral agencies and export credit agencies) play an important role in providing impact financing, especially during the earlier stages of deployment.
- **Regulated reductions**. Enacting legislation to reach climate targets provides transparency and accountability. To this end, several countries have mandated emissions reduction targets through legislation. Many countries have legislated net-zero emission commitments by 2050: France, the United Kingdom, Sweden, Denmark,

Netherlands, Iceland, and New Zealand. At the subnational level, California and New York in the US and Victoria in Australia have all enacted legislative commitments to net-zero. Some commitments are economy-wide; others are sector-specific (e.g., electricity). Commonly, these regulated reductions are paired with incentives and supported by advisory or statutory bodies (e.g., the UK's Climate Change Committee, created by the Climate Change Act of 2008). Some countries with net-zero commitments have overtly provided policy support for CCS deployment. In the Netherlands, CCS has been highlighted as a crucial technology in the electricity sector, and accompanying policy packages have allocated subsidies to assist with deployment.

- **Procurement policy**: Public procurement has emerged as an important instrument of innovation policy. Governments are one of the largest buyers of materials and services and can have a significant influence over the development of markets. In OECD nations, public procurement accounts for 12 percent of GDP, and up to 30 percent in many developing countries (Hasanbeigi et al., 2019). In the context of CCS, this is most relevant for hard-to-abate sectors, from which governments procure either directly or indirectly in large volume, including cement, steel, paper, and fuel. Traditionally, governments have bought the first generation of clean energy technologies, playing a key role in creating supply chains, stimulating innovation investments, and reducing initial costs. However, many policies that guide procurement predate the Paris Agreement and restrict the adoption of low-carbon choices. Governments must modify procurement policies and standards accordingly.

Costs and Avoided Costs

In considering what policy mix can achieve a net-zero economy and how to value emissions reductions, two key questions emerge: What should we do first, and how much will this cost? Focusing on 2030 as a near-term milestone underscores these questions: the longer the delay in reducing CO_2 emissions towards zero, the larger the likelihood of exceeding a 1.5°C increase, and the heavier the implied reliance on net-negative emissions after midcentury to return warming to 1.5°C.

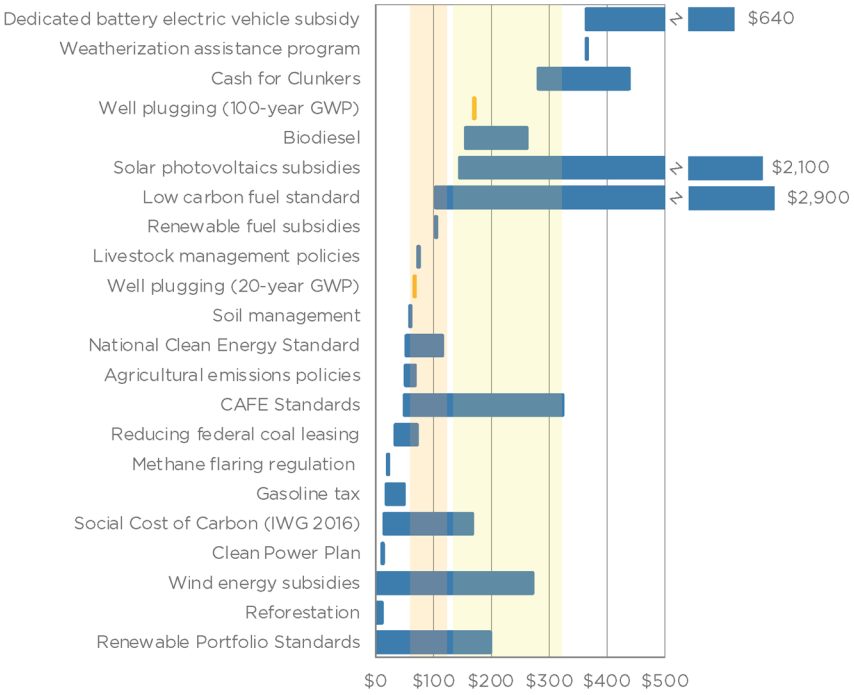
In this context, CCS has two specific values: low total costs in comparison to other options and avoided costs of climate change impacts through rapid mitigation and emissions reduction.

The Energy Transitions Commission (2018) states that achieving net-zero emissions in hard-to-abate sectors without CCS "will probably be impossible, and certainly [be] more expensive." It describes CCS as the most cost-effective route to decarbonizing chemicals, steel, and hydrogen production. One advantage CCS has is the ability to retrofit existing facilities without their premature retirement. Attaching CCS operations to emitting plants allows continued operation and production in existing infrastructure and logistics chains, preventing the capital losses associated with premature decommissioning (Friedmann et al., 2020). The prize can be substantial—applying carbon capture to the most feasible individual fossil power generators in the US would capture approximately 200 million MT per year (Brown, 2019) and at lower system costs than other low-carbon options (Jenkins et al., 2018; NPC, 2019).

To compare CCS with other clean energy options requires a common metric. To determine

the relative abatement costs associated with carbon removal technologies and policies, Friedmann et al., (2020) propose a levelized cost of abatement (LCCA). LCCA provides specific quantitative measures regarding the cost and abatement associated with specific investments, technologies, or policies, allowing "apples-to-apples" comparisons between CO_2 reduction and removal options. Gillingham and Stock (2018) compare these costs across many carbon reduction or removal policies, revealing that CCS remains cheaper than many decarbonization pathways. (Figure 7)

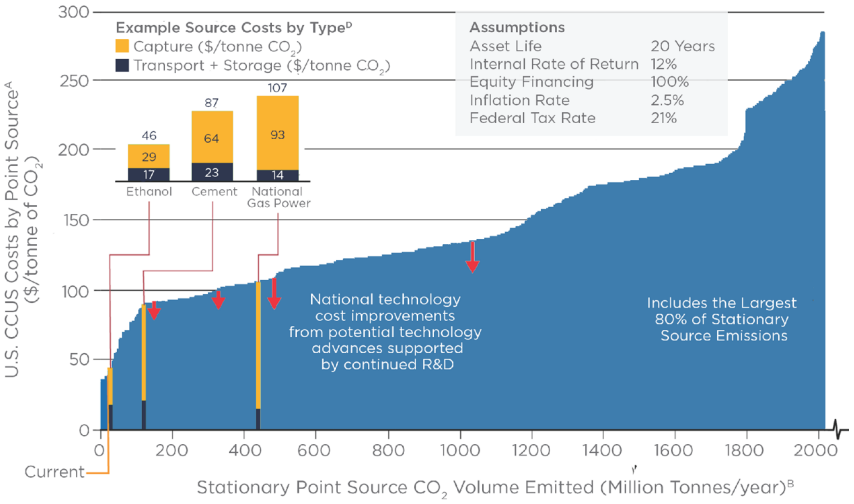
Figure 8: Estimated CO_2 abatement costs from selected US policies. Most of these policy options cost much more than the cost of carbon capture (orange shading) or even direct-air capture (yellow shading). Data from Gillingham and Stock, 2018. CCS cost data from GCCSI 2019 and NPC 2019. DAC costs from Rhodium Group, 2019.



Source: Bordoff et al., 2020.

The recent NPC (2019) report estimated the marginal abatement costs (MAC) for virtually every large emitter in the US, creating a MAC curve for CCUS deployment (Figure 8). It represents specific US facilities and builds the curve with individual costs assuming a specific existing technology and casts them in the context of policy ambition. Their estimates indicate that almost half a gigaton of reduction is possible for less than $110/ton CO_2, again substantially less than other options discussed by Friedmann et al., (2020) or Gillingham and Stock (2018).

Figure 9: Marginal abatement cost (MAC) curve for application of carbon capture and storage technology to individual existing US point sources (both power and industrial sites).



Source: NPC, 2019

Finally, it is important to remember the likely costs and consequences associated with inaction. Stern and Stiglitz (2017) estimate enormous costs associated with climate change, ranging from 5–20 percent of global GDP. The estimated costs and impacts on health, infrastructure, and biodiversity are enormous even under a 2o C scenario (IPCC 1.5o C report, 2018). In this, CCS provides an option that takes advantage of existing infrastructure at lower marginal cost and lower system cost (IEA, 2020).

Ecosystem Support

Some clean energy technologies, such as hydropower or biofuels, enter mature markets with well-developed infrastructure, legal, and regulatory systems. That mature market ecosystem

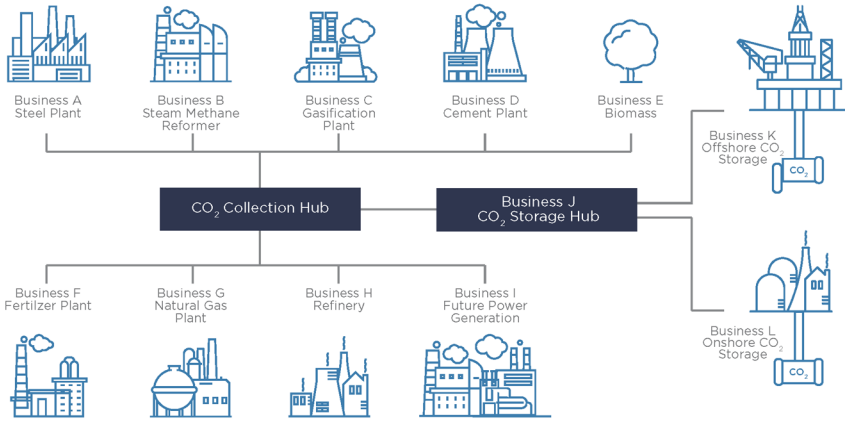
has helped speed adoption rates. Between now and 2030, components of the CCS ecosystem require support, clarification, and development to facilitate deployment.

Infrastructure: Pipelines, Storage Centers, and Minimizing Cross-Chain Risk

CCS facilities may involve one source, one sink, and one pipeline. In a disaggregated business model, there is significant cross-chain risk for all members of the value chain. This risk is a significant barrier to investment and manifests, ultimately, as a higher cost of capital and higher project costs. Common infrastructure dramatically lowers costs and risks to market entry and lets participants focus on their core business and skills. Shared transport and storage networks significantly improve the economics of CCS facilities because of the benefits of economies of scale and overall de-risking, and developing this infrastructure is essential to achieving widespread deployment of CCS systems (GPI, 2020).

An important option (discussed earlier) is the hub and cluster model (Figure 9). Here, value is provided through risk reduction across the value chain. A transport and storage network gathers CO_2 and manages disposal with a single entity, which significantly reduces unit cost of CO_2 disposal, enables market entry for new players, and reduces cross-chain risk by creating multiple customers for the operators of the CO_2 transport and injection business. Hubs and clusters offer high levels of operational flexibility, clear and constant prices for CO_2 services, reduced operational risk, and can serve to attract additional local investment, production, manufacturing, and jobs.

Figure 10: Hub and cluster model



Early investors in a new transport and storage network will face all the costs and risks of a single source until others join the network. This exposes them to cross-chain risks, greatly limiting numbers of early-movers. Guarantees must be provided for revenue during the early stages of development, as they are for new power transmission lines or new natural gas pipelines. For CCS projects in most jurisdictions, the balance of risk and return is insufficient to attract private sector investment in a CO_2 transport and storage network, requiring government investment or loan guarantees early on. The benefit to governments, beyond rapid and profound emission reduction, would include new investment attracted by the infrastructure and associated jobs and community support.

This model of government making the initial investment in infrastructure followed by later privatization is proven in other sectors such as road and rail transport, power generation and transmission, and telecommunication. Alternatively, governments could invest in establishing a regulatory framework that provides the private sector with the right incentives to invest in transport and storage networks. This may be preferable in regions where this is already common among infrastructure providers and where governments are restricted in funding transport and storage networks.

Long-Term Liability

A significant barrier to investment in CO_2 storage is risk associated with long-term liability. If there are no limitations on liability, either magnitude or duration, storage operators will face indefinite obligations of uncertain size. It is very difficult for private sector investors to accept essentially unlimited and perpetual liabilities. To mitigate this risk, it is critical for governments to implement a well-characterized legal and regulatory framework that clarifies operators' potential liabilities.

Multiple governments have adopted a remedy, whereby the storage operator bears the risk of short-term liability during the operational period of the project and for a specified post-closure period only. The Australian government provides one example:

> Following the completion of a period of at least 15 years, from the issue of the Site Closure Certificate, the title-holder may apply to the Minister for a declaration confirming the end of the 'Closure Assurance Period'. A declaration at the end of this period concludes the title-holder's liability for the storage site. Importantly, the Offshore Petroleum and Greenhouse Gas Storage Act also provides the former title-holder with an indemnity from the Commonwealth Government for any liability accrued after the Closure Assurance Period (Havercroft, et al., 2015).

This approach has been replicated in a number of other jurisdictions including the Australian states of Victoria and Queensland, the European Union, and the Canadian province of Alberta. It recognizes that the risk of leakage from a geological storage resource is highest during injection of CO_2, reduces immediately upon cessation of injection, and continues to reduce with time. Consequently, the risk accepted by governments starts small and shrinks thereafter.

Another proposed option is for governments to bear some or all of the risk during and after

storage operations. This mechanism has been adopted in many states in the US, which have legislated policies that accept liability for early projects. Under this arrangement, the private sector operator would be responsible for risks incurred below a cap, while government would take responsibility for all additional risks above a cap (Pale Blue Dot, 2018). Note that all risks, not just long-term liability risks, could be subject to risk-sharing under this model.

Amendment of International Marine Law

Enormous opportunities exist to store CO_2 offshore, most importantly in Europe and Australia. Even in the 1990s, many early analyses focused on the maritime setting for CO_2 injection and storage activities. Initial legal and regulatory assessments of CCS operations identified international and regional marine agreements as potential barriers to the technology's deployment, notably the 1972 London Convention and its proposed Protocol, a key element of the CCS ecosystem that merits diplomatic attention and work. The Protocol (the first international agreement codified to protect marine environments from wastes) adopts a stringent, precautionary approach to the disposal of wastes, with parties required to prohibit the dumping of all wastes at sea, save for those listed in the Protocol's Annex.[5]

The completion of various CCS-focused legal and technical reviews and the Protocol's entry into force in 2006, resulted in several parties submitting a proposal to amend the Protocol's Annex to allow the storage of CO_2 in sub-seabed geological formations. At the first meeting of the contracting parties to the London Protocol in November 2006, a formal resolution was adopted and entered into force in 2007. This category consists of "Carbon dioxide streams from carbon dioxide capture processes for sequestration" and provides a formal basis for the regulation of CO_2 sequestration in sub-seabed geological formations under the Protocol's mechanisms.

Shortly after the 2006 amendment, it became apparent to parties who were keen to export their CO_2 for storage or to host storage projects within their territory that these activities were not permitted under the Protocol. While principally aimed at preventing the export of wastes to non-parties, Article 6 of the Protocol had the effect of prohibiting transboundary transportation of CO_2 for geological storage. The position was confirmed by a technical working group, who recommended proposed text to amend the Protocol, introduced in October 2009 as a formal amendment. The amendment has yet to enter into force due to insufficient signatories. Although an agreement was reached in 2019 to allow the provisional application of the 2009 amendment as an interim solution, ratification of the 2009 amendment remains important.

Beyond 2030

Given the long lead times associated with developing CCS projects, the steps taken between now and 2030 will determine whether CCS technology will be deployed at the scale necessary to meet net-zero emissions by 2050. The arithmetic similarly demands that between 2030 and 2050 the rate of deployment of CCS grows exponentially. This implies that a rapidly growing demand for CCS projects emerges from debt and capital markets before 2030. For this to happen, investments in CCS must be significantly de-risked during the intervening years.

Governments must also anticipate the logistical barriers to be overcome by 2030. This will

involve planning and investment at large scale, such that the infrastructure to enable private investments in capture facilities is already available by the time the CCS market is de-risked and financiers are primed to invest. A handful of countries may already be on this path and will be well positioned to host projects beyond 2030.

Nonetheless, significant work remains to ensure that key nations, ones for which CCS will be an essential component of their climate objectives, follow suit. Parts of the world lack the capacity to develop the necessary infrastructure, human capital, or policies. In many cases (e.g., Southeast Asia) high cost of capital will severely limit investment potential. Novel arrangements should be explored to create options for these regions. One idea is for a group of OECD and non-OECD countries to cooperate in creating trade-based hubs and clusters enabled through shipping CO_2. Each country could then play to its strengths to create a cost-effective network of low-carbon goods, services, and infrastructure. International engagement, both bilateral and multilateral and in some cases long-lived, will be important to lay the foundations for projects and trade networks of this kind. Similarly, work is needed now to identify and assess viable geological storage options in regions like India, Southeast Asia, and Latin America. This may involve capacity building exercises, data transparency, and joint international surveys as the rest of the policy framework for geospheric return matures.

Such approaches can only succeed through robust policy measures and the availability of affordable financing. Developing countries will be at a disadvantage, and in some cases country risks would translate into a high cost of capital. To overcome these barriers, support from OECD countries, e.g., through climate finance mechanisms, may prove essential. This support can only become available if there is a concerted effort from within the international community to target large-scale planning and implementation of CCS projects globally.

SUMMARY – IT'S ABOUT TIME

The benefits of the modern energy system are many and varied, including wealth, health, art, and growing equity. The emissions from this system, past, present, and future, present a grave threat to these benefits and to the natural world. **Urgent action is required to achieve net-zero emissions and ultimately to remove legacy emissions** from our air and oceans. The work is pressing, mammoth, and enduring.

For this work, there is no substitute for carbon management. Both conventional CCS and engineered CO_2 removal are essential contributors to a net-zero global economy. All of the above starts with the world "all." **Throughout the next 10 years**, specific investments in infrastructure and innovation and specific policy actions will determine if net-zero is possible in our lifetimes. The focus must be on returning any carbon taken from the geosphere back to the geosphere and enabling policies that can hasten deployment. The most important policy options are as follows:

- ***Invest in CO_2 transportation and storage infrastructure***, most importantly CO_2 pipelines, industrial hubs and clusters, and qualified storage sites.
- ***Provide financial support to projects***, either through incentives (e.g., contract for differences, grants, tax credits, green bonds) or regulation (e.g., mandates, emissions standards, cap and trade).
- ***Clarify key regulatory and policy issues, such as pore-volume access***, long-term liability resolution, and the amendment of the London Convention of the Seas.

Due to the urgency of the climate crisis, time is of the essence. There are no important technical barriers to scale-up. The costs are well within the conventional boundaries of global energy investments and the policy options well understood. The next ten years will prove decisive – if the governments of the world are to meet their climate goals, these key policies must enter into force with deliberate speed.

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NOTES

1. Assuming solar PV capacity factor of 0.25 for 20 MW PV capacity, 10 MW electrolyzer and 50 kWh per kg of H_2 produced and necessary large scale battery storage.
2. Assuming 50 kWh of electricity per kg of H_2 produced.
3. 90 percent of this potential was via net-negative hydrogen production, combining biomass gasification with CCS.
4. The ratio of debt to equity in a project can vary significantly, by project specifics, availability of capital, and risk profile of the project owners.
5. The International Maritime Organization (IMO) acts as the secretariat for both the Convention and Protocol and views the Protocol as a key element of the international community's response to climate change.

