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WORKING PAPER

TECHNOLOGICAL CARBON REMOVAL IN THE UNITED STATES

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EXECUTIVE SUMMARY

Highlights

- The ambitious emissions reduction measures modeled in most global emissions pathways are not enough to achieve the Paris Agreement targets for limiting temperature rise. In these pathways, it is also necessary to undertake efforts to remove carbon dioxide (CO_2) from the atmosphere at the gigaton scale—billions of metric tons per year globally.
- This paper explores candidate technological approaches for carbon removal in the United States, including bioenergy with carbon capture and storage (BECCS); direct air capture and storage (DACS); and several frontier technologies, including biochar, plant selection or engineering, enhanced weathering, and seawater capture.
- Deploying each of these technologies at a large scale will require addressing a set of key needs related to technological maturity and cost reduction, enabling infrastructure and markets, and better understanding of climate benefits and ancillary effects. Ultimately, all carbon removal technologies will depend on sustained public support, including funding.
- This paper illustrates policy ideas that could begin to address these needs and create an environment that helps accelerate the development and deployment of promising technologies and the surfacing of new ones.

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback, and to influence ongoing debate on emerging issues. Working papers may eventually be published in another form and their content may be revised.

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Background

Heightened abatement of greenhouse gas (GHG) emissions is needed to achieve the goals of the Paris Agreement and limit warming to well below 2°C, with efforts to limit warming to 1.5°C, to avoid the most dangerous climate impacts. Furthermore, most scientific estimates show that to keep these goals within reach, the global emissions trajectory must not only reach net-zero[1] by the second half of this century but also continue downward into net-negative emissions. Global climate models therefore illustrate the need to pursue both aggressive emissions reductions and significant deployment of carbon removal.[2] They rely upon carbon removal approaches to offset the last remaining GHG-emitting activities that are too challenging or expensive to eliminate, and to compensate for any temporary overshoot of temperature goals.

Carbon removal is the process of removing CO_2 from the atmosphere and storing it. It is distinct both from solar radiation management, which seeks to reflect incoming sunlight to reduce warming rather than remove carbon from the atmosphere, and from carbon capture and storage (CCS) from point sources of emissions such as fossil-fuel-burning power plants or industrial facilities. Approaches to carbon removal traverse a spectrum from land management approaches to technological options, including carbon management in agricultural soils, forests, and agroforestry; BECCS[3]; DACS; and frontier technologies such as biochar, plant breeding or engineering,[4] enhanced weathering, and seawater capture. The intention of carbon removal is to store CO_2 in plants, soils, and oceans, as well as nonbiologically in geological formations and products (e.g., building materials), augmenting the net transfer of carbon from the atmosphere that naturally takes place as part of the carbon cycle (Minx et al. 2018) (see Box ES-1). In some cases, storage is permanent; in others the CO_2 may return to the atmosphere over time.

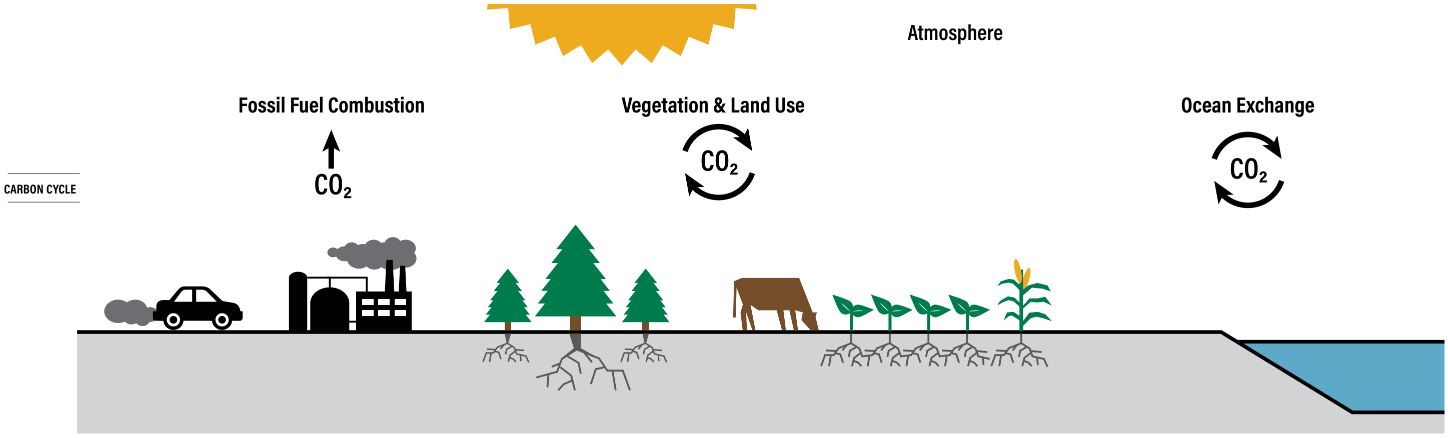
Box ES–1 | Carbon Removal and the Carbon Cycle