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The CHAIRMAN. Thank you, Senator King and Dr. Friedmann, we look forward to that information.

Let's now turn to Senator Cassidy, who is with us online.

Senator CASSIDY. Thank you all. It has been a very stimulating conversation.

Now Dr. Friedmann, that kind of analysis in terms of the subsidy we are currently getting as opposed to the subsidy that would be required is, again, very enlightening. You had mentioned, obviously we have to sequester once we withdraw it, however we withdraw it. Now Louisiana has a lot of Class 6 wells that could be used for this. We have other advantages as well. And so, I say, what can the Federal Government do for Class 6 wells and CO_2 pipelines to make sure that the permitting is done in a timely manner, understanding the capital deployment depends upon that regulatory certainty?

Dr. FRIEDMANN. So let me say that the Gulf of Mexico, including Louisiana, is the Saudi Arabia of pore volume. It is the best global resource for storing CO_2 anywhere. It is a terrific natural resource the United States should take the opportunity to maximize. In that, access to the subsurface is the most important piece. In a place like Canada or Saudi Arabia, the government owns the pore volume. That is not the case in the United States. So federal lands are places where the United States owns the pore volume. State lands are places where states own the pore volume. Getting access to the pore volume is actually the rate-limiting step. After that, in terms of the permitting, say for Class 6 wells, as you asked, it is worth revisiting the current requirements around Class 6. I spent a lot of time working on this under Secretary Moniz at the Department of Energy and we worked closely with the EPA to think about how to streamline and improve the Class 6 process.

The most important thing we need to do right now, number one task, get more people. At the EPA today there is a half a person to permit Class 6 wells.

Senator CASSIDY. That is not good.

Dr. FRIEDMANN. There is not even one full-time employee, no. So one of the things they could do is hire more people and train them, not just at the EPA headquarters but also in the regional offices. So for Region 4, in Louisiana, getting more people familiar with how to permit these wells would be good.

Senator CASSIDY. Okay.

Now, secondly, let me just ask because I think I know that for direct air capture, a humid environment is a better environment and I am sitting there thinking that is another reason why the Gulf Coast, of course, Louisiana in particular, would be a wonderful place for this investment because not only do you have the wells in which you could sequester and the industry located from which you could offload, but you also have the humid environment. Any thoughts about that?

Dr. FRIEDMANN. Sure——

Ms. ANGIELSKI. Senator Cassidy, if I could?

Senator CASSIDY. Sure.

Ms. ANGIELSKI. I would love to just share thoughts about that because the other aspect of this that we don't talk enough about is that the oil and gas industry expertise is going to be essential for

CCUS industry to actually be catalyzed in this country. And we were talking about the effects of the pandemic and, of course, prior to that the oil industry was finding itself in distress for a variety of global issues. You have the expertise and the geology, the perfect geology in your State of Louisiana for this to be not necessarily a pivot or a transition, but a perfect opportunity for maintaining jobs from the oil and gas industry, but transitioning those jobs into a carbon capture industry. We can't do it without their ability to site and build and construct pipelines as well as inject CO_2 in injection wells. So I think that this is a really unique opportunity for the State of Louisiana to capitalize on.

Senator CASSIDY. I agree with that. By the way, I discussed this with geologists. We already have our geology mapped. He said those wells don't work, they are too shallow. These wells work because they go so deeply. A lot of the work that would be required has already been done. So I am with you entirely on that.

Now, that said, the economic challenge, Dr. Friedmann, you mentioned that we are already paying for this, the subsidy that would be required from the Federal Government, we are already—you mentioned for ethanol it is $500 per metric ton or $600 and that direct air capture would be $400. Is that the all-in price, not just the capture, but the sequestration as well?

Dr. FRIEDMANN. So this is why we look at these things from a levelized cost of carbon abatement perspective. It has to have real capital costs, it has to have real operating costs and it needs to compare at an equal level. If you do that, direct air capture is already cheaper than sustainable aviation fuels today, like already cheaper, and it is well below the cost of all kinds of incentives that we provide for clean energy.

Senator CASSIDY. And that is an all-in, that——

Dr. FRIEDMANN. All-in costs, yes.

And I want to be clear about this, those other incentives are extremely important and valuable. I'm not throwing shade at those other things. We want the EV incentives. We want solar rooftop incentives. We want all these things, but the cost in dollars per ton for those incentives in many markets exceeds the cost of direct air capture today.

Senator CASSIDY. Okay, well, thank you. I yield back.

The CHAIRMAN. There were a lot who wanted to jump in on this. I saw Mr. Mackler wanted to dive in, Assistant Secretary, even Senator King. So we can continue this, although I do want to go to Senator Cortez Masto, but Senator King, if you wanted to——

Senator KING. No, no, that is okay.

The CHAIRMAN. Okay, all right.

Let's go to Senator Cortez Masto online.

Senator CORTEZ MASTO. Thank you. And to the Chair and Ranking Member, thank you and the panelists. This is a fantastic conversation that we need to have in this country.

Let me jump back to a little bit on the workforce piece, because we have all been talking about CDR technology. Sometimes I think that scares people that there will not be jobs for the future, there will not be opportunities to take advantage of this new technology and what we need to do to not only transition existing jobs, but for our workforce development as well. So I would like to open it up

to the panel and maybe Dr. Friedmann, start with you. Can you talk a little bit more about the workforce piece and what we should be doing here to continue to not only ensure that the jobs are available for the future but educating our workforce and particularly the existing workforce that they might already have the skills that are transferable to this new technology?

Dr. FRIEDMANN. Thank you.

Three very quick points. First of all, chemical engineers, roughnecks, boilermakers and steel union makers, organized labor, these people already have a lot of the skills we need. So creating the industry for them to move into is part of the task. Second of all, we do need new human capital. It's exactly why Columbia University is creating the Climate School. We need to get those kinds of things up and running.

I would point you to two other reports that are relevant to this, one of them is the recent Rhodium Group report I mention in my testimony that suggests that hundreds of thousands of jobs are waiting for us just in direct air capture alone. In my testimony I also point out the same thing is true for forests. The same thing is true for soils. The same thing is true for carbon mineralization. There are hundreds of thousands of jobs out there. The final report I'd like to point you to is actually one that Joe Hezir had an important role in managing—the Energy Futures Initiative—wrote about, every year they write about the jobs in the clean energy industry that have begun to look at this topic and look to Joe.

Mr. HEZIR. Thank you, Senator, if I could just jump in on that. Thank you, Julio.

I just want to add one other thing in addition to our work on the job survey. We've also, Secretary Moniz and President Richard Trumka, entered into an MOU back in April to set up the Labor Energy Partnership, and as part of that program we are doing more of a deeper dive on identifying job opportunities as part of the energy transition. And carbon capture and sequestration is one of the ten priority areas that we identify and as Dr. Friedmann said, the workers currently in the oil and gas industry really have the, kind of, the skill base to really move directly into carbon capture and storage opportunities, including in the various infrastructure. And so we're looking to identify, not only to quantify that, but also identify policies and programs that would help accelerate that effort.

Mr. MACKLER. Yes, Senator, if I might also jump in on this one?

If we take a step back and look at carbon removal writ large, we see that there's, you know, as we've emphasized throughout this hearing, there are a number of different approaches that we can take to remove CO_2 from the atmosphere and really when it comes to the arithmetic, we need to be doing it all. And the good news is that when it comes to the more nature-based solutions, forestry and agriculture in particular, those are labor intensive activities. And so we can actually start doing carbon removal today, scale it up on the natural solution side of things and put a lot of people back to work very quickly. As we build out the more advanced technologies like direct air capture and even biomass with CCS, which, by the way, is less technologically sophisticated than direct air capture, it's using technologies that are already available today and

we can start to deploy those technologies using skills and expertise from the power sector that exist today to start removing CO_2 from those facilities as we build out the technologies that do the more broad scale, direct air capture at some point in the future.

Senator CORTEZ MASTO. Thank you. Thank you. I notice my time is running low. I will submit the rest of my questions for the record.

Thank you, again, for this incredible conversation.

The CHAIRMAN. Thank you, Senator Cortez Masto.

I am checking to see if Senator Hoeven, excuse me, Senator Gardner would be next. I know he was going to be coming on virtually. We have also had votes started, so he may have gone to do that first and also Senator Hoeven, I think, was going to go to the vote first.

So if I don't see their faces pop up, I am going to come back to questions here.

When I first had the opportunity to ask questions, I kind of teed up the issue of blue carbon but didn't really give anybody much of an opportunity to elaborate on the benefits of coastal blue carbon removal options. So let me ask you, Dr. Friedmann, you have taken a look at this. Any comments on that that you might want to share with the Committee?

Dr. FRIEDMANN. Yes, and having grown up in the ocean state along with Senator Whitehouse, we've got a lot to say about this. Blue carbon is a real thing. It's a real opportunity. Most people think about it as coastal mangroves and in places like Florida that's a real undertaking and would provide resilience, would provide adaptation, buffering for coastal storms, all these kinds of benefits. But it is not restricted to that. It also includes things like kelp and in my own work we've been dealing with a number of companies that are seeking to expand and grow kelp in novel ways. The innovation is quite impressive and we can see opportunities to get hundreds of millions of tons or possibly more of CO_2 removal through kelp cultivation and either conversion or destruction. The National Academies wrote about this in depth. It was a section of the Energy Futures Initiative report as well. The—I'm glad that this is starting to gain people's interest. We need to stimulate and support the innovation and the industrialization of blue carbon.

The CHAIRMAN. Well, thanks for that and you have, several have mentioned different places to be looking for that level of expertise, but we will certainly come back and circle in with you and your folks.

Let me ask about the CCUS export potential. I liked the exchange that was had, prompted from the comments from the Senator from Louisiana, and a recognition there that what they have in Louisiana is truly a national asset and you are lucky to be blessed with both the geology as well as the humidity, I guess. I did not appreciate the humidity part of it. But about 85 percent of all global carbon dioxide emissions come from outside the country. We have talked about that demand for coal-fired power generation growing across much of Asia. So as we look to how we can make CCUS deployment a priority, I think we have an opportunity as a nation here to become the global supplier for some of these critical technologies. So how do you see our role, and I would turn to you,

Assistant Secretary Winberg. How do you see our role in helping to facilitate that more broadly, because I do think it is an important part of the recognition that it can't just be the advancements in one country that are going to turn the tide here?

Mr. WINBERG. Yeah, well, thank you for the question and you were exactly correct, the rest of the world is going to continue using fossil energy whether it's coal or oil or natural gas and that's why we have moved forward quickly on the Coal FIRST program because it offers the opportunity to, for what I think of as 21st century coal. Right now, the Chinese own the space in power generation, coal-fired power generation. We have an opportunity to take technology and springboard over what the Chinese are building which is basically 1970s vintage technology that we built and then they now have improved slightly, but they're selling it around the world to countries that have coal under their feet and they're going to continue using that coal.

But with the Coal FIRST program, we can move into power generation and we can move into hydrogen production because these countries also, as they build out their transport sector, may not do it the same way as developed countries. They may move more swiftly into hydrogen. And so there's an opportunity there to take our technology, using their natural resources that are under their feet, and produce zero-emitting power generation and zero-emitting hydrogen and perhaps even net-negative hydrogen and net-negative electricity. And they can use that hydrogen in the transportation sector as well as the industrial sector. So I think there are opportunities for us, and we're availing ourselves of that.

The CHAIRMAN. Well, it is that kind of leadership that, I think, really will make that difference and that has been mentioned here, not only by you, coming from the Department of Energy, but others as well.

Senator Cantwell, we have had a fabulous discussion this morning on what is going on with the innovation, the technology, the leadership, the opportunity in so many different areas. So you are up.

Senator CANTWELL. Great, well, thank you for that.

I wonder if two questions have been brought up. One, methane and what we need to do to stop more methane flaring and the use of natural lands as a way to reduce CO_2. Obviously Alaska is a great example of helping us to reduce CO_2, but I don't know if that was addressed so far today.

The CHAIRMAN. We did——

Dr. FRIEDMANN. Senator, if I might start the conversation.

Senator CANTWELL. I know the Secretary was with us but left, former Secretary, is that right? So——

The CHAIRMAN. Yes.

Mr. MACKLER. Yeah, thanks for the question, Senator.

My name is Sasha Mackler, and I work for the Bipartisan Policy Center and we are doing a variety of things with respect to carbon removal and we also have a farm and forest natural climate solutions initiative that we're launching. So we're very much engaged in this issue of lands and how they can become a sink for CO_2 over time. And we have had some discussion——

Senator CANTWELL. What compensates people for that?

Mr. MACKLER. Well, so, the development of markets for carbon storage in forests and in agricultural soils will be critical to actually encouraging the best practices and the development of the technologies and the flow of private capital into these activities which will be key. And so there are a number of things happening today that are beginning to stimulate activity in these areas, but more is needed, particularly on the measuring, the monitoring, the verification side of things and the establishment of credible accounting standards so that private companies, for example, know what they're investing in and they're pragmatic enough that they can be, you know, they can enable simple transactions.

Senator CANTWELL. So you don't think we have any price points today?

Mr. MACKLER. In terms of the cost of storage? I mean, we——

Senator CANTWELL. Or value.

Mr. MACKLER. Yeah, I mean——

Senator CANTWELL. Value as a solution juxtaposed to some—I mean, obviously when we are talking about technology, we kind of know what the development cycle looks like, the investment, the return that people might get, but has somebody put a price as to how that relates to how lands——

Mr. MACKLER. Sure, so there are things happening today in forests and in soils with respect to carbon offsets and we, kind of, know that those, they start at around $10 per ton and they go up from there. So there are, there's certainly activity in the offset market in soils and in forests, carbon storage.

Senator CANTWELL. So $10 right now.

Mr. MACKLER. Well, so that's, yeah, that's, sort of the beginning price. It depends on what activity you're looking for. But and then as you do more sophisticated activities and as you move from natural lands in the agricultural, the sort of the most simple to execute to some of the more complex, more labor intensive things, like forest restoration, those become more expensive, but they have a number of other co-benefits, for example, wildfire management, that are really, you know, quite vital to the local areas.

Senator CANTWELL. Yes, well, we definitely got very aggressive about that for that very, one of the reasons you just mentioned.

Mr. MACKLER. Yeah.

Senator CANTWELL. So——

Mr. MACKLER. Yeah.

Senator CANTWELL. And what about methane? We obviously tried very hard to get the Administration to understand that this is one of the lowest hanging fruits that you could deal with, and yet we still have methane flaring beyond what we should. What are your thoughts there?

Mr. MACKLER. Well, it's, it is an enormous issue and it's one that, you know, the good news is the technology exists to really control methane upstream and we really need to just figure it out. And I know the industry is working hard on this as well as, you know, my colleagues in the NGO community, as well as the Federal Government. We see signals that the cost of managing upstream methane emissions are manageable, and we also see some progress in the deployment of those technologies. As the regulatory frameworks get sharper and as the customers of natural gas in the

utility industry or the direct customers start to account for the upstream burden of methane leakage in what they're looking to purchase, I think there's a big opportunity to start to cut those emissions out of our supply chain, but there's a lot of work that needs to be done there, no doubt about it.

Senator CANTWELL. But you consider it a low-hanging fruit that the applications we could do today and the reduction we could do today?

Mr. MACKLER. For the leakage and flaring of methane, I think that's absolutely true. The technologies exist. We just need to deploy them.

Senator CANTWELL. Thank you. Thank you, Madam Chair.

Dr. FRIEDMANN. Right, Senator, I would add to Sasha's comments. We've written a lot about this at the Center on Global Energy Policy. Rob Kleinberg has done a lot of work on the specifics of the technology, the cost, the opportunity size and we've done this in partnership with EDF. Happy to answer questions on the record as you ask.

Senator CANTWELL. Thank you.

The CHAIRMAN. Thank you, Senator Cantwell.

Let's go to Senator Gardner, online. Welcome.

Senator GARDNER. Thank you very much, Madam Chair.

Mr. Hezir, both you and Secretary Moniz, both from your time at the Department of Energy, know how critical our national labs are across the country, obviously Colorado, home to the National Renewable Energy Laboratory which houses the Wind Technology Center, solar electric and fuel cell vehicles, smart homes, buildings, they have it all. In Colorado, NREL has a robust economic impact. The University of Colorado recently assessed that NREL had an economic impact of about $875 million in Colorado, $1.4 billion nationwide in Fiscal Year 2019 alone. And over the last several years, in fact, one of the things I am most proud of since I came to the Senate is that I have been able to help increase NREL's funding by nearly 50 percent over the last several years.

I know you would agree that NREL is instrumental in this effort, talking about carbon capture, utilization and storage today as one of the many low-carbon technical options. But as the nation moves toward developing advanced clean energy systems, renewable energy will play a key role toward reaching that goal as well. My question is for you, Mr. Hezir. With the integration of high amounts of renewable energy proving more viable than previously thought and thanks to DOE and NREL's leadership in advancing this, how would carbon capture, utilization and sequestration fit an international portfolio of clean energy solutions and how does it, along with renewables and nuclear, fit into an all-of-the-above energy strategy and what can our labs, academia and industry do to help advance these low-carbon solutions?

Mr. HEZIR. Thank you for the question.

We, obviously when Secretary Moniz was at the Department, advancing the work of the national laboratories was a major priority and not only that, he was instrumental in forming the Office of Technology Transitions, an office that was set up to actually accelerate the movement of new inventions and new innovation to lab-

oratories into the marketplace. The current Administration now has picked up on it—invest in CDR—a major project——

The CHAIRMAN. Mr. Hezir?

[Distorted sounds coming through WebEx feed.]

The CHAIRMAN. Mr. Hezir, can you hear me?

Mr. HEZIR. ——landscape.

The CHAIRMAN. Okay.

Mr. HEZIR. And as part of that study we came up with criteria and some recommendations about, really, technology areas with breakthrough potential and clearly, CCUS and CDR were on the short list for that. And so, earlier in the hearing today we did talk about opportunities for innovation, particularly in direct air capture and some of the other technologies that involve innovations in materials, innovations in sorbents and things like that, areas of strengths for the national laboratories.

And I would just add one final point that is relative to NREL and the other national laboratories, one of the other things that we did at the Department was to encourage more cross-cutting research initiatives across the laboratories. And I think the one that's been the most successful has been in the grid modernization initiative for which NREL was a major, was one of the co-leaders really, and we would think that we would like to see something like that occur as well in the areas of CCS and CDR.

Senator GARDNER. Thank you, Mr. Hezir.

I know we are in the middle of a vote, so I don't want to go over time here. I would just point this out. I mentioned that we have increased funding at NREL by over 50 percent over, well, nearly 50 percent over the last several years, and I would note that the U.S. spends about 2.7 percent of its gross domestic product on research and development, but China is close behind us at 2 percent. In 2018, for the first time in fact, China actually surpassed Europe, the EU, in spending for research, spending $8 billion while the U.S. led by just a hair at $8.2 billion. So we have a lot more work to do in this space. We passed legislation in the American Innovation and Competitiveness Act a couple years ago, we are funding NREL, we have increased funding for NIH and others, but we have more work to do so that we can—this leadership because imagine if that next great breakthrough is somewhere else, all of those jobs go with it if it is not here in the United States. Thank you very much for your leadership.

Madam Chair, I will yield back.

The CHAIRMAN. Thank you, Senator Gardner.

Senator Hoeven is on the line and will ask the next question and also the last question. Senator Hoeven, if I can ask you, at the conclusion of your remarks, you can adjourn the Committee virtually for us, if you will so that I can go vote. Our 30 minutes is up.

But before I leave and turn it over to Senator Hoeven, I want to thank all of our witnesses, those of you who have traveled to be here in the office and those who are here virtually, thank you for your endorsement. I think each and every one of you spoke to the benefits of our energy bill, the American Energy Innovation Act. You have been positive about some of the legislative efforts that we have here, the EFFECT Act, the CREATE Act and we are working on more and reminded us of the benefits of the 45Q. So some good

reminders here today, but I think the thing that I am leaving with, with the most inspiration is just the wide array of technologies that we are looking at, the innovation that we are looking at and just the momentum that we are seeing when we speak about various ways to deal with carbon and carbon removal technologies. So thank you for joining the Committee.

Senator Hoeven, you can have more than five minutes if you want. The clock is yours, so thank you.

Senator HOEVEN [presiding]. Thank you, Madam Chairman, I appreciate it very much and thanks for holding this hearing. I will certainly be happy to adjourn the meeting once finished here with questions for the witnesses. I want to thank the witnesses for being here as well, and I will start with Assistant Secretary Winberg.

Thank you, Secretary Winberg, for all your work on the whole gamut of energy issues there at the Department of Energy. I also appreciate you coming out to North Dakota to see what we are doing in North Dakota. My first question to you is, you know, you have been part of and you have worked very hard to get the 45Q regulatory guidelines in place, and that is very important, so that not only coal-fired electric plants but ethanol plants and others can utilize that 45Q tax credit. But my first question is what else can we do to enhance that tax credit so that we can really get these power plants capturing and sequestering CO_2 and do it on an economical, viable basis.

Mr. WINBERG. Senator Hoeven, thank you for the question.

I think there are a couple things that can be done. First of all, extending out the 45Q tax credit, I think, is extremely important because a lot of these companies have been teed up, ready to go for the last two years waiting on the 45Q finalization from the IRS. And of course, in the midst of this time or during this time period, COVID has hit our country quite hard and has had a profound, profoundly negative impact on balance sheets and income statements. So allowing companies to—extending out the timeframe for the 45Q will create some flexibilities for these companies that are in very much a recovery mode.

Number two, we need to take a really hard look at how long it's taking to permit a variety of CCUS projects and we have CCUS projects with capture systems and also, as you well know, pipeline systems and getting permits for the capture system and the pipeline system and even for the wells, the injection wells, is just an incredibly long period of time and especially if you're doing a project that has commercial ramifications and implication to your bottom line, those long permitting times are just unsustainable. So I think that's a key to all of these across the CCUS value chain, shortening down the permitting times and then increasing 45Q, the length of time to utilize it so that these companies can, indeed, install these technologies and demonstrate to the world that they're commercially viable.

Ms. ANGIELSKI. Senator Hoeven, could I just add to the enhancements? This is Shannon from CURC.

Senator HOEVEN. Yes, please do.

Ms. ANGIELSKI. In my testimony I point out the fact that—also for the reasons that Steve mentioned with the recovery and pandemic—currently, taxpayers have to go out to the tax equity mar-

ket to try to get tax equity investment in the 45Q, and CCS projects has fully monetized the 45Q tax credits. Allowing a taxpayer to elect for what we term direct payment, which would be a direct cash payment from Treasury, as an alternative to resorting to the tax equity markets is another way of actually trying to bring more value of the 45Q tax credits into a project and get financing and it opens up the capital markets for that. So that's something that we've been an advocate for in trying to see if we could make a statutory or legislative change here in Congress.

Senator HOEVEN. So you would say then that it would be very important to have the direct pay option as well as the tax credit option, correct?

Ms. ANGIELSKI. Well, we didn't want to eliminate the tax equity option at the moment, but I think the value would be in the direct cash payment and likely probably see more taxpayers elect for that as opposed to resorting to the tax equity market. Part of the reason for that might be in coming out of a recovery or going into recovery as it's still questionable how much tax liability even those big investment firms are going to have in the out years in order to actually be able to take advantage of tax equity structures. So I think it's really critical that we move forward with a direct cash payment option in this Congress but not close out any of the other options that are currently on the books.

Senator HOEVEN. Thank you, I agree.

Dr. Friedmann, I am going to ask you two things. That same point which she just made, I want you to give me your opinion in regard to that direct pay option, but also I want to know if you have any other policy proposals that would bring 45Q in line with, you know, value wise with existing, other existing renewable tax credits. So if you could, kind of, touch on those—45Q direct payment but then also other ideas to enhance—increase its value, you know, more in line with what we would see in CCUS.

Dr. FRIEDMANN. Thank you, Senator, absolutely.

First of all, I agree with Shannon. Under Section 1603, Direct Payment is an option that was done during the 2009 stimulus for a bunch of renewable tax credits. We should create that optionality under 45Q given the current economic crisis as well. I also agree with prior testimony that we need to extend the timeline out at least five years in order to get more companies accepting and pursuing this option. That certainty is important.

Our Center recently published an analysis in April on what it would take to enhance 45Q to get power sector uptake. We looked at coal plants and gas plants. We looked at utility ownership and we looked at merchants. And basically, to get uptake from utility-scale coal plants, something like $60 a ton gets you pretty close for saline aquifer storage. For gas plants if it's owned by a utility, it's more like $80 a ton or $85 a ton and for merchant plants, it's more like $110 a ton. People should realize though that the wind production tax credit at various times and in various context has ranged between $60 and $120 a ton. So this kind of incentive is well in line with other subsidies and incentives that we've provided in the past.

Senator HOEVEN. Thank you, Doctor. I think that is a very important point you just made. I appreciate it very much.

Secretary Winberg, I would like to come back to you on those issues, direct pay and relative incentive—and get your, kind of, follow-up comment on that and then I want to shift for just a minute to the strategic petroleum issue.

Mr. WINBERG. I'm sorry, Senator, could you repeat the first one? You broke up a little bit.

Senator HOEVEN. Sure.

I would like you to comment both in terms of your opinion on the direct pay option for—45Q and its importance that we should have that and then again, as Dr. Friedmann mentioned getting that incentive to the range that the——

Mr. WINBERG. Okay, sir, that's a very simple response from me. Yes, I do. We need to create more optionality for these developers and whether it's a utility or an independent power producer, the value that we have on the 45Q tax credit will work for some but not for a lot. So if we're looking for broad-scale deployment of CCUS, we need to have flexibility in how they can avail themselves of the 45Q credit as well as the value that goes to them for the capture system.

Senator HOEVEN. Thank you.

Is the Department continuing to advocate for authorizations as well as CCS funding through putting more oil in the Strategic Petroleum Reserve?

Mr. WINBERG. Yes sir, we are. We have asked Congress for $3 billion. As you know, we opened up—we didn't get the $3 billion in the first round of stimulus—so we opened up the SPRO and we are storing oil for private sectors, but we still have available sufficient capacity in the SPRO to purchase oil and put a number of oil field workers back to work producing that oil and storing it in the SPRO and then at a point in the future, Congress can have us sell that oil and we think that it will be a significant return on investment to the taxpayer because we'll be selling that oil at a considerably higher price than what we would buy it for.

Senator HOEVEN. Yes, I really appreciate that point.

I do have one more question for you, Secretary, and that is on CarbonSAFE. Are you continuing to prioritize funding for CarbonSAFE and moving, advancing it, continuing to get your dollars out to those power plants that are undertaking that effort because that is critical in terms of enabling them to strip off that CO_2——

Mr. WINBERG. Yeah, thank you for that. It's a great question. The CarbonSAFE program is a very necessary part of the carbon value chain. So we recently have five Phase III projects. One of them is the North Dakota CarbonSAFE Phase III project which is the University of North Dakota and EERC. That's a $25 million program that we have and we have four others as well moving into that Phase III. We also have other projects in Phase I and Phase II development. So we're very active in that and looking forward to moving those projects to the point where we actually create a sequestration field and each one will be at least 50 million metric tons that will allow a number of CCUS projects to inject CO_2 into those CarbonSAFE projects. So we're very much active in that and looking forward to continuing that work.

Senator HOEVEN. All right.

Mr. Hezir, I just want to express to you I truly enjoyed working with former Secretary Ernie Moniz when he was the Secretary of Energy. A true gentleman, obviously extremely knowledgeable with a tremendous record, but what a gentleman and if you would tell him I appreciate all the times he was out in our state and just give him my very best, if you would.

Mr. HEZIR. I will do so.

Senator HOEVEN. All right, sir, thank you.

To all of the witnesses, thank you very much, we appreciate it, appreciate your time, appreciate your testimony today. With that, this hearing is adjourned. Thank you.

[Whereupon, at 12:08 p.m. the hearing was adjourned.]

APPENDIX MATERIAL SUBMITTED

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to the Honorable Joseph Hezir

[No Responses Received as of the time of Printing.]

Questions from Chairman Lisa Murkowski

Question 1: Can you please elaborate on how important it is for the deployment of carbon removal technologies to become a global effort? How important it is to have many different countries removing carbon dioxide from the air, instead of just a few?

Question 2: When you were at the Department of Energy during the Obama administration, you oversaw several attempts to reduce silos in research and development. What are some issues and challenges you foresee for an effort such as this?

Question 3: If the proposal you suggest could not be funded at the scale you suggest, what areas should be prioritized?

Question 4: What are some of the biggest challenges to deployment of large-scale carbon storage on the order of magnitude of one gigaton per year?

Questions from Ranking Member Joe Manchin III

Question 1: In 2009, Congress passed the 48C advanced energy manufacturing tax credit that invested in retooling, expanding, or building new manufacturing facilities for clean energy equipment. This tax credit could be revived to also include support for supply chains related to carbon dioxide removal technologies.

a. Do you think a tax credit like the 48C manufacturing tax credit would be helpful in achieving our COVID-19 recovery goals?

b. How do you see it supporting carbon capture, utilization, sequestration, and other carbon removal technologies?

c. What additional policies are needed to complement such a tax credit?

Question 2: We need to consider carbon dioxide removal on a global scale – both because climate change is a global issue and because market penetration of these technologies is as important in international markets as it is in domestic ones.

a. Where do you see the greatest advantage for U.S. companies for exporting carbon dioxide removal technologies and solutions abroad?

b. Where do you see policy obstacles to doing so or opportunities to create further incentives for exporting the carbon dioxide removal technologies developed in the U.S.?

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to the Honorable Joseph Hezir

[No Responses Received as of the time of Printing.]

Question from Senator Mazie K. Hirono

Question: In Secretary Moniz's testimony, he outlined the potential benefits of Blue Carbon techniques, including expanding plant growth in coastal areas. What is the potential scale of carbon removal that could be achieved by coastal and ocean carbon removal technologies if we made the $1.6 billion investment in research recommended in the testimony?

Question from Senator Catherine Cortez Masto

Question: In Secretary Moniz's written testimony, he noted that, "Other countries are currently moving forward with research initiatives on technological carbon dioxide removal (CDR) approaches."

a. What countries are making the largest investments in CDR technologies, and is there room for the Unites States to take on a leadership role in building some of the collaborative framework Secretary Moniz mentioned in his testimony?

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to the Honorable Steven Winberg

QUESTIONS FROM CHAIRMAN LISA MURKOWSKI

Q1. As you know, the Department is spending a lot of time working on characterizing carbon storage options in the United States. What are some of the biggest challenges to large-scale carbon storage on the order of magnitude of one gigaton per year?

A1. The Department of Energy's (DOE) research and development (R&D) and field validation over the past 20 years have confirmed the feasibility of large volume CO_2 storage in the United States through efforts such as the National Risk Assessment Partnership (NRAP), the Science-Informed Machine Learning to Accelerate Real-Time decisions for the subsurface (SMART-CS) Initiative, Regional Carbon Partnerships, and the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative.

Two of the main challenges to gigaton scale deployment of carbon storage are limited opportunities for investors to earn a financial return on storage investments and limited regional pipeline infrastructure. The Internal Revenue Service's (IRS) 45Q tax credit, along with other incentives at the state level, such as California's Low-Carbon Fuels Standard (LCFS), are current examples of incentive-based policies that improve investment conditions and will help increase U.S. deployment of carbon storage. The size ($/tonne), certainty around long-term availability, and qualification flexibility are examples of essential features of incentives that improve investment conditions. While there is significant CO_2 pipeline infrastructure along the Gulf Coast and in the southwest to support the chemical industry and enhanced oil industry, there is minimal available pipeline capacity in other regions for moving CO_2 from point sources to storage locations. Absent shared pipeline infrastructure, each storage project must bear the financial burden of self-supporting infrastructure.

The IRS has made substantial progress and issued a 45Q draft rule, but a final rule is essential to create the degree of certainty required by the investment community. The regulatory environment for permitting carbon storage wells already exists. States are showing increased interest in seeking primacy to regulate carbon capture, utilization, and

storage operations, with both North Dakota and Wyoming having already been granted primacy. Regulatory streamlining and mechanisms to manage long-term (albeit low) storage liability would further improve the investment environment for storage projects.

Q2. Your testimony goes in depth into "blue hydrogen" technologies that are derived from fossil fuels but carbon neutral. What does the Department see as a realistic timeline for these technologies to enter the commercial market at a large scale?

A2. Fossil fuels are the source for nearly all 70 million tons of hydrogen produced worldwide today. Seventy-six percent of this total is produced from steam reforming of natural gas. Twenty-two percent is produced by coal gasification.

When carbon capture, utilization, and storage (CCUS) is added to the hydrogen production process, the manufacture of hydrogen from fossil fuels becomes close to carbon-neutral. The resulting hydrogen is sometimes referred to as "blue hydrogen". If a blend of fossil fuels and biomass are used in a hydrogen production process equipped with CCUS, the produced hydrogen could be carbon-negative.
To further illustrate the potential for carbon-negative hydrogen, a gasification process with a 90% CCUS capture rate will have net-negative carbon emissions when using a blended fuel of 20-30% biomass and 70-80% coal.

Coal gasification, natural gas steam methane reforming, plastic pyrolysis, and CCUS are all commercially-available technologies. The work that remains is combining these technologies into integrated systems that can produce carbon-neutral or carbon-negative hydrogen. Large scale introduction of any hydrogen to the market will also require development of sufficient hydrogen economy infrastructure, such as hydrogen storage, transport, and distribution systems. Also, there must be market demand for the hydrogen in such applications as power generation and heavy duty vehicles.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to the Honorable Steven Winberg

With supporting R&D, coupled with effective market incentives (e.g., the 45Q tax credit), initial deployments of carbon-neutral hydrogen technology can occur this decade.

Q3. How does the cost of blue hydrogen compare with "green hydrogen" generated from renewable energy?

A3. "Blue hydrogen" is hydrogen from fossil (and sometime fossil-biomass hybrid) fuel-fed processes that incorporate CCUS. Blue hydrogen, depending upon the process design, rate of carbon capture, and type of fuel feed, and ratio of fossil to biomass feedstock ranges from nearly carbon-neutral to carbon-negative.

"Green hydrogen" is the production of hydrogen from renewable energy (wind, hydropower, and solar power) through electrolysis. It is a process that splits water into it basic elements - water and hydrogen – using electric currents. The hydrogen produced is neutral. Colorizing hydrogen is sometimes helpful to explaining concepts, but it is not an objective measure of what is "clean."

On average, producing carbon-neutral hydrogen from fossil energy with carbon capture and storage is economical compared to producing hydrogen from renewables. The projected costs for "blue hydrogen" of under $3kg-H2 (reference: the Hydrogen Strategy: Enabling a Hydrogen Economy document) are currently less than the $5-6/kg-H2 projections for "green hydrogen" today (reference: DOE HFTO Program Record20004: https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf) Representative costs are shown in the figure below from the DOE report

Q4. The Department is spending a lot of time working on characterizing carbon storage options in the United States. What are some of the biggest challenges to deployment of large-scale carbon storage on the order of magnitude of one gigaton per year?

A4. See answer to question 1 as that answer is also applicable to this question.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to the Honorable Steven Winberg

QUESTIONS FROM RANKING MEMBER JOE MANCHIN III

Q1. Point source carbon capture and carbon dioxide removal technologies will both be needed to meet U.S. climate goals. I have been encouraged by recent funding announcements at the Department of Energy and the National Energy Technology Laboratory that include R&D for carbon capture technology on coal and natural gas plants, and the work at DOE and NETL should be complemented by similar investments in carbon dioxide removal technologies.

Q1a. Can you provide some insight to the considerations DOE took when developing the budget for CO_2 removal technologies?

A1a. When developing its fiscal year 2021 (FY21) budget for CO_2 removal technologies, the Department took several factors into consideration. First, the Department considered the existing research and development (R&D) that has been conducted, such as carbon capture technologies, and how those technologies can be leveraged for CO_2 removal. It also incorporated the results from its workshop on direct air capture (DAC) technologies that was held in July 2019. Finally, DOE was one of the funding sponsors of the National Academies of Sciences, Engineering, and Medicine (NASEM) report, *Negative Emissions Technologies and Reliable Sequestration* that was published in 2019 and defined the challenges and opportunities for technologies, such as CO_2 removal. The results from this report were also considered when developing the FY21 budget request, along with prioritizing other R&D throughout the Department and the appropriate government role.

Q1b. What timeframe does DOE expect from each phase of carbon dioxide removal technology development?

A1b. The timeframe for development of CO_2 removal technologies will depend on the generation (i.e., first generation, second generation, etc.) of the technology. There are several first generation DAC technologies that are at pilot- or demonstration-scale. Second generation technologies are being developed that can leverage past and current efforts, such as the carbon capture, utilization, and storage (CCUS) R&D conducted by

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to the Honorable Steven Winberg

DOE and investments in facilities such as the National Carbon Capture Center. DOE estimates that laboratory- and bench-scale R&D for second generation technologies could take approximately six years, pilot-scale testing another five years, and front-end engineering design (FEED) and large-scale testing up to eight years. However, there is potential overlap for each of these phases as individual DAC technologies will develop and mature at different rates.[1]

[1] U.S. Department of Energy, Office of Fossil Energy Infographic on Direct Air Capture, https://www.energy.gov/sites/prod/files/2020/01/f70/Direct%20Air%20Capture%20Infographic_0.pdf.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to the Honorable Steven Winberg

QUESTIONS FROM SENATOR BILL CASSIDY

Q1. On a percent basis, how much of the Department of Energy's (DOE) carbon capture program budget is currently being allocated for natural gas carbon capture applications?