Carbon circulates between the land, atmosphere, and ocean through various natural and human-induced processes (see Figure ES-1.1):

- Plants use sunlight and absorb carbon dioxide (CO_2) through photosynthesis, generating oxygen.
- Humans and animals inhale oxygen and exhale CO_2.
- Decomposition of organic carbon in soils, plants, and animals emits CO_2.
- CO_2 dissolves in the ocean, is consumed by phytoplankton through photosynthesis, and released back into the atmosphere.
- Fossil fuel combustion and deforestation or other land use changes emit CO_2.

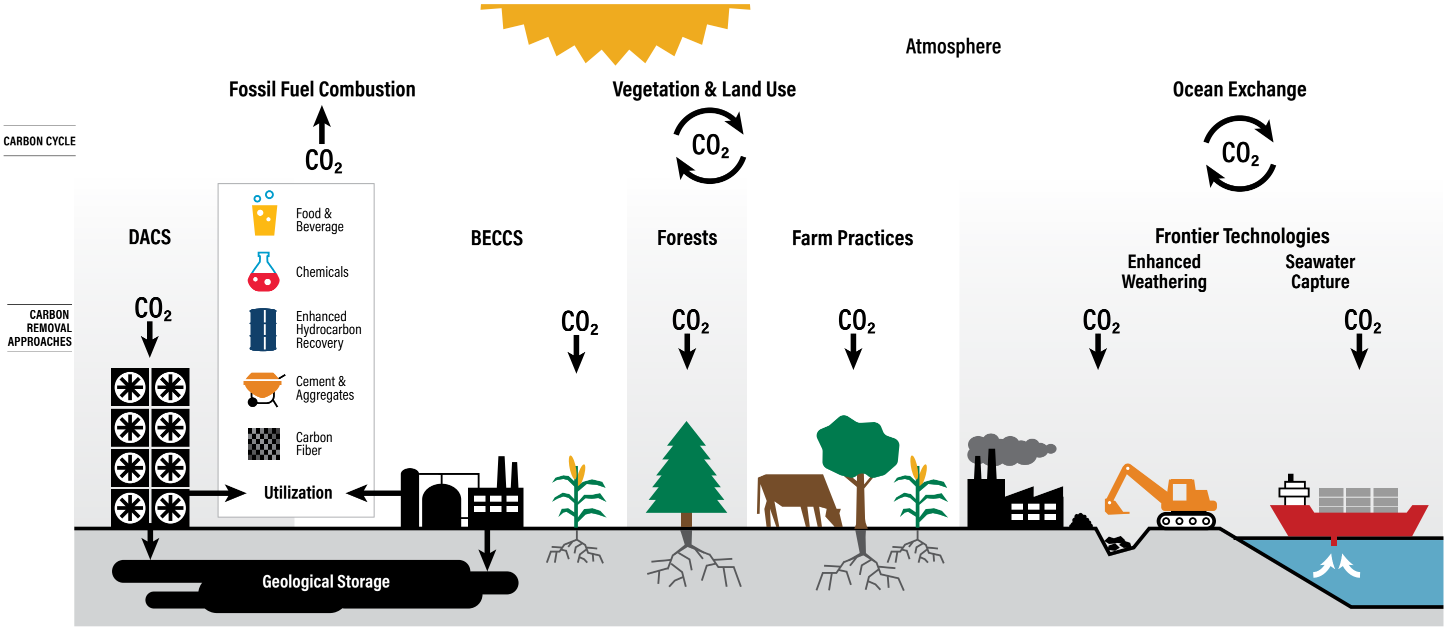
Carbon removal is intended to help address global warming by reducing atmospheric concentrations of the primary greenhouse gas, CO_2, accelerating or augmenting the net transfer of CO_2 from the atmosphere (see Figure ES-1.2).