A1. Many of the technologies developed by the carbon capture program have applicability for multiple applications including coal and natural gas power, industrial sources, hydrogen production, and direct air capture. In fiscal year 2020 (FY20), the DOE carbon capture program was congressionally directed to spend at least $7 million in funding on carbon capture systems for natural gas. This represents 6% of the carbon capture program budget. An additional 75% of the capture budget applies to multiple fuels, including natural gas. In addition, the program recently selected two projects at $13 million each for engineering-scale testing of capture technologies specifically for natural gas, and one project at 44.1 million that will test on both coal and natural gas flue gas streams. DOE also provided nearly $7 million in FY19 and FY20 funding to the National Carbon Capture Center to add a natural gas combustor to the facility.

Q2. How can Congress and DOE help advance new scalable methane conversion technologies, such as methane pyrolysis, to create commercially valuable carbon which could be utilized as structural materials?

A2. DOE has a specific program (Natural Gas Infrastructure) within the Office of Fossil Energy (FE) focused on the detection, reduction, and quantification of methane emissions with a recent focus on scalable methane conversion technologies. Research in this new area will focus on the application of process intensification at modular equipment scales suitable for being deployed to, and transported between, remote sites where methane is being lost due to venting and flaring.

In April 2020, FE selected 14 projects valued at $20 million to initiate a research effort to develop Process-Intensified Technologies for the Upcycling of Flare Gas into Transportable, Value-added Products. Four of these projects, valued at $11 million,

relate directly to the pyrolysis of natural gas and the production of structural carbon-based materials, such as micro- and nano-scale carbon fibers. Over the next three years these projects will validate their technologies at bench scale and develop designs for prototype scalable, modular equipment. A follow-on R&D effort is anticipated to manufacture and demonstrate the successful technologies at field sites using actual associated natural gas and real-world conditions. In addition, 10 proof-of-concept projects, valued at $9 million, that focus on the production of value-added chemicals, such as benzene/toluene/xylene and methanol, were also selected. The focus of these projects is on novel catalysts and separation materials development. Successful technologies will move to a next phase to develop equipment and process concepts based on their materials.

Q3. What plans does the department have to further invest in alternative carbon utilization projects and technologies, including ones at the Carbon Hub at Rice University? What actions will be taken to encourage collaboration across natural gas industry, technology partners, and end users of structural carbon?

A3. The Department plans to continue to invest in early-stage R&D on carbon utilization technologies, such as catalytic conversion to higher value products (e.g., nutraceuticals, chemicals, and polymers; mineralization to building products; generation of solid carbon products; and biological conversion into products). DOE plans future requests for proposals (RFPs) with selections made via competitive solicitations. Organizations, such as the Carbon Hub at Rice University, can submit applications for consideration. Further, many of DOE's funding opportunity announcements encourage collaboration on applications, and project awardees frequently include multiple partners. Specifically for carbon capture, utilization, and storage (CCUS), DOE recently integrated each of these programs into one joint annual meeting to encourage more collaboration among industrial partners, including the coal, natural gas, and industrial sectors; technology developers and vendors; and potential end-users. The Department continues to explore opportunities to

further engage and build connections between various stakeholders across the CCUS value chain.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to the Honorable Steven Winberg

QUESTIONS FROM SENATOR MAZIE K. HIRONO

Q1. According to the Energy Information Administration, natural gas operations in the United States vented or flared on average 1.28 billion cubic feet per day in 2018, the highest ever annual average level and the latest year for which data is available. Leaks from gas pipelines are another source of methane, a potent greenhouse gas. In April, the International Energy Agency warned that the recent decline in revenues from oil and gas operations could mean that companies pay less attention to efforts to tackle methane emissions. Do you agree that it would make sense to minimize natural gas venting, flaring, and pipeline leaks in the first place, rather than paying the damaging costs of increased climate change, or paying to remove the carbon from the atmosphere in the future if the carbon removal technologies in their early stages of development become affordable and effective? What is the Office of Fossil Energy doing to increase the ability of industry and the public to identify where leaks, venting, and flaring are happening and then stopping them?

A1. DOE has a specific program within the Office of Fossil Energy (FE) focused on the detection, reduction, and quantification of methane emissions. In April 2020, FE selected 16 projects from a $25 million Funding Opportunity Announcement (FOA) to enhance the safety and efficiency of the Nation's natural gas production, gathering, storage, and transmission infrastructure. The three focus areas of this solicitation were: Advanced Technologies to Mitigate Methane Emissions and Increase the Efficiency of the Natural Gas Transportation Infrastructure;

1. Process-Intensified Technologies for the Upcycling of Flare Gas into Transportable, Value-added Products; and
2. Advanced Methane Detection and Measurement Technology Validation.

Over the next three years these projects will advance integrated sensor and control systems with real-time data collection; provide continuous monitoring of natural gas quality and pipeline material conditions; reduce methane emissions from compressors and controllers; and improve methods to inspect, identify, and analyze legacy pipeline materials. New research is developing technologies for the conversion of otherwise

flared or vented gas into high-value easily transportable products and validation of methane emissions detection and quantification technologies.

FE continues to track data and trends across oil and natural gas production, transmission, and storage infrastructure with a specific focus on emissions activity. This includes analysis of state-level natural gas flaring and venting regulations currently implemented by oil and gas producing states. FE analysis explaining state-level flaring and venting regulations is provided across 33 fact sheets and is available at: https://www.energy.gov/fe/findyourstate-natural-gas-flaring-and-venting-regulations-fact-sheets-state

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to the Honorable Steven Winberg

QUESTIONS FROM SENATOR CATHERINE CORTEZ MASTO

Q1. Throughout your written testimony, you mentioned the cost and manpower of carbon capture, utilization, and sequestration (CCUS) research and development (R&D) projects taking place within the Department of Energy (DOE).

Q1a. What long-lasting impacts has the ongoing COVID-19 pandemic had on R&D within the agency?

A1a. Throughout the COVID-19 pandemic, DOE has remained mission ready and is working with other Federal agencies and stakeholders to review the status of the energy industry, review the impacts of COVID-19, and provide recommendations to the President and the Administration to maintain a secure and robust economy. At this time of unprecedented economic disruption and worker displacement throughout our Nation and the global economy, the DOE is working tirelessly to maintain economic well-being, national security, and energy independence.

Q2. In your written testimony, you also noted that DOE is working to reduce the costs associated with carbon capture.

Q2a. Can you speak a little more about what specifically the Department is doing to reduce CCUS costs?

A2a. The cost of carbon capture typically accounts for approximately 75% of the cost of carbon capture, utilization, and storage (CCUS). DOE is conducting several activities to reduce CCUS costs. For example, DOE is investing in technologies that are developing advanced materials that allow more CO_2 to be captured per unit of material than current technologies. This reduces the energy consumed in the capture process, making it more efficient and thereby reducing operating costs. These material improvements can also reduce the size of the equipment, resulting in capital cost savings. Additionally, the application of advanced manufacturing techniques can help reduce material waste and facilitate new, more efficient process designs.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to the Honorable Steven Winberg

The development of new ways to utilize CO_2 to create value can offset some of the costs of capture. There are several existing markets for CO_2, such as enhanced oil recovery and the food and beverage industry. DOE is exploring other opportunities such as catalytic conversion of CO_2 to higher value products like nutraceuticals, chemicals and polymers; mineralization to building products; generation of solid carbon products; and biological conversion into products.

For carbon storage, DOE is investigating ways to make the processes of site characterization, storage operations, and site closure more efficient through: 1) the application of high performance computational tools, such as artificial intelligence and machine learning; 2) improved monitoring and characterization tools and systems; and 3) more advanced modeling and simulation capabilities.
When combined, all of these technologies have the potential to reduce costs and improve the efficiency of CCUS operations.

Q3. Is the Department already engaging with states and local communities about carbon dioxide removal technologies and geological sequestration?

A3. Yes, the Department of Energy (DOE) has a long history of engaging with state and local communities about carbon dioxide (CO_2) removal technologies and geological sequestration. State and local officials frequently request opportunities to discuss DOE's programs, projects, and opportunities for collaboration. Additionally, many of DOE's large-scale projects engage with state and local officials and communities to communicate the status and benefits of the project. Finally, DOE's Regional Carbon Sequestration Partnerships have historically worked closely with state agencies and local governments as part of their geological sequestration project activities over the past 15 years.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Ms. Shannon Angielski

Questions from Chairman Lisa Murkowski

Question 1: Bioenergy with carbon capture (BECCS) seems like a unique removal technology because it is both negative emission and supplies energy. How much bioenergy with carbon capture could feasibly be developed in the United States?

CURC's emphasis on carbon capture, utilization, and storage (CCUS) technologies in the power sector has traditionally focused on fossil fuel-based applications. CURC is only beginning to study in detail the feasibility of BECCS and is not yet in a position to make specific recommendations to the Committee.

We refer you to a 2019 Report entitled "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda", by the National Academies of Sciences, Engineering, and Medicine (NASEM) which dedicates a chapter to BECCS, including discussions of technical potential, costs, and research needs. We would direct the Committee towards the assessment of NASEM in that report. Below is a segment from the Report which estimates CO_2 flux potential, or how much CO_2 could be removed from the atmosphere from U.S. BECCS capacity:

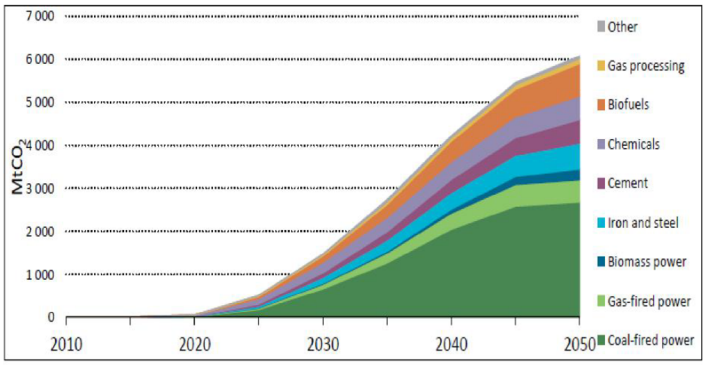
"Using biomass availability data, NASEM estimated the economically feasible (i.e., without significant impacts on current land and biomass use) BECCS CO_2 flux potential for the United States. The economically feasible lower bound is 522 Mt/y CO_2. The U.S. economically feasible upper-bound BECCS CO_2 flux (or CO_2 emissions reduction) potential is estimated to be 1,500 Mty CO_2 by 2040."

Question 2: How does the cost compare with coal or natural gas carbon capture?

As you can see from the below graphic, the International Energy Agency previously analyzed the contribution of different CCS-based technologies need to cost-effectively achieve the 2° scenario by 2050. In their breakdown, you can see that coal- and natural gas-based CCS is projected to cost-effectively contribute upwards of 50% of the total needed CCS-related emissions reductions (globally), while BECCS (biomass power and biofuels) are projected to cost-effectively contribute upwards of 10-12% of total needed CCS-based emissions reductions.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Ms. Shannon Angielski

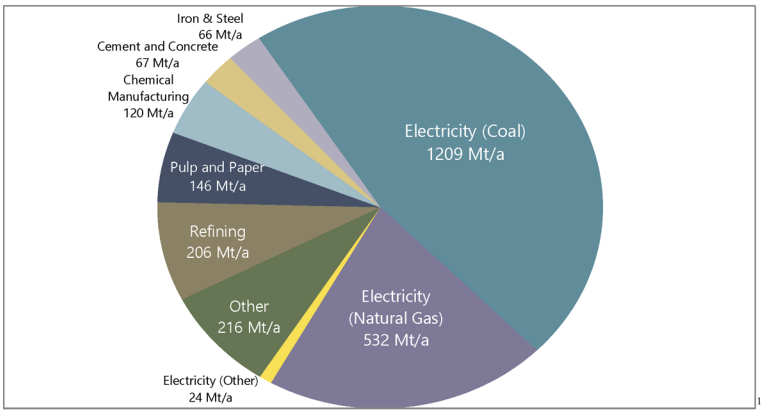
Global Carbon Capture by Industry to Achieve 2° Scenario



Source: Derived from *Energy Technology Perspectives 2016 (IEA, 2016)*.

We do not have any similar analysis that focuses on only the U.S. emissions reductions potential at this time. However, nearly 75% of U.S. point source CO_2 emissions are from electric power sector, from coal and natural gas. In 2017, approximately 2.6 Gigatons of CO_2 were reported to the U.S. Environmental Protection Agency (EPA) as being emitted from industrial point sources in the U.S. The graphic below shows the breakdown of CO_2 emissions reported to the EPA Greenhouse Gas Reporting Program in 2017.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Ms. Shannon Angielski



[1]

The U.S. electric power sector is where the most significant reductions can occur. Also, given the existing coal and natural gas asset base, it will be important to evaluate the economic potential of utilizing those existing assets with the application of CCS, and the potential for those assets to utilize biofuels to achieve negative emissions reductions.

Question 3: Are there areas of research and development that need to be expanded to capitalize on this opportunity?

Carbon capture systems that would be utilized in BECCS applications do not differ substantially from those that are currently and that can be utilized in fossil-based CCUS applications. Co-firing applications using biofuels is something that needs to be evaluated for both new and existing natural gas and coal generation facilities. DOE maintains a world-class carbon capture research and development program to advance such technologies through to commercialization. Congress could consider providing additional appropriations to DOE to study how existing and future fossil fuel-based CCUS technologies could be utilized to support co-firing of biomass and fossil fuels and to support additional BECCS demonstration projects.

The biomass component of BECCS requires additional research. For power applications, the NASEM report indicates that R&D is needed for biomass pretreatment and logistics for the conversion of conventional pulverized coal power plants to biomass and for high-efficiency biomass power generation.

The report also states that future research can be conducted in the following areas:

[1] U.S. EPA GHGRP 2017 data by point sources (https://www.epa.gov/ghgreporting)

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Ms. Shannon Angielski

- The field requires spatially explicit optimization of biomass-to-fuel and power implementation to design optimal BECCS network configuration accounting for plant scale, location relative to biomass supply, competition for biomass supply, CO_2 transport network, and CO_2 and/or char sequestration sites.
- Integration of biomass power plants with an electricity grid that may have a high fraction of various renewable energy technologies (e.g., solar, wind) in the future will present challenges in terms of load following, requiring improved understanding and control over ramping and flexibility.
- Reductions in the capital cost and energy consumption of CCS are needed to improve economic and technical viability of BECCS, with particular attention paid to any challenges that biomass feedstocks may introduce for CCS.
- The quality and variability of CO_2 produced from biomass power plants and the impacts on carbon capture system components will need to be analyzed to understand long-term impacts on pipeline, wellhead, and subsurface equipment.

Question 4: Could BECCS be combined with improved forest and wildfire management to further multiply the amount of carbon removed?

This question is outside the scope of CURC's expertise.

Question 5: How do we balance the carbon dioxide removed using BECCS with potential changes in land-use patterns?

This question is outside the scope of CURC's expertise.

Question 6: What has the impact of the renewed 45Q tax credit been so far? You mentioned both refundability and extension as important reforms. Is refundability or further extension more important to realizing the value of this credit?

Upon enactment in 2018, the revisions to the Section 45Q tax credit immediately spurred public and private interest in CCUS project development and deployment. As written, Section 45Q will be the most impactful incentive in the world to promote CCUS deployment. However, the 2+ year delay in IRS issuance of guidance on issues critical to implementation of the credit meant that uncertainties with regard to implementation have not been formally resolved, resulting in delays in private investment. Now that IRS has proceeded with its formal rulemaking on Section 45Q implementation, we are hopeful that projects will soon be able to fully utilize the revised credit.

Going forward, both refundability and an extension of the commence construction date will be critical to promote CCUS project deployment in the wake of the COVID-19 pandemic. Many project developers do not have the tax liability to fully monetize the Section 45Q credit, and there are growing concerns that even tax equity investment firms may have limited tax liability over the next several years due to economic impacts of the pandemic. Making the tax credit refundable and providing an option for direct payment in lieu of the tax credit would help developers fully monetize the credit and avoid the need for tax equity partnerships. There is precedent for providing a cash payment mechanism for energy projects from the American Recovery and

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Ms. Shannon Angielski

Reinvestment Act in 2009, which provided for a grant in lieu of a tax credit option for renewable projects. We believe the direct pay/refundable option is a better use of taxpayer dollars than the grant, as a project must be operating, capturing and storing CO_2 and can only claim a direct payment in the taxable year in which the project stores CO_2. Unlike the grant in lieu of a tax credit, this does not impact the federal budget in year one nor does it require some level of estimation of the cost of the project, which cannot project with certainty the cost of a project when estimating the percent value of the needed upfront cash grant. The Recovery Act program led to some projects overestimating costs and receiving more than the percent tax credit that should have been applied against a project and, alternatively, can be less than what is needed. Providing similar treatment of a refundable credit for an emerging CCUS industry will help to stimulate investment capital needed in CCUS projects and achieve deployment results over the next decade.

As noted above, CCUS project development has already been delayed as project developers and investors have waited for the final regulations from Treasury and IRS to implement the 45Q tax credit program. During this time, the available window to commence construction on CCUS projects has been reduced to less than four years (from nearly six years at the time of enactment).

Extension of the commence construction date for projects claiming 45Q will provide certainty to project developers and investors and ensure greater deployment of CCUS over the coming decade. This certainty is even more critical in a post-pandemic world. CURC has recommended a 10-year extension of the commence construction date, which will be necessary to allow capital markets to recover and provide the time needed for CCUS projects to successfully meet the deadline.

Question 7: IRS finally released its updated guidance for the 45Q regulations. Are your member companies satisfied with what the IRS released?

CURC's member companies are encouraged by the recent IRS proposed rulemaking on the Section 45Q tax credit. However, the regulations still require further clarification on important issues that must be addressed in the final regulations in order to accomplish the key policy objectives of Congress through implementation of the revised 45Q program.

In comments made to the IRS, CURC provided IRS with the following recommendations to improve the final rulemaking:

- Reduce the five-year lookback period to a maximum of three years for recapture in the proposed rule, as the length of the lookback period will deter tax equity investment in projects;
- Include language in final regulations to clarify the party that will earn tax credits in the event that multiple entities own different pieces of equipment within a single carbon capture project;
- Include language that makes it clear that the capture owner may transfer the credits to the person that contracts with the capture owner to dispose of, utilize, or use for EOR the qualified carbon oxide even if that person does not physically perform those tasks and contracts with a third party to physically perform those tasks on their behalf;

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Ms. Shannon Angielski

- Provide guidance that says the owner of the carbon capture equipment does not have to recognize income upon the transfer of the credits;
- Extend construction safe harbor deadline for 45Q projects to provide as much administrative flexibility as possible in the wake of the COVID-19 pandemic.
- Ensure that Congressional intent of 2018 tax credit revision is upheld through guidance ensuring that economic substance doctrine and Section 7701(o) do not apply to taxpayers that invest in carbon capture projects.

Separately, CURC submitted joint recommendations alongside the Clean Air Task Force, ClearPath, Environmental Defense Fund, Oxy Low Carbon Ventures, Shell Oil Company, and The Nature Conservancy focused on secure geologic storage of CO_2 and recapture of the credit, pathways for establishing transparency, and rules governing third party verification of secure geologic storage.

Question 8: Are there companies that can realistically take advantage of the 48A coal carbon capture tax credit as currently written?

As written, the Section 48A tax credit cannot be utilized by companies seeking to retrofit existing coal-fired facilities with CCUS technologies. Only companies that are going to build new facilities in accordance with the technical requirements of the tax credit program can currently take advantage of the tax credits. The 2008 revision to the Section 48A credit required that a carbon capture system be installed in order to be eligible for the credit. However, the 2008 revision did not remove the existing requirement that a plant achieve a certain efficiency threshold in order to qualify for the credit. Because the installation of a carbon capture system necessarily leads to a decrease in efficiency due to parasitic load required to power the capture system itself, these projects cannot realistically comply with the credit requirements. The Carbon Capture Modernization Act (S. 407 / H.R. 1796), introduced in both the Senate and the House, would rectify this issue by allowing projects that utilize CCUS technologies to be eligible for the credit without meeting the existing efficiency improvement requirement. If enacted, the bill would help to ensure that the original intent of Congress to promote CCUS on coal-fired power plants is satisfied.

Questions from Ranking Member Joe Manchin III

Question 1: In 2009, Congress passed the 48C advanced energy manufacturing tax credit that invested in retooling, expanding, or building new manufacturing facilities for clean energy equipment. This tax credit could be revived to also include support for supply chains related to carbon dioxide removal technologies.

a. Do you think a tax credit like the 48C manufacturing tax credit would be helpful in achieving our COVID-19 recovery goals?

A substantial amount of energy equipment is manufactured offshore and imported. For example, the majority of wind turbines and solar panels purchased by U.S. companies are manufactured in China due to their low manufacturing costs. Incentivizing the manufacturing of equipment in the U.S. through Section 48C would ensure that the U.S. is able to capitalize on the opportunity to establish an alternative domestic manufacturing capability for equipment in new, emerging energy industries, where there is currently no market to incentivize

the construction of new manufacturing facilities. In a post-pandemic world, U.S. based manufacturing will create U.S. supply chains for energy sector projects that can be used here and exported to other countries, which will have significant benefits to the balance of trade. The tax credit also represents an opportunity to create new energy manufacturing jobs.

b. How do you see it supporting carbon capture, utilization, sequestration, and other carbon removal technologies?

U.S. manufacturing of CCUS and other CO_2 removal equipment will improve economies of scale for an emerging technology like CCUS, which will help to reduce the cost of implementing CCUS and CO_2 removal technologies. It will also incentivize more market pull for technology development by the private sector.

c. What additional policies are needed to complement such a tax credit?

Policies that ensure U.S. equipment is purchased from domestic suppliers for new, emerging energy technologies would complement the tax credit. For CCUS, policies that encourage the use of CCUS in industrial operations would be helpful, similar to the way renewable portfolio standards coupled with multiple tax incentives helped to deploy wind and solar. Additionally, increased investments in research, development and demonstration of new technologies will act to reduce capital costs and ensure they are utilized in commercial applications.

Question 2: We need to consider carbon dioxide removal on a global scale – both because climate change is a global issue and because market penetration of these technologies is as important in international markets as it is in domestic ones.

a. Where do you see the greatest advantage for U.S. companies for exporting carbon dioxide removal technologies and solutions abroad?

CDR technologies require the ability to utilize or store significant volumes of CO_2, and the U.S. has an enormous capacity suitable for storing CO_2 in EOR and in other geologies. The U.S. also has a very mature oil and gas industry with both the expertise to transport and inject CO_2, as well as existing infrastructure to both move and store CO_2. Although needed on a global scale, initial CDR deployment will take place in the U.S. because of this, thereby allowing U.S. companies to become global technology leaders.

Additionally, DAC technologies, for example, can be flexibly sited, allowing them to be more distributed and co-located near CO_2 storage sites, which can help to reduce overall costs.

Significant work is already being done and supported through DOE's world class research program in carbon capture and storage, which is investing in research and development to reduce the cost of capture and develop suitable geologic storage sites for CO_2 storage. DOE is also standing up a new direct air capture R&D program and investing in BECCS technologies.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Ms. Shannon Angielski

Although outside the jurisdiction of this Committee, Congress could encourage the export of domestically-produced CCUS technologies through policies pertaining to the Export-Import Bank.

b. Where do you see policy obstacles to doing so or opportunities to create further incentives for exporting the carbon dioxide removal technologies we innovate?

Failure to enact policies that take advantage of U.S. geological storage capacity and technological innovation would stymie efforts to export technologies developed domestically. In order to properly demonstrate promising capture technologies, it is imperative that the U.S. dedicate the appropriate federal resources to build out large-scale CO_2 storage complexes that can accept industrial CO_2 from multiple sources. Moreover, we must invest in the infrastructure to bring captured CO_2 to those industrial sites from the source. Failure to demonstrate the viability of the entire CCUS ecosystem with U.S. technology would implicitly prevent technology export, as it would make unlikely the level of cost reductions that might be required for future export to countries that wish to utilize U.S. technology.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: *The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage*
Questions for the Record Submitted to Dr. S. Julio Friedmann

Questions from Chairman Lisa Murkowski

Question 1: In general, what is the relative scale of coastal carbon removal (both wetlands restoration and agricultural) compared to technological options?

In their 2018 report of CO2 removal, the National Academies [1] estimate that coastal CO_2 removal (a subset of "blue carbon") is limited – for the US, about 0.02 gigatons of CO2 per year (Gt/y) and globally about 0.13 Gt/y.

In contrast, the technology options are effectively limitless – much greater than 10,000 Gt of total capacity and estimated potential to scale to more than 5 Gt/y removal

Question 2: What policies could help advance coastal blue carbon as an effective carbon removal option?

1) *Create a coastal restoration fund: recommended one-time, lump-sum $300M spent over 5 years. This would be shared between NOAA and the Army Corps (possible role for Coast Guard)*
2) *Direct NOAA & DOE to assess high value sites for project. Report in 18 months. Additional weighting for projects that deliver both CO2 removal and adaptation/resilience benefits.*

Question 3: What is the employment potential from greatly scaling up carbon removal technologies?

The potential is enormous.

- *In the short term, forest approaches have the highest potential.*
  - *Just one potential policy, lifting the cap on the US Forestry Service's Reforestation Trust Fund would create ~1200 jobs in rural communities.*
  - *A similar approach, removing hazardous fuels from forests, would create ~18 jobs/$1M invested.*
- *In the long term, approaches like DAC and Carbon Mineralization have much larger potential.*
  - *Rhodium Group estimates the jobs from a single million ton/y DAC plant would be over 3500 jobs, including manufacturing, construction, and operation. If the US gets to 100Mt/y by 2040, that's over 300,000 jobs.*
  - *Estimates for carbon mineralization would be to create another 30,000-50,000 jobs in areas existing mining infrastructure and potentially doubling that into new areas.*
  - *For geological storage, estimates are similarly large. Global CCS Institute [3] estimates well over 100,000 jobs by 2040 as well as helping sustain jobs in key sectors of the economy, such as cement, steel, and other heavy industry.*

Question 4: You mentioned in your testimony how important pore space access is for carbon sequestration. What Federal policies would help enable pore space access?

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: *The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage*
Questions for the Record Submitted to Dr. S. Julio Friedmann

Geological sequestration of CO2 requires access to deep, large pore volumes. The good news is that the U.S. has the very best pore-volume resource base in the world. That's an opportunity, provided one can get access. Here are three policy actions that would help:

- ***Low-cost lease on federal lands**: The U.S. Geological Survey has mapped where there are substantial CO2 storage resources under federal lands [4]- see figure below. Providing access to these resources through a leasing program (e.g., through BLM) would be a great start. I would further recommend ultra-low, speedy leasing between now and 2025 as a way to jumpstart the industry.*
- ***Unitization**: In many jurisdictions around the country, there is no basis for unitization of pore-volume for projects. This means a single landowner could block a project as a holdout, increasing costs and delaying investment and project commencement. Some states have unitization laws associated with enhanced oil recovery which are possible legislative models. Louisiana is contemplating a saline formation unitization process which could also serve.*
- ***Accelerated permitting**: First, as I mentioned in my testimony, the EPA is tragically, hilariously understaffed and undertrained with respect to permitting of class VI wells for saline formation injection. Hiring and training is needed both at headquarters and at regional EPA offices.*

  Second, the EPA should shortly undertake a review of class VI practice. This is a chance for them to streamline an reduce encumberances around this well class, using new and valuable technical and scientific information gathered since the class VI permit was created. This was proposed under the USE IT act at one point.
- ***Condemnation with payment**: Although unpopular, condemnation of the pore volume remains a policy option. One way to reduce the friction associated with this is direct payment to landowners as a stimulus measure as fair compensation. Obviously, this is fraught, but must be mentioned and considered as an option.*

Finally, although it is not directly related to pore-volume access, policies that transfer liabilities to the government after 25 years of post-injection site care validates secure storage would bring more players and private capital to this enterprise. Open-ended liabilities lie outside of what most companies or entities can accept.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Dr. S. Julio Friedmann

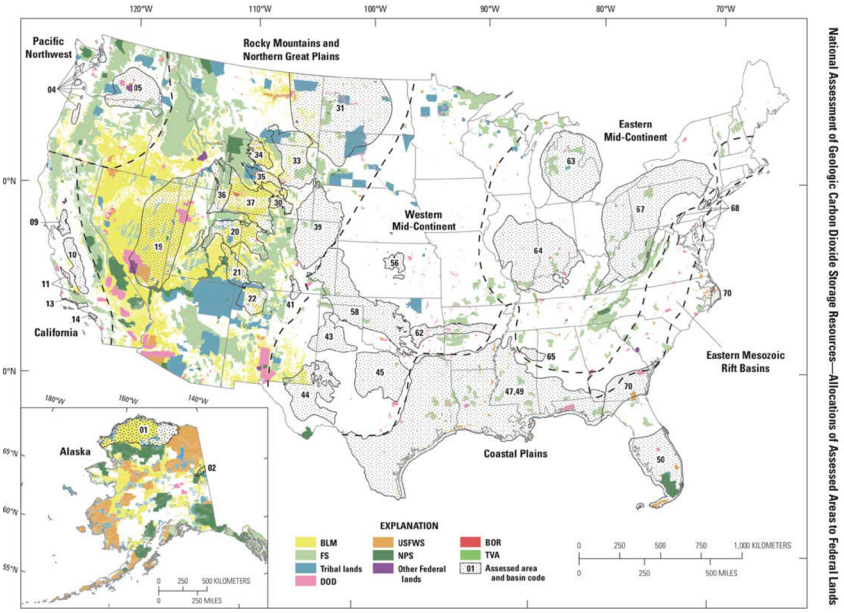


Figure 1A. Federal lands and lands from selected general land-ownership categories overlying assessed areas listed in order of prevalence (BLM, FS, Tribal, DOD, USFWS, NPS, other, BOR, TVA).

Question 5: Direct air capture (DAC seems to be the most flexible of carbon removal technologies as it does not have physical constraints. Can you tell us more about the current and projected future costs of DAC, and how those compare with costs projected for sectors where it is harder to limit emissions, and the relative cost of other Federal clean energy and climate policies?

- The current costs for DAC are ~$400/ton CO2. This is based on commercial facilities operating today.
- The expected costs for the first 1 million ton/y plant are $125-325/ton [5][6]
- Many believe that the costs will drop swiftly, with regular turn-key DAC delivered at <$200/ton by 2030. This requires first and foremost deployment of existing technology.
- These costs and estimates require low-cost, low-carbon heat and electricity [1]

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: *The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage*
Questions for the Record Submitted to Dr. S. Julio Friedmann

Question 6: What are the differences on a technology and cost basis between "blue hydrogen" and "green hydrogen", and how should the development of these two pathways be viewed from a policy perspective?

Both blue and green hydrogen approaches (and others) are means to produce low-carbon hydrogen. Both approaches (and others) can create hydrogen with a near-zero footprint. There are trade-offs to consider in terms of price, volume, and technical readiness [7][8]

- *Blue hydrogen is made by converting natural gas to hydrogen and capturing some or all of the associated CO_2. The US has two large-scale facilities that do this today and five world-wide. Large volumes of blue hydrogen can be made today in many US geographies, notably the Gulf of Mexico, California, the Midwest, Wyoming, Utah, Colorado, and Alaska, at a 20-50% increase in cost compared to unabated hydrogen production. It requires CO_2 storage systems to be viable.*
- *Green hydrogen is made by electrolyzing high purity water with zero-carbon electricity (e.g., hydro, renewables or nuclear). The US has no large-scale facilities that do this today, although small facilities are being built in other countries. Potentially, large volumes could be made almost anywhere in the U.S. at a 200-800% premium. These costs are expected to drop dramatically through deployment.*
- *One can also make hydrogen by converting biomass (forestry wastes, crop residues, and municipal solid wastes), mostly through gasification and CO_2 separation. If combined with CCS, this hydrogen could have negative emissions and remove CO_2 from the air and oceans.*

From a policy perspective, the key issues are scale-up and finance. All approaches would benefit from tax credits or revenue enhancements for production (e.g., contact for differences, production tax credit). Green hydrogen would benefit from improved transmission infrastructure, and blue hydrogen would benefit from expanded CO_2 pipeline and storage infrastructure.

[1] https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
[2] https://rhg.com/research/capturing-new-jobs-and-new-business/
[3] https://www.globalccsinstitute.com/resources/publications-reports-research/the-value-of-carbon-capture-ccs/
[4] https://pubs.usgs.gov/sir/2015/5021/pdf/sir2015-5021.pdf
[5] https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/
[6] https://www.cell.com/joule/pdf/S2542-4351(18)30225-3.pdf
[7] https://www.iea.org/reports/the-future-of-hydrogen
[8] https://www.schatz.senate.gov/download/sccc-climate-crisis-report

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: *The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage*
Questions for the Record Submitted to Dr. S. Julio Friedmann

Questions from Ranking Member Joe Manchin III

Question 1: In 2009, Congress passed the 48C advanced energy manufacturing tax credit that invested in retooling, expanding, or building new manufacturing facilities for clean energy equipment. This tax credit could be revived to also include support for supply chains related to carbon dioxide removal technologies.

a. Do you think a tax credit like the 48C manufacturing tax credit would be helpful in achieving our COVID-19 recovery goals?

YES, it could

b. How do you see it supporting carbon capture, utilization, sequestration, and other carbon removal technologies?

This tax credit could lower the capital costs associated with manufacturing heavy equipment, such as compressors, gas separation units, electrolyzers and fuel cells, etc. Since CO2 utilization is manufacturing at its heart, it could stand to receive the highest benefit.

c. What additional policies are needed to complement such a tax credit?

Policies to support CO_2 infrastructure development and innovation would complement and support a tax policy approach [9]. These could include new authorities (like the EFFECT Act), grants and loan authorities for pipelines (like the Invest CO_2 act).

Question 2: We need to consider carbon dioxide removal on a global scale – both because climate change is a global issue and because market penetration of these technologies is as important in international markets as it is in domestic ones.

a. Where do you see the greatest advantage for U.S. companies for exporting carbon dioxide removal technologies and solutions abroad?

I think you mean where will the best markets for CCS equipment and services occur. I see the nearest term opportunities in southeast Asia, followed soon by China and ultimately India. Applications will include both the recent coal-power plant builds and heavy industry (esp. steel, hydrogen, and chemicals)

b. Where do you see policy obstacles to doing so or opportunities to create further incentives for exporting the carbon dioxide removal technologies we innovate?

We discussed this in some depth in our report on power sector applications [10] as well as in the NPC 'Dual Challenge' report [11]. Punchline: We need infrastructure (CO_2 pipelines) [12] and

more financial support, either revenue enhancements (production tax credits, contracts for differences) or capital cost relief (e.g., investment tax credits, private activity bonds).

[9] https://www.energypolicy.columbia.edu/research/commentary/next-generation-federal-clean-electricity-tax-credits
[10] https://energypolicy.columbia.edu/research/report/capturing-investment-policy-design-finance-ccus-projects-us-power-sector
[11] https://dualchallenge.npc.org
[12] https://www.betterenergy.org/wp-content/uploads/2020/06/GPI_RegionalCO2Whitepaper.pdf

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: *The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage*
Questions for the Record Submitted to Dr. S. Julio Friedmann

Questions from Senator Catherine Cortez Masto

Question 1: In your written testimony, you liken carbon management now to solar and electric vehicles (EV) in 2005. In 2005, the solar and electric vehicle sectors were expensive, out of reach for many, still maturing, and awaiting policy to launch commercial development.

Fortunately, the U.S. has made strides in solar and EV innovation over the past 15 years and both have been widely deployed throughout the country. However, as a nation, we still rely too heavily on other countries to support some supply chains, such as those for solar panels.

a. As Congress looks to invest in carbon dioxide removal technologies, should we also be looking ahead to ensure that domestic manufacturing and workforce training is keeping pace with the innovation occurring in this sector to ensure that as a nation we are able to meet the demand of this new industry as carbon management systems reach their market potential?

Absolutely! This includes (a) provisions to stimulate American manufacturing base and supply chains for indigenous technology, (b) support for US companies overseas, perhaps through the Export-Import Bank and/or the Foreign Trade Service, (c) ensuring that US workers are well paid and supported to ensure an excellent, healthy labor pool, (d) investments in domestic innovation and competitiveness, and (e) creating domestic markets for CCS goods and services to help US companies thrive.

We learned lessons here. Many of the innovations in wind technology developed in the US were commercialized overseas when we stopped sustaining domestic innovation, production, and commercialization.

Question 2: Your written testimony also mentioned that the United States Geological Survey (USGS) conducted an initial effort to map and assess the carbon mineralization resources in the United States. However, you noted the need for an expanded carbon mineralization assessment.

a. In your opinion, how long would it take to gather the more detailed information necessary to help inform scientists and those looking to invest in carbon mineralization?

We could make a LOT of progress in 2 years' time with a targeted effort. This would not be comprehensive or final, but would greatly assist early actors, pioneers, and entrepreneurs.

b. How soon would that assessment need to be completed so as not to delay progress in the development of carbon mineralization solutions?

As above, a 2 year USGS effort would be very effective. It should be paired with DOE efforts to understand more about the science & technology of carbon mineralization, and followed by a 3-5 year effort to provide more details to project developers.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Dr. S. Julio Friedmann

Question 3: Another component of your written testimony included the need for Congress, and this Committee specifically, to further consider and enhance nature-based approaches. You pointed to State Forest Action Plans and their ability to increase rates of carbon drawdown, enable ecosystem restoration and resilience, and help states in their efforts to address high wildfire risk.

a. What more should Congress do to build on existing efforts to utilize nature-based approaches to sequester carbon?

It varies substantially depending on the sector and key practices:

- *For farms and soils, the MOST IMPORTANT effort must be done to quantify soil carbon uptake and provide robust, reliable, low-cost monitoring. Programs like ARPA-E's ROOTS [13]and SMARTFARM [14] efforts are a start, but much more is needed.*
- *For forests, the MOST IMPORTANT effort is to support existing programs in forest restoration. This is most important in either degraded marginal lands or federal lands badly damaged by wildfires.*
- *For wetlands and blue carbon, an innovation agenda is needed to understand what approaches will prove most valuable and effective. The National Academies [1] and Energy Futures Initiatives [15] laid out specific recommendations in their reports.*

b. Apart from DOE, what are the roles of other federal agencies to bolster and ensure this sequestration of carbon?

Much of this is discussed in the EFI report summary for policy makers [15]. There is a difference between carbon drawdown using managed ecosystems and for engineered pathways.

- *For managed ecosystems (nature-based solutions), the US Dept. of Agriculture, including the U.S. Forestry Service; the Dept. of the Interior, including the Bureau of Land Management; and the Dept. of Commerce, including NOAA.*
- *For engineered approaches, The Dept. of Commerce, especially Natl. Inst. of Standards & Technology (NIST), NASA, Dept. of Defense (including the Defense Research Laboratories and DARPA) all have roles.*
- *In an ideal world, this would be coordinated across the Govt. through a group like OSTP.*

[13] https://arpa-e.energy.gov/?q=arpa-e-programs/roots
[14] https://arpa-e.energy.gov/?q=arpa-e-programs/smartfarm
[15] https://energyfuturesinitiative.org/s/EFI-Clearing-the-Air-Summary.pdf;
https://www.dropbox.com/s/2y36ngfrcbpv37f/EFI%20Clearing%20the%20Air%20Full%20Report.pdf?dl=0

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

Questions from Chairman Lisa Murkowski

Question 1: How do you envision federal agencies participating in terrestrial carbon removal and management?

Federal agencies have a role to play at all stages of carbon removal: from early-stage research to incentivizing practices for widescale adoption. Current research programs on terrestrial carbon removal at the Department of Agriculture, U.S. Geological Survey, the DOE National Laboratories, and the Advanced Research Projects Agency-Energy require continued support from Congress. For example, ARPA-E's Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) program seeks to develop advanced crop cultivars that sequester 50% more carbon while reducing nitrous oxide emissions by 50%. There is a need for increased investment to spur innovation in agriculture and forestry practices, especially in digital and automated remote and in situ sensors to measure soil carbon on farms and in forests.

Federal agencies could also take a more active role in implementation, measurement, and verification of forest and soil carbon practices. For example, natural carbon removal should be an explicit management and implementation goal in public forests and grasslands managed by the U.S. Forest Service, Bureau of Land Management, National Park Service, and other agencies of the Department of Interior. Expanded adoption of improved forest management, reforestation, and restoration activities in federally managed forests could increase the overall health of U.S. forests while providing carbon removal benefits. Additionally, restoration of native grasslands and support for sustainable grazing practices on federally managed grassland could improve soil health and soil carbon sequestration of American grasslands.

Federal agencies could improve data collection on forest health and soil conservation practices. The creation of a consistent national plot network that collects long-term data would be especially valuable. Although they were not established for carbon and emissions measurement purposes, the Forest Service's Forest Inventory and Analysis and the USDA Natural Resources Conservation Service's Natural Resources Inventory (NRI) collect and provide critical information on the status and condition of U.S. forests and soils including baseline data on land-based carbon sequestration and emissions. Additional funding to these programs would allow for more frequent measurement of inventory plots across the country. NRCS has conducted rapid carbon assessment across thousands of NRI sites to collect soil carbon data. Expanding this data collection and updating the NRI regularly will be critical for soil carbon data management at the federal level. USDA should continue to populate the COMET greenhouse gas quantification tool to establish credible carbon sequestration rates for all types and locations of forests and soils, thereby reducing the need for expensive monitoring paid for by farmers and forest landowners. Improving the accessibility of these databases is also critical to ensure landowners and other stakeholders can easily find and use the collected information.

Existing Farm Bill programs could be leveraged to incentivize and provide technical assistance for carbon removal and greenhouse gas emissions management on private farms and forests. These programs include the Conservation Reserve Program, Regional Conservation Partnership Program,

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

Environmental Quality Incentives Program, Conservation Stewardship Program, Agricultural Conservation Easement Program, Healthy Forest Reserve Program, and the Forest Legacy Program. In the near term, USDA could be directed to continually update its standards for conservation practices and convene a multi-stakeholder process to identify ways to reduce and simplify paperwork for producers subscribing to Natural Resources Conservation Service programs.

Question 2: Which areas of natural solutions have the greatest potential, and which are the lowest cost to implement?

Forests and soils have the greatest potential for natural carbon sequestration. According to The National Academy of Sciences, Engineering and Medicine (NASEM), U.S. forests can sequester an additional 250 million metric tons of carbon dioxide per year ($MMTCO_2/y$) by implementing forest practices such as reforestation and improved forest management.[1] Of that 250 $MMTCO_2/y$, 150 $MMTCO_2/y$ can be achieved through increased afforestation and reforestation and 100 $MMTCO_2/y$ from forest management practices. Agricultural soils have the potential to sequester another 250 $MMTCO_2/y$ making the total carbon sequestration potential from forests and soils 500 $MMTCO_2/y$, or about 9 percent of the nation's annual greenhouse gas emissions. Although the carbon removal potential from coastal blue carbon approaches, such as restoration of coastal wetlands and seagrass meadows, is lower than that of forest and soil practices, they are still worth exploring. NASEM estimates that by 2030, implementation of blue carbon practices in the U.S. could sequester 37 $MMTCO_2/y$. Depending on the extent of technological advancements, this could increase to 77 $MMTCO_2/y$ by 2060.

Cost estimates for soil carbon sequestration practice range from $30 to $100 per metric ton of carbon dioxide removed, whereas forests fall in the range of $10 to $100 per metric ton, depending on the practice and geographic region.[2] Within agriculture, cover crops offer the greatest sequestration benefit at the lowest cost.[3] At $50 per metric ton, avoided grassland conversion and alley cropping could mitigate approximately 100 $MMTCO_2/y$ and 70 $MMTCO_2/y$, respectively. In forestry, natural forest management offers the greatest carbon removal potential (approximately 60 $MMTCO_2/y$) at a low cost of $10 per metric ton. At a higher $50 per metric ton, reforestation offers the greatest amount of carbon sequestration, followed closely by natural forest management. Coastal blue carbon projects are perhaps the lowest cost natural carbon removal option because investments in these projects provide a variety of

[1] NASEM. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259; Mulligan, J., A. Rudee, K. Lebling, K. Levin, J. Anderson, and B. Christensen. 2020. Available at: https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
[2] NASEM. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259; Mulligan, J., A. Rudee, K. Lebling, K. Levin, J. Anderson, and B. Christensen. 2020. *CarbonShot: Federal Policy Options for Carbon Removal in the United States*. Working Paper. Washington, DC: World Resources Institute. Available at www.wri.org/publication/carbonshot-federal-policyoptions-for-carbon-removal-in-the-united-states; Fargione et al. 2018. *Natural climate solutions for the United States*. Science Advances, Vol. 4, No. 11. DOI: 10.1126/sciadv.aat1869.
[3] Fargione et al. 2018. *Natural climate solutions for the United States*. Science Advances, Vol. 4, No. 11. DOI: 10.1126/sciadv.aat1869.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

co-benefits including improved coastal resilience. If projects are implemented for other reasons or in addition to carbon sequestration, then the only costs associated with carbon removal are the carbon monitoring costs ($0.75/MTCO$_2$ for tidal wetlands and $4/MTCO$_2$ for seagrass meadows).[4]

Question 3: What is the level of job creation associated with farm and forest carbon solutions, both a small scale level and on a large scale level?

On a large scale, investment in farm and forest carbon solutions can lead to significant job creation across the country. According to the Economic Policy Institute, a total of 13.4 direct, indirect and induced (DII) jobs are created for every million dollars of final demand in the forestry industry.[5] (Direct jobs are those specifically related to an industry, indirect jobs support that industry, and induced jobs result from the increased spending of those employed in direct and indirect jobs). In agriculture, the estimate is 16.0 DII and 14.4 DII jobs created in crop agriculture and animal production, respectively, per million dollars in final demand. In addition, support activities for agriculture and forestry generates 11.8 jobs for every $1 million in final demand.

There is great potential for job creation in agricultural innovation as well. In a recent report, the Breakthrough Institute found that thousands of jobs could be created through stimulus and recovery investments in agricultural research and development.[6] Funding the maintenance backlog at USDA Agricultural Research Service facilities and land-grant universities would support over 140,000 jobs alone.

On a small scale, agriculture, forestry, and wildland firefighting jobs are traditionally focused in rural areas and support for these industries would generate local economic benefits, including for many rural Native American, Alaska Native, and indigenous communities. The federal government currently funds two domestic conservation job corps programs, the USFS Jobs Corps Civilian Center Wildland Fire Program and the AmeriCorps National Civilian Community Corps, which train youth and younger veterans for careers in natural resources, including wildland firefighting. Additional funding for these programs could increase the number of wildland firefighters and trained workers to complete natural resource management projects on public lands and in communities across the country.

Question 4: Forest products, such as cross-laminated timber, have the potential to act as carbon storage. It is also my understanding that sustainable timber harvests and forest restoration can also have a powerful impact on climate change. Can you talk about how these activities can help with carbon storage?

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[4] NASEM. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259; Mulligan, J., A. Rudee, K. Lebling, K. Levin, J. Anderson, and B. Christensen. 2020. Available at: https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
[5] Josh Bivens, "Updated employment multipliers for the U.S. economy," Economic Policy Institute, Jan. 23, 2019. Available at: https://www.epi.org/publication/updated-employment-multipliers-for-the-u-s-economy/
[6] Dan Blaustein-Rejto, "Accelerating Economic Recovery Through Agricultural Innovation," The Breakthrough Institute, June 29, 2020. Available at: https://thebreakthrough.org/articles/econ-recovery-ag-innovation

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

Forest restoration involves activities that recover lost or degraded forest structure, ecological functioning, and biodiversity. Forest restoration can improve the carbon sequestration rate of forests by returning natural vegetation, stocking degraded forests, and thinning overstocked stands in fire-prone regions to prevent carbon losses due to wildland fires. However, forest restoration for wildland fire management creates a large amount of low-value timber that have limited uses in current wood products markets.[7]

Approximately 20% of the annual U.S. forest carbon sink is stored in wood products.[8] Expanding markets for high-value wood products could encourage investments in forest restoration and reforestation activities, increasing the timber supply and thereby the amount of stored carbon. If up to 80% of wood waste from current harvesting and manufacturing practices were buried in a landfill designed for slow decomposition, an additional 100 to 300 MMT CO_2 per year could be sequestered in the U.S.[9] Sustainable harvesting takes this one step further and involves landfilling wood waste *plus* increased harvesting of secondary forests to optimize all available growth. Sustainable harvesting could sequester an additional 100 to 700 MMT CO_2 per year in the U.S. without impacting protected forests, food supply, or biodiversity.

Questions from Ranking Member Joe Manchin III

Question 1: In 2009, Congress passed the 48C advanced energy manufacturing tax credit that invested in retooling, expanding, or building new manufacturing facilities for clean energy equipment. This tax credit could be revived to also include support for supply chains related to carbon dioxide removal technologies.

a. Do you think a tax credit like the 48C manufacturing tax credit would be helpful in achieving our COVID-19 recovery goals?

Yes, a tax credit like the 48C manufacturing tax credit would be highly useful in supporting our post-pandemic recovery goals. The 48C manufacturing tax credit established under the American Reinvestment and Recovery Act (ARRA) of 2009 was a successful tool to help reinvigorate and modernize the U.S. energy and automotive manufacturing sectors, while helping to create and save high quality jobs in the process. If a similar program were to be established today, the energy sector is poised

[7] Bonnie, R., T. Vujic, V. Plutshack, S. Arata. "Rural Investment: Building a Natural Climate Solutions Policy Agenda that Works for Rural America and the Climate." NI Report 20-04. Durham, NC: Duke University. Available at: https://nicholasinstitute.duke.edu/sites/default/files/publications/Rural-Investment-Building-a-Natural-Climate-Solutions-Policy-Agenda.pdf
[8] Kenneth E. Skog, "Sequestration of carbon in harvested wood products for the United States," USDA, Forest Service, Forest Products Laboratory, June 2008. Available at: https://www.fpl.fs.fed.us/documnts/pdf2008/fpl_2008_skog001.pdf
[9] NASEM. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259; Mulligan, J., A. Rudee, K. Lebling, K. Levin, J. Anderson, and B. Christensen. 2020. Available at: https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda

to use the tax credits for necessary manufacturing in areas like energy storage, offshore wind, carbon dioxide capture and removal, fuel cells, and advanced transportation.[10] In 2009, approximately $2.3 billion in funds were allocated toward a 30% tax credit under IRS Section 48C. Interest in and funding through the program were significant, far exceeding DOE's expectations; there were over 500 applications that requested a combined total of over $8 billion in credits. Ultimately, awards were provided to 183 companies until the $2.3 billion was exhausted. These credits were matched by private funding of around $5.4 billion. Due to the success of the program, another phase was held in February 2013 for an additional $150 million in remaining tax credits that were not fully utilized by previous grantees.[11] Following the considerable investments of ARRA, including the 48C tax credit, the share of domestically produced wind turbines installed in the U.S. rose from 25% in 2006/2007 to 72% in 2012.[12] GE used its 48C funding ($25 million in credit funding to support GE's overall investment of $600 million) at their Appliance Park Facility in Louisville, Kentucky to relocate its production of energy efficient water heaters from China back to the U.S.[13]

Expanding the list of eligible technologies to include a more robust list of energy and carbon dioxide capture and removal technologies under a program like 48C has the potential to provide additional benefits beyond what was experienced under ARRA.

b. How do you see it supporting carbon capture, utilization, sequestration, and other carbon removal technologies?

If CCUS and carbon dioxide removal technologies were to be included under a new, more technology-inclusive energy manufacturing tax credit, it would likely result in a greater number of projects being developed and built in the U.S. using American manufactured technologies. We observed a similar shift towards more domestically produced wind turbines as a result of the manufacturing tax credit available under the ARRA of 2009. Furthermore, manufacturing support could enable the development of more modular CCUS or carbon dioxide removal technologies, which would accelerate the cost-effective scaling and commercialization of these technologies.

In addition, although state support for clean energy technologies has expanded since the era of ARRA, CCUS or carbon dioxide removal technologies are generally not prioritized. Therefore, a new federal energy manufacturing tax credit that includes CCUS and carbon dioxide removal technologies would be useful for new U.S. CCUS project development, and expanded export potential for American-based companies.

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[10] Executive Office of the President of the United States, Council of Economic Advisors, "A Retrospective Assessment of Clean Energy Investments in the Recovery Act," Feb. 2016, Available at: https://obamawhitehouse.archives.gov/sites/default/files/page/files/20160225_cea_final_clean_energy_report.pdf
[11] *Ibid.*
[12] *Ibid.*
[13] Executive Office of the President, Council of Economic Advisors, "The Economic Impact of the American Recovery and Reinvestment Act of 2009 – Fourth Quarterly Report," July 14, 2010. Available at: https://obamawhitehouse.archives.gov/files/documents/cea_4th_arra_report.pdf

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

c. What additional policies are needed to complement such a tax credit?

There are many ways to complement an energy manufacturing tax credit program. Passage of the Enhancing Fossil Fuel Energy Carbon Technology (EFFECT) Act (S.1201) currently in the American Energy Innovation Act (AEIA) (S.2657), would facilitate much needed development and deployment of advanced carbon removal and carbon capture technologies. Further, in BPC's near-term stimulus and recovery recommendations, we emphasize the importance of extending the existing 45Q tax credit, expanding the use of private activity bonds and master limited partnerships to support carbon capture projects, passing a direct pay tax policy, and improving the existing DOE Title 17 Innovative Clean Energy loan guarantee program.

Since there have been delays in the issuance of federal regulations for implementation and use of the 45Q tax credits by the IRS, BPC recommends that the tax credit be extended by five years. Private activity bonds (PABs) are tax exempt municipal bonds used to attract private investment to projects that have a public benefit. PABs have generally not been extended to carbon capture projects; however, passage of the Carbon Capture Improvement Act of 2019 (H.R. 3861 and S. 1763) would begin to remedy this issue but would need to be expanded to include direct air capture projects. Applying master limited partnerships (MLPs) to clean energy will ensure a broader range of necessary technologies are eligible for lower-cost financing. Employing direct pay tax provisions in lieu of tax credits provides financing optionality that can be highly beneficial for project developers looking to deploy innovative technologies during an economic downturn. Furthermore, administrative improvements to the existing DOE Title 17 loan guarantee program would unlock financing for project developers using innovative clean energy technologies. Changes outlined by BPC include expanding Title 17 to allow federal grants, including direct cash grants, to count toward developers' equity contributions for all projects; expanding Title 17 by making certain state financing entities eligible to use the program; increasing appropriations by $25 million for the administration of the Title 17 program; and appropriating $2.6 billion in credit subsidies across all three Title 17 technology areas with a sunset date 24 months after enactment.

Another option Congress may consider is the creation of Clean Energy Deployment Administration (CEDA), which would be an independent, business-driven federal financing agency with access to a range of financing instruments that could leverage private investment and accelerate the deployment of clean energy technologies – including CCUS and carbon removal solutions - in the U.S.

Question 2: We need to consider carbon dioxide removal on a global scale – both because climate change is a global issue and because market penetration of these technologies is as important in international markets as it is in domestic ones.

a. Where do you see the greatest advantage for U.S. companies for exporting carbon dioxide removal technologies and solutions abroad?

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

The U.S. has an opportunity to be a global leader in innovation and benefit from growing carbon markets by increasing its investment in carbon removal technologies. In 2015, the global market for physical CO_2 was valued at USD $6 billion, and the market is expected to grow to $10 billion by 2027.[14] Further expansion of the opportunity is expected to be significant as nations develop programs to encourage carbon reduction and removal. While the greatest export market opportunities for CCUS/point-source capture technology may exist in countries where economic activity will continue to be based on new or existing fossil fuel plants, carbon dioxide removal technology companies have a much broader market opportunity. Many carbon dioxide removal technologies, such as direct air capture, do not need to be adjacent to a specific emissions source. There are also export opportunities for natural carbon removal solutions including soil and forest carbon monitoring technologies, precision agriculture and forestry technologies, crop cultivars for enhanced carbon sequestration, and wood products technologies.

b. Where do you see policy obstacles to doing so or opportunities to create further incentives for exporting the carbon dioxide removal technologies we innovate?

There are numerous examples (including in solar photovoltaics and lithium ion batteries both produced primarily now in China) where U.S.-based companies have successfully developed novel technologies but lost the manufacturing race to global competitors. There is the risk that this pattern will occur with U.S.-developed carbon dioxide removal technologies as well. Luckily, since this is a new industry, the U.S. federal government can carefully consider industrial policies that could strengthen and entice U.S.-based technology companies to develop manufacturing capacity and its associated jobs in America. A diverse portfolio of policies should be considered including tax policies like the now expired 48c manufacturing tax credit, financial tools like government-backed direct loans and loan guarantees, and workforce training and education programs, to support U.S.-based manufacturing of carbon dioxide removal technologies. Strong incentives should be established to keep the high-value portions of the technology development process and supply chain in the U.S. so that our country can expand its clean energy – and carbon dioxide removal – technology leadership.

Questions from Senator Mazie K. Hirono

Questions: Hawaii has set the goal of being carbon neutral by 2045. Combined with our transition to 100 percent renewable power by 2045, Hawaii is looking toward using land and water-based solutions for reducing carbon in the atmosphere. As you observe, natural carbon removal is among the most affordable options and creates economic opportunities for rural and farm communities. What improvements do you think could be made in the existing USDA and Interior Department programs for promoting natural carbon solutions? Are there other agencies that should be part of a larger federal response on natural carbon solutions?

[14] Grand View Research, "CO2 Market Size Worth $10.00 Billion By 2027 | CAGR: 3.4%," Feb. 2020. Available at: https://www.grandviewresearch.com/press-release/global-carbon-dioxide-co2-market

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

Expansion of federal research programs is essential to a larger federal response to carbon sequestration. Current research programs on terrestrial carbon removal at USDA, the U.S. Geological Survey, the DOE National Laboratories, and the Advanced Research Projects Agency-Energy require continued support from Congress. For example, ARPA-E's Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) program seeks to develop advanced crop cultivars that sequester 50% more carbon while reducing nitrous oxide emissions by 50%. There is a need for increased investment to spur innovation in agriculture and forestry practices, especially in digital and automated remote and in situ sensors to measure soil carbon on farms and in forests.

Within the Interior Department, natural carbon removal should be an explicit management and implementation goal in federally managed forests and grasslands. Expanded adoption of improved forest management, reforestation, and restoration activities in federally managed forests could increase the overall health of U.S. forests while providing carbon removal benefits. Additionally, restoration of native grasslands and support for sustainable grazing practices on federally managed grassland could improve soil health and soil carbon sequestration of American grasslands.

There are also many USDA Natural Resources Conservation Service, Farm Service Agency, and Forest Service programs that currently contribute to terrestrial carbon removal. The tables below are from a recent Bipartisan Policy Center report on natural carbon solutions and provide an overview of how these USDA programs could be modified or enhanced.[15]

[15] Lesley Jantarasami, "Natural Carbon Solutions in U.S. Farms and Forests: Building a Policy Agenda for Congressional Action," Bipartisan Policy Center, July 30, 2020. Available at: https://bipartisanpolicy.org/report/natural-carbon-solutions-in-u-s-farms-and-forests-building-a-policy-agenda-for-congressional-action/

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

Natural Resources Conservation Service and Farm Service Agency Farm Bill Programs

Name of Program	Current Purpose	Opportunities for Modification to Support Enhanced Carbon Sequestration	Focus on Soils, Trees, or Both?
Environmental Quality Incentives Program (EQIP)	Pays for practices or activities that benefit air quality, water quality, soil and water conservation, and wildlife habitat (subject to some restrictions).	• Increase program funding specifically for agriculture, forest management, and grazing practices that sequester carbon in soils and trees. • Authorize program to subsidize more of the upfront costs of project implementation for first-time participants. • Authorize program to allow project aggregation (described below).	
Conservation Stewardship Program (CSP)	Pay-for-performance program to maintain, improve, and expand activities that benefit natural resources (including soil, water, air, and wildlife habitat) or conserve energy.	• Increase program funding specifically for agriculture, forestry, and grazing practices that sequester carbon in soils and trees. • Authorize program to allow project aggregation (described below).	
Conservation Reserve Program (CRP)	Provides yearly rental payment to remove environmentally sensitive land from agricultural production and plant species that will improve ecosystem health and quality.	• Expand the acreage cap. • Open the program to allow tree planting on marginal pastureland. • Allow grazing within the CRP grasslands program while maintaining important grasslands. • Increase incentives to target flood prone lands, peatlands, or other areas where carbon gains could be substantial.	
Conservation Innovation Grants (CIGs)	Provides cost-sharing grants to support new conservation practices. New to the 2018 Farm Bill, CIG "on-farm trials" implement on-the-ground conservation activities and then evaluate their impact. Incentive payments help offset the risk to producers.	• Focus on-farm trials on evaluating agriculture, forestry, and grazing practices that sequester carbon in soils and trees. • Direct the program to prioritize CIG projects with carbon offset protocol developers.	
Conservation Technical Assistance Program	Provides technical assistance from NRCS, or from employees of other entities or agencies under the technical supervision of NRCS, to address opportunities, concerns, and problems related to the use of natural resources.	• Direct the program to assist producers in understanding: o The numerous agronomic and ecological benefits of healthy soils. o How to access NRCS and other programs that offer financial assistance for implementing soil and forest carbon-building practices.	
Regional Conservation Partnership Program	Promotes coordination between NRCS and eligible partners to engage in conservation activities using funding from EQIP, CSP, and ACEP (see below).	• Direct the program to prioritize project applications that list carbon sequestration and GHG reductions as a natural resource priority to be addressed.	

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

Natural Resources Conservation Service and Farm Service Agency Farm Bill Programs

Name of Program	Current Purpose	Opportunities for Modification to Support Enhanced Carbon Sequestration	Focus on Soils, Trees, or Both?
Agricultural Conservation Easement Program (ACEP)	Provides financial assistance from the NRCS to eligible partners for the purpose of purchasing easements that protect agricultural land and limit non-agricultural uses of land.	• Direct the program to prioritize easements for eligible partners that demonstrate the potential to increase soil carbon and otherwise reduce GHGs in the land under consideration. • Focus the Wetland Reserve Enhancement Partnership on carbon sequestration benefits from wetlands restoration.	
Healthy Forests Reserve Program	Assists private landowners with 10-year restoration agreements and 30-year or permanent easements for specific conservation actions.	• Direct the program to increase the cost-share percentage landowners receive to further incentivize program enrollment. • Direct the program to prioritize easements and agreements for eligible partners that demonstrate the potential to increase carbon sequestration and restore forests in ways that reduce the threat of carbon loss from fire and other disturbances.	

USDA Forest Service Programs

Name of Program	Current Purpose	Opportunities for Modification to Support Enhanced Carbon Sequestration	Focus on Soils, Trees, or Both?
Forest Legacy Program	Identifies and conserves forest areas that are threatened by conversion to non-forest uses. Protects private forests by purchasing conservation easements or land from forest owners, who participate voluntarily.	• Increase program funding in recognition of the climate-change mitigation benefits of preventing conversion of forests to non-forest uses.	
Forest Stewardship Program	Provides technical assistance to private landowners to manage their forests and woodlands, including developing forest management plans. Administered cooperatively between the U.S. Forest Service, state forestry agencies, cooperative extension, and conservation districts.	• Increase program funding to expand technical assistance to private forest owners interested in changing management practices to improve carbon sequestration on their lands.	
Community Forests Program	Provides grants to local governments, tribal governments, and qualified nonprofit entities to establish community forests on lands that are threatened with conversion to non-forest uses and that provide multiple community benefits.	• Increase program funding in recognition of the climate-change mitigation benefits of preventing conversion of forests to non-forest uses.	
Urban & Community Forestry Program	Supports the integration of urban forestry at all scales in the context of city, regional, and state master plans. Delivers urban natural resources science, technology, and information to local and state partners.	• Increase program funding in recognition of the climate-change mitigation benefits of urban and community forests.	

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

Question from Senator Catherine Cortez Masto

Question: In your written testimony, you emphasized the importance of pursuing and ultimately achieving "net-zero" emissions.

a. How can the federal government standardize and improve its accounting and verification of negative emissions moving forward?

The United States currently does not have standardized, federal government-wide accounting methods for quantifying and verifying negative emissions from natural or technological carbon dioxide removal technologies/strategies. We have three near-term recommended actions the federal government should take to begin laying a strong foundation of emissions accounting to support CDR investments and markets:

(1) The federal government should create mechanisms for better coordination among federal agencies and a shared information portal for project developers.

Greater clarity and an overarching federal structure and information clearinghouse is needed to facilitate development of robust incentive programs and markets for developers of carbon removal projects. Project developers need a consistent carbon accounting framework to provide business certainty that the carbon removal benefits of their projects are real and verifiable.

Interagency coordination and collaboration could be led by the Large-Scale Carbon Management Program within the National Science and Technology Council proposed in the bipartisan CREATE Act (S. 4341). The Council or a similar interagency body should establish consistent federal methods for monitoring, reporting, and verification (MRV) of natural and technological carbon dioxide removal technologies/strategies. Consistent methods are needed for different storage avenues (whether nature-based, geologic storage, in durable products, or through enhanced oil recovery) in order to reduce uncertainty and ensure consistency of crediting for negative emissions across facilities, projects, and storage processes.

(2) The federal government should evaluate current national and international accounting and verification methods to assess gaps and identify improvements to create a robust and workable negative emissions accounting framework.

As part of developing a consistent national carbon accounting framework for negative emissions, the federal government should assess current carbon accounting methodologies. Three examples of existing protocols include:

- The federal government's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, which is developed annually consistent with internationally accepted accounting practices.

U.S. Senate Committee on Energy and Natural Resources
July 28, 2020 Hearing: ***The Development and Deployment of Large-Scale Carbon Dioxide Management Technologies in the United States, including Technological and Natural Carbon Removal, Carbon Utilization, and Carbon Storage***
Questions for the Record Submitted to Mr. Sasha Mackler

- The Environmental Protection Agency's Mandatory Greenhouse Gas Reporting rule (40 CFR Part 98) Subpart RR, which was developed in consultation with the Departments of the Treasury, Energy, and Interior.
- The International Standards Organization's standard for quantifying long-term storage of carbon dioxide (CSA/ANSI ISO 27916:19).

An interagency body, as recommended above, could be tasked with leading this evaluation and applying any lessons learned to the development of a federal MRV framework. A U.S. accounting framework should take into consideration the ongoing development of international protocols in order to increase opportunities for domestic project developers to access global markets.

(3) The federal government should continue data collection and research to simplify accounting and verification to minimize burden and maximize participation of project developers.

Federal investment in research is needed to improve and simplify measurement and verification processes that can be used by project developers. Current methods can impose significant costs on project developers and have been cited as a barrier to the ability of some carbon removal projects (particularly smaller scale projects) to pencil out. Special attention should be paid to balancing the burden of MRV with accuracy, transparency, and accountability.

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August 10, 2020

The Honorable Lisa Murkowski
Chairwoman
Senate Energy and Natural Resources Committee
522 Hart Senate Office Building
Washington, D.C. 20510

The Honorable Joseph Manchin
Ranking Member
Senate Energy and Natural Resources Committee
306 Hart Senate Office Building
Washington D.C. 20510

Re: Hearing to "Examine Development and Deployment of Large-Scale Carbon Dioxide Management Technologies"

Dear Ms. Chairwoman, Ranking Member, Members and Staff;

Last week we had the opportunity to virtually attend your July 28th hearing to "Examine Development and Deployment of Large-Scale Carbon Dioxide Management Technologies". This hearing was timely given that carbon dioxide levels in the atmosphere today are higher than at any point in the past 800,000 years.[1] As of June 2020 we currently have 416.39 ppm of CO2 in Earth's atmosphere (up from 413.52 just since April 2019)[2]. Meanwhile, scientists are unequivocally telling us that, if we want a livable planet, we must substantially reduce atmospheric carbon as quickly as possible.[3] While Chairwoman Murkowski acurately pointed out that we cannot simply rely on planting new trees to mitigate the climate crisis, it is also true that attempting to rapidly deploy unsound technologies such as Carbon Capture and Storage won't solve the climate crisis either. Below we submit our concerns, backed by science, on why the CCS approaches promoted during this hearing and via witness testimony would not be a wise investment for American taxpayers if the goal is to stabilize our planet's climate and protect communities from climate related impacts.

[1] https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide#:~:text=The%20global%20average%20atmospheric%20carbon,least%20the%20past%20800%2C000%20years.
[2] https://www.co2.earth/
[3] https://johnmuirproject.org/wp-content/uploads/2020/05/200TopClimateScientistCongressProtectForestsForClimateChange13May20.pdf

1. Continuing to Rely on and to Accelerate Fossil Fuel Use Under the Promise of an Engineered our Way Out of Carbon Emissions is Not a Climate Solution

While it is true that fossil fuels will continue to be utilized at some level during our necessary and rapid transition away from such energy sources, relying on this fact to extract more federal subsidies and promote less regulation of the fossil fuel industry, while promoting increased production, as was done at the hearing, is *extremely* troubling.

One of the main solutions offered up by witnesses was the idea of Carbon Capture, Utilization and Storage [CCUS]. CCUS is an ineffective and counter-productive technology at scale (see below), and one which is most closely associated with maintaining the status quo with regard to oil, gas, and coal extraction and production while increasing reliance on trees for fuel (biomass energy and BECCS). As discussed at the hearing, CCUS would require **more** infrastructure for the fossil fuel industry, including additional production facilities and pipelines, and would not actually lower our carbon emissions, it would just simply try to hide those emissions somewhere else.

With regard to Carbon Capture and Storage, there simply is no potential upside. Taking carbon emissions either as they are generated or trying to devise a way to capture CO2 that resides in our atmosphere and then pumping these emissions into the ground is, and we are not overstating this, *a recipe for disaster*.

First, this is an ineffective and counterproductive approach at scale, since it would: **a)** increase earthquakes as it is scaled up, leading to catastrophic releases of CO2, along with lethal toxic contaminants like Hydrogen Sulfide, which can kill people, animals, and plants, with the CO2 then going into the atmosphere; **b)** require a 30% increase in fossil fuel production and combustion facilities nationally (and globally) in order to generate the enormous amount of additional power that would be required to produce and install thousands of miles of CO2 pipelines and compress CO2 into liquid form for transport in the pipelines; **c)** acidify aquifers, poisoning drinking water; **d)** increase local emissions of toxic pollutants and fine particulates into communities (typically disproportionately affecting lower-income communities and communities of color), undermining health and safety, due to the continued and increased fossil fuel combustion that scaling up CCS would entail; and **e)** cause a huge increase in diversion of water from rivers and streams for industrial cooling purposes.[4]

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[4] i) https://onlinelibrary.wiley.com/doi/pdf/10.1002/wcc.266; ii) http://shalegas-bg.eu/download/ccs/100106-Health-Risks-CCS.pdf; iii) https://iopscience.iop.org/article/10.1088/1748-9326/11/2/024011/pdf; iv) https://www.pnas.org/content/pnas/109/26/10164.full.pdf.

Second, even if it was effective, which it is not, we could not deploy it in the time frame necessary to actually mitigate the worst effects of climate change.[5]

Third, Carbon Capture and Storage is just another subsidy to the fossil fuel and biomass logging industries, the explicit goal of which is to perpetuate and expand the carbon fuel economy.

Fourth, it is a dangerous distraction, creating the false notion that we don't actually have to change how we power this country, or reduce how much power we use and the emissions we generate, in order to combat the climate crisis.

Fifth, it takes limited federal dollars away from actual transition - money that could otherwise be allocated to solar energy expansion would instead augment the already enormous subsidies going to the carbon fuel economy.

2. Reforestation is Not Needed on Public Lands, but Proforestation Is.

Testimony submitted by witnesses at the hearing gave a nod to forests as a carbon dioxide management solution, however their focus was misplaced and failed to acknowledge the most readily available and effective natural terrestrial system to draw carbon out of the atmosphere - our *existing* forests.

The protection of existing forests is known as *proforestation.*[6] Proforestation is by far our cheapest and most effective option for reducing atmospheric carbon dioxide, and this technology which is part of nature is already deployed at scale. Proforestation is the act of allowing trees that are already growing to continue to do so, which enables them to reach their ecological potential in terms of carbon storage, with the added benefits of clean air, clean water, wildlife habitat and recreation. Our forests are currently substantial carbon sinks [7], absorbing more carbon than they emit, but they could absorb much more carbon than they currently do if they were protected from logging and development. Logging is the real source of carbon emissions from forests, emitting CO2 annually in excess of the residential and commercial sectors combined, and having an annual carbon impact that is similar to coal.[8] By way of comparison, in U.S. forests, logging of all types (*e.g.*, thinning, clearcutting, group selection, etc.) emits 10 times more carbon than is emitted from wildland fire and tree mortality from drought and native bark beetles *combined.* Dead trees and downed logs within forests also continue to store carbon, decay extremely slowly (decades to a century or

[5] https://www.pnas.org/content/pnas/109/26/10164.full.pdf
[6] https://www.frontiersin.org/articles/10.3389/ffgc.2019.00027/full
[7] *e.g.* Harris, N.L., et al. 2016. Attribution of net carbon change by disturbance type across forest lands of the conterminous United States. Carbon Balance Management 11: Article 24
[8] https://johnmuirproject.org/wp-content/uploads/2020/05/200TopClimateScientistCongressProtectForestsForClimateChange13May20.pdf

more), and continuously return their nutrients to the soil, which helps maintain the productivity and carbon sequestration capacity of the forest.[9]

Reforestation was promoted in testimony during the hearing, especially in relation to public lands that have experienced wildland fire. However, reforestation: will not have a significant climate mitigation benefit for decades because seedlings sequester and store very little carbon; will actually exacerbate climate change (as discussed below); and *is simply not necessary*. The truth is that forests naturally regenerate very well even after the biggest fires.[10] A confounding aspect of the concept of reforestation is that reforestation is almost exclusively preceded by environmentally damaging, carbon emitting logging--mostly clearcutting. The US Forest Service and other federal land management agencies are currently in the commercial logging business, selling public timber to private logging companies and keeping most of the revenue to pad their agency budgets. Logging activities, especially after fires, include clearcutting on public lands, and the agencies are required to plant trees after they clearcut. However, appropriated funding for tree planting is limited, which then limits the amount of clearcutting that occurs on public lands. Increased funding for tree planting on National Forests and other public lands would, in practical effect, increase funding for clearcutting, since clearcutting and tree planting are inextricably linked. Ironically, clearcutting after forest fires, as was recommended by witness testimony, actually kills most of the natural forest regeneration, as the conifer seedlings and saplings are crushed under the treads of logging machinery.[11] So, rather than actually contributing to drawing carbon out of the atmosphere, spending more money on reforestation on public lands would actually increase logging, which would increase carbon emissions while preventing the forests from reaching their full carbon storage potential, thus exacerbating climate change.

Contrary to some of the written testimony, wildland fires, including large mixed-severity fires, only consume about 1% to 2% of the biomass of trees in the forest. The carbon that is emitted is far less than many mistakenly assume, and it is soon re-absorbed by natural post-fire regrowth, which is enhanced by nutrient cycling resulting from the fires. Therefore, such fires do not cause a carbon reversal as Mr. Mackler falsely claimed. We know this from field-based studies of actual fires in actual forests. The problem is that federal and state agencies use theoretical models to estimate carbon emissions from forest fires and dead trees, but the models wildly exaggerate carbon emissions from decay and fire. For example, in the 257,000-acre Rim fire of 2013, field-based data determined that only *one-tenth of 1% of the carbon in trees was actually consumed by the fire*, whereas the theoretical models

[9] (a) Harris, N.L., et al. 2016. Attribution of net carbon change by disturbance type across forest lands of the conterminous United States. Carbon Balance Management 11: Article 24; (b) Meigs, G., et al. 2009. Forest fire impacts on carbon uptake, storage, and emission: The role of burn severity in the Eastern Cascades, Oregon. Ecosystems 12:1246–1267; (c) Campbell, J.C., J.B. Fontaine, and D.C. Donato. 2016. Carbon emissions from decomposition of fire-killed trees following a large wildfire in Oregon, United States. Journal of Geophysical Research: Biogeosciences 121: 718-730.

[10] https://www.elsevier.com/books/the-ecological-importance-of-mixed-severity-fires/dellasala/978-0-12-802749-3

[11] https://www.elsevier.com/books/the-ecological-importance-of-mixed-severity-fires/dellasala/978-0-12-802749-3

falsely assume levels of consumption that are dozens, or hundreds, of times higher than this.[12] What does cause carbon reversals is when we log our public lands, which is why we need to protect federal public lands from logging, rather than promote measures that would increase logging.

3. The Proposals for Woody Biomass Supported by the Witnesses and Senators Would Harm our Environment, Biodiversity and the Climate.

The series of Biofuels proposals, specifically those related to woody biomass, are the most paradoxical. Converting coal plants to biomass plants and subsidizing cutting down our forests to convert them into wood pellets to then burn them to generate inefficient electricity is not in any way "green" or "carbon neutral". Logging, whether you call it thinning, vegetation management, forest management or biomass removal, is simply another part of the carbon economy.

Since no witness at the hearing addressed the carbon cost of logging, we thought we would share some statistics here. Because most of the carbon in trees that are logged is incinerated as "slash" (branches and tree tops) and milling/manufacturing waste for energy production, *most* of the carbon in trees that are logged ends up in the atmosphere almost immediately, with only 19% ending up being stored in wood products.[13] Logging also removes nutrients from forests and compacts soils, reducing the overall productivity and function of the forest ecosystem as well as its carbon sequestration and storage capacity.[14]

Incinerating trees for energy production (biomass logging) produces substantially more greenhouse gas emissions than burning coal, for equal energy produced.[15] Biomass logging is a climate change nightmare, and it is troubling to see legislators who truly want to solve the climate crisis appearing to promote this climate-polluting activity.

Biomass is also an environmental justice disaster. According to a Dogwood Alliance Report, wood pellet production facilities are twice as likely to occur in or near environmental justice (EJ) communities. EJ communities are communities below the state median income with at least 25% non-white population. The Environmental Integrity Project's investigation also found that the 21 U.S. wood pellet mills currently exporting to Europe emit a total of 16,000 tons of health-threatening air pollutants per year, including more than 2,500 tons of particulate matter (soot), 3,200 tons of nitrogen oxides, 2,100 tons of carbon monoxide, and

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[12] Stenzel, J.E., et al. 2019. Fixing a snag in carbon emissions estimates from wildfires. Global Change Biology 25: 3985-3994.
[13] Hudiburg, T.W., Beverly E. Law, William R. Moomaw, Mark E. Harmon, and Jeffrey E. Stenzel. 2019. Meeting GHG reduction targets requires accounting for all forest sector emissions. Environmental Research Letters 14: Article 095005.
[14] (a) Walmsley, J.D., et al. 2009. Whole tree harvesting can reduce second rotation forest productivity. Forest Ecology and Management 257: 1104-1111; (b) Elliot, W.J., et al. 1996. The effects of forest management on erosion and soil productivity. Symposium on Soil Quality and Erosion Interaction. July 7, 1996, Keystone, CO.
[15] Sterman, J.D., L. Siegel, and J.N. Rooney-Varga. 2018. Does replacing coal with wood lower CO2 emissions? Dynamic lifecycle analysis of wood bioenergy. Envir. Research Letters 13: Article 015007.

7,000 tons of volatile organic compounds. These plants also emit 3.1 million tons of greenhouse gases annually, according to the report.

Biomass plants are also uneconomical compared to solar and wind energy, as without massive government subsidies, biomass can't compete with solar and wind. Research both in the US and the UK underscores how wind, solar, and energy efficiency are far less costly than biomass energy, making wood-burning plants uncompetitive in today's electricity markets and a losing investment. A 2017 study found that by 2025, the UK's existing biomass conversions will be more expensive to run than building completely new solar and wind capacity, including grid integration costs. A 2018 analysis found that the US based company, Dominion Energy's least-expensive biomass electricity is more than double the cost of energy efficiency and is approximately 50% higher than the cost of electricity from onshore wind and utility-scale solar. Electricity from Dominion's 4 Virginia biomass plants is more expensive than 88% of power generation available in the regional energy market, including from wind and solar. This was true even after factoring in federal tax credits and state Renewable Energy Certificates, which Dominion used to justify its investment in biomass. Dominion has since shuttered or significantly cut reliance on its biomass plants. Simply put, biomass plants are not economically viable to run.

Some of the speakers at the hearing, who are affiliated with logging interests or funded by agencies involved in commercial logging and the biomass industry, repeatedly promoted increased logging—*i.e.*, increased removal of carbon from our forests—supposedly as a climate solution. This is a form of climate change denial because it not only denies the ability of our forests to continue acting as carbon sinks, but also denies the role of logging in making climate change worse. Notably, numerous studies find that logging conducted under the guise of "thinning", "fuels reduction", "woody biomass extraction" and fire management actually causes a large net loss of forest carbon storage and a substantial net increase in carbon emissions.[16]

Overall this hearing was a distraction from the climate crisis situation at hand; a way to ensure shields for polluting industries to have access to immense federal subsidies to simply continue with business as usual while giving other countries license to continue polluting as well. It was truly disheartening that not a single committee member offered any opposition or even questioned the validity and safety of the proffered technologies. For the United States to be successful in their goals to mitigate climate change and lower carbon emissions we must immediately and unequivocally move away from fossil fuels and logging. The world needs technology and strong policy to move in a new direction as science clearly tells us that we need to remake our energy system and eliminate CO2 emissions. This is the time to take a global stand, to do the uncomfortable work of breaking our addiction to carbon fuels and logging and

[16] (a) Campbell, J.L., M.E. Harmon, and S.R. Mitchell. 2012. Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? Frontiers in Ecology and Environment 10: 83-90; (b) Hudiburg, T.W., et al. 2013. Interactive effects of environmental change and management strategies on regional forest carbon emissions.

show our fellow global citizens that it is possible to survive and thrive on truly clean and renewable energy. With greater understanding of the climate challenge, we can avoid one-dimensional solutions and make huge strides in developing the policy and technology we need to move toward true climate solutions.

We hope that you have found the above information helpful and we urge you to consider the foregoing, and to reject false climate solutions that would make climate change worse and increase risks to vulnerable communities. We need to increase protection of our forests from logging, and focus resources on truly clean and renewable energy, not double down on fossil fuels. The recommendations made by the witnesses at the hearing, and the comments made by some committee members, would take us in the wrong direction. We would be happy to answer questions or provide additional information, so please feel free to contact us if you would like to continue this dialogue.

Sincerely,

Chad Hanson, Ph.D.
Chief Scientist and Director
John Muir Project

Jennifer Mamola
D.C. Forest Protection Advocate
John Muir Project

WESTMORELAND MINING LLC

Written Testimony of Joe Micheletti

Chief Operating Officer

Westmoreland Mining Holdings LLC

Before the Senate Committee on Energy and Natural Resources

Hearing to "Examine Development and Deployment of Large-Scale Carbon Dioxide Management Technologies"

Washington, D.C.

July 28, 2020

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Chairman Murkowski, Ranking Member Manchin, Members of the Committee, and, specifically, Senator Daines, thank you for inviting me and Westmoreland Mining to submit testimony to discuss Carbon Management, Carbon Capture Utilization and Storage (CCUS) technologies, and the future of power generation in the United States, North America, and the world.

My name is Joe Micheletti. I am the Chief Operating Officer of Westmoreland Mining LLC. For over 150 years, Westmoreland has been part of the fabric of the energy industry, navigating significant challenges and continually emerging as an industry leader. We provide jobs for hard working people, invest in local schools and community enhancements, and provide a valued resource to generate power for homes and businesses. Westmoreland has demonstrated a commitment to sound safety and environmental stewardship practices at our mines while also continuing to position ourselves to be an integral part of the multi-faceted energy future.

Westmoreland's roots began in the coal fields of Pennsylvania, but its core now resides across North America where hard work, resiliency, and commitment to family and community still mark the measure of success.

Westmoreland has weathered the Civil War, two World Wars, the Great Depression, and dramatic changes in markets and political landscapes. We continue to evolve and redefine our role in growing communities, industries, businesses, families, and returns to investors. To thrive in these changing environments, Westmoreland has adapted to the times along the way.

Westmoreland's success has depended upon our ability to adapt. Moreover, our longevity is built on the hard work and loyalty of dedicated and loyal employees and their families, the confidence of our investors and the forward-thinking vision of our leadership team. Westmoreland, its leadership and its employees have steadfastly maintained its commitment to good stewardship, and a collective interest to leave a positive and lasting legacy everywhere we operate. We are proud of our rich history and look forward to continuing to create jobs and enhance the communities we serve.

But as proud as we are of our history, we have to be realistic. Simply put, our industry, our company and our employees stand, once again, at a fork in the road – one in which we must again make a crucial decision. We must either adapt to the economic and environmental realities brought to our doorstep by climate change or fail.

For the sake of our investors, employees, their families, and the communities in which we operate, we have decided, as NASA's famed Apollo 13 Mission Director Gene Krantz once did, that failure is not an option. That is why as a company we have decided to diversify our business activities into a portfolio that includes minerals, energy, and technology verticals. We believe that this diversification gives us the greatest chance to succeed in the future.

Similarly, the future of our children, our grandchildren and our civilization, depends on policymakers, industry, and NGOs taking fundamental, coordinated and meaningful steps toward addressing climate change. Here too, failure is not an option.

As I mentioned previously, over the past year-and-a-half or more, Westmoreland has begun to take concerted efforts to change our business model and our operations. For example, we have started to examine ways in which we can use renewable energy technologies at our mines to not only lower our own carbon footprint, but also lower our own energy usage costs.

We have also begun to seriously investigate the deployment of carbon capture utilization and storage (CCUS) technologies as a viable and clean way to provide clean, reliable and inexpensive baseload electricity to an ever energy hungry public and economy. Most of our coal mining operations are what are known as "mine-to-mouth" operations. In other words, the power plant for electric generation is located in close proximity to its fuel source – in our case, thermal coal. The infrastructure of this system has been in place for decades. It is efficient, it is cost effective, and it is reliable. Moreover, it provides irreplaceable, permanent, high-skilled and high-paying jobs for thousands of workers and communities around the United States, North America, and the world. For example, at our mine in San Juan County, New Mexico, which supplies

thermal coal to the San Juan Generating Station (SJGS), we employ together with the SJGS roughly 657 engineers, miners and administrative support personnel – nearly half members of the Navajo Nation. The average salary at our San Juan Mine is $85,000 per year. The average salary at the SJGS is $86,000.

If we are to be pragmatic and serious about addressing climate change without destroying the foundational bedrock of an economic system – if not a way of life -- that has increased the prosperity of billions of people around the world, then we must be careful not to throw the baby out with the bathwater. As Shannon Angieliski, Executive Director of the Carbon Utilization Research Council, points out in her written testimony for this hearing:

> Fossil fuels [like thermal coal] will continue to play an essential role towards reaching a decarbonized future. The U.S. Energy Information Administration (EIA) projects that fossil fuels will still account for 50% of U.S. power generation and 77% of total U.S. energy consumption in 2050 under current policies. Moreover, EIA projects that, despite substantial projected renewable energy deployment, fossil fuel consumption will more than double globally by 2050, as fossil fuels are low cost, abundant and widely available in emerging economies.[1]

Against this backdrop, I think it is important to point out that even if we were able to switch to 100 percent renewable energy sources by 2050, we would still not achieve enough emissions reductions to limit warming to below 2°C above pre-industrial levels by 2050. There are just too many other sources of CO_2 -- from agriculture, transportation, petrochemical production, etc. – for renewable energy sources to have the necessary impact on emissions to achieve net-zero goals. As Secretary Moniz pointed out in his written testimony for this hearing:

[1] Written Testimony of Shannon Angielski, Executive Director, Carbon Utilization Research Council (CURC), Before the United States Senate Energy and Natural Resources Committee, A Hearing to Examine Development and Deployment of Large-Scale Carbon Dioxide Management Technologies July 28, 2020

> Achieving net zero emissions by solely relying upon complete elimination of carbon from our energy systems likely will not be viable in the timeframes needed to address climate change. We also must develop the tools for large scale carbon management – CCUS and CDR. Negative-carbon technologies will also make possible, in the long term, a reversal of ever increasing GHG concentrations in the atmosphere, thereby reducing the impact of past actions[2]

To put it bluntly, Madam Chairman, the problem is not a particular industry or a particular fuel source. The problem is not fossil fuels. The problem is not coal. The problem is not industry. The problem is not manufacturing. The problem is not agriculture. The problem is not any number of things that some have pointed to and said, "we must eliminate that." These are all things than a modern civilization needs to move forward and prosper. Without them, we retreat and wither.

As Secretary Moniz seems to suggest in his testimony, then, the problem we face today is pretty clear. The problem is emissions past, present, and future. Fortunately, if we pursue prudent, rational and forward-thinking public policy choices that embrace proven as well as new and innovative technologies, we can have a future were we do not have to live with CO_2 emissions that harm our planet instead of help it.

We have technologies available to us today – like carbon capture utilization and storage (CCUS), that can help effectively address the problem of excess CO_2 emissions. More importantly, we can limit or eliminate greenhouse emissions using CCUS and other technologies without dismantling our current, highly efficient, and highly reliable power generation system. We have been doing it for decades with emission control technologies for NOx, SOx and PM. Carbon emissions and ambient carbon concentrations in the atmosphere and oceans are no different – they can be mitigated and eliminated.

[2] Statement for the Record, the Honorable Ernest J. Moniz, 13th Secretary of Energy, Energy Futures Institute, Before the Senate Energy and Natural Resources Committee, July 28, 2020.

We at Westmoreland are hoping to base the future of our company around those technologies and the burgeoning carbon economy.

As the Committee may know, Westmoreland has long been the coal provider for the Boundary Dam project in Estevan, Saskatchewan and therefore we are closely tied to CCUS from its early uses in North America.

More recently, we decided to begin working with Enchant Energy and the City of Farmington in San Juan County, New Mexico, to retrofit the San Juan Generating Station (SJGS) with a proven and most advanced CCUS technology available today – a technology was developed by Mitsubishi. We are extremely excited about the Enchant project because we believe that it represents the future of clean, reliable, and economical base-load electricity production in the United States. Once retrofitted SGJS will generate 847 MW of capacity with a 90 percent reduction in CO_2 emissions. More importantly for the community, however, is that the project will preserve 1,450 high paying jobs, create thousands of new construction jobs, and protect and expand the community's current tax base.

We envision that the Enchant project will be a "win-win" for the San Juan County / Farmington community, the State of New Mexico, the United States and our environment. Furthermore, we believe that once the SJGS CCUS retrofit is completed, it can be easily replicated in other communities around the United States and North America – effectively revitalizing COVID impacted local economies by creating "Carbon Capture Hubs" that will attract new investment in American jobs and manufacturing innovation.

With that in mind, we believe that following the San Juan / Enchant project, the Colstrip Steam Electric Station located in Senator Daines' state of Montana is the next best opportunity for CCUS in North America.

While we are excited about the future of our company as it begins to explore ways to enter a new and potentially vast carbon capture economy, I worry that we are

only one company. While there may be many other innovative and entrepreneurial companies that wish to enter the market, the reality is that the problem that we are trying to solve – while trying to minimize economic disruption and dislocation – is much too large and on much too short of a time frame to address through normal means. Simple tax credits and incentives to business will not be enough. What is needed is a coordinated approach that encompasses true public private partnerships between the entire array of stakeholders – from industry, to NGOs, to governments at the local, state or provincial, and Federal levels.

If we are serious about addressing climate change, then we must stop using what amounts to gauze to treat a gunshot wound. We must also stop pointing fingers at potential partners within industry, like Westmoreland, who are already looking for ways to address the problem while minimizing economic disruptions.

That is why we commend the Committee for beginning that process by introducing the American Energy Innovation Act.

We also urge Congress to immediately extend the 45Q tax credit for at least another five years. And like some of the other panelists who appeared before the Committee in this hearing, we further urge Congress to passed direct pay tax provisions related to the 45Q tax credit that would support better incentives for the deployment of commercial-scale carbon capture projects in the United States, especially in times like now where an economic downturn may make tax credits less appealing to potential investors. One such bill we are looking at is the “Redeeming Effectiveness to Carbon Oxide Utilization Plus Sequestration (RECOUPS) Act” (H.R. 7896) introduced in the House by Representative Jack Bergman (R-MI) and Lizzie Fletcher (D-TX). This bill would allow investors to treat 90 percent of their eligible 45Q credits for equipment installed after 2018 as an overpayment of their taxes. While the devil is in the details on this bill, we at Westmoreland believe that it is a good start and would urge the committee to review it if it should pass the House.

Lastly, we cautiously agree with panelist Sasha Mackler of the Bipartisan Policy Center who called for significant increases in federal innovation budgets and for increased "efforts to deploy 'first of a kind,' breakthrough technologies here in the United States." As Mr. Mackler pointed out, for many technologies, targeted federal support can make the difference between failure and commercial success. Given the enormous amount of capital and risk required to undertake a single CCUS project, the only entity with truly enough scale to help get many of these projects off the ground in the time frame needed is the federal government.

Again, Madam Chairman, Ranking Member Manchin and Senator Daines, thank you for inviting Westmoreland to submit testimony to this important hearing. We look forward to working with you and the Committee in the future to develop practical and pragmatic public policy that will help launch and sustain these important technologies and projects.

8