Figure ES-1.1 | The Carbon Cycle



Source: Adapted from U.S. DOE NETL 2018b.

Figure ES-1.2 | **Augmenting the Net Transfer of Carbon from the Atmosphere via Carbon Removal Approaches**



Source: Adapted from Minx et al. 2018.

To date, a gap exists between the need for rapid emissions reductions to stabilize the climate at the temperature targets established in the Paris Agreement and the availability of cost-effective measures that can provide those reductions (UNEP 2017). Advancements in carbon removal can help close that gap. However, each carbon removal approach available today faces its own challenges, potential pitfalls, and limitations. The full potential of each remains uncertain. Given this uncertainty, a portfolio of approaches and technologies could yield greater opportunities for achieving large-scale carbon removal (Minx et al. 2018; Fuss et al. 2018).

About This Working Paper

The purpose of this working paper is to explore the potential for technological carbon removal in the United States, identify needs likely to arise on the pathway to large-scale deployment, and consider ways to begin addressing those needs. The working paper is part of a World Resources Institute (WRI) publication series CarbonShot: Creating Options for Carbon Removal at Scale in the United States. The series presents findings from a WRI-led assessment of needs for scaling candidate carbon removal approaches and technologies in the United States, drawing on a synthesis of the scientific literature. This paper focuses on the technological options, including BECCS, DACS and frontier technologies. It concludes by describing a series of near-term policy ideas that could help begin to address these needs in the United States.

Key Findings

Several emerging technologies offer the prospect of removing CO_2 from the atmosphere at a large scale in the United States. These technologies will require significant and sustained policy investments in continued technological development, enabling infrastructure and markets, and scientific understanding of net climate benefits and ancillary effects. Developing capabilities for large-scale technological carbon removal may prove critical for stabilizing global temperatures, given the overall apparent need for carbon removal and limitations on land management approaches to carbon removal.

BECCS can take many forms—in several different sectors with several different biomass feedstocks. The net climate benefits and ancillary effects of these forms vary widely. Some forms of BECCS could be detrimental for food security and natural ecosystems. Some forms provide emissions reduction but not carbon removal. Some forms may not provide climate benefits at all, given direct and indirect land use change and other accounting issues. Appropriate safeguards and proper accounting would be needed to ensure that the deployment of BECCS is beneficial. These safeguards would inevitably limit the potential scale of carbon removal achievable with BECCS.

Developing capabilities for deploying BECCS at a large scale principally entails driving down the cost of CCS technology, building out CO_2 transport infrastructure and storage operations, and resolving persistent uncertainties related to net climate benefits and ancillary effects. Deploying beneficial forms of BECCS at scale would also require developing supply chains for feedstock derived from sources other than dedicated energy crops, such as forest by-products, agricultural residues, and municipal waste.

There is no obvious way to bound the technical potential of DACS. Its economic potential is currently limited by high costs and intensive requirements for low-carbon energy inputs. But costs appear to be lower than previously estimated, and continued technological development could further reduce them. Geological storage capacity in the United States appears to be sufficiently large, although sites must be individually validated.

Developing capabilities for deploying DACS at a large scale principally entails driving down the cost of the technology and building out CO_2 storage operations. Markets for CO_2 utilization products could also help support early-stage deployment for DACS systems. Additionally, because DACS requires a significant amount of low-carbon heat and power, the prospect of its deployment at scale in the United States could have implications for the desired composition of the U.S. energy sector in the coming decades.

Additional research, development, and demonstration (RD&D) are needed to advance promising frontier technologies and identify new technologies. Progress in technological development and related scientific inquiry would help provide clarity on whether these emerging technologies could be brought to scale and bring to light the kinds of investments needed to do so.

Investing in three categories of action could help address key needs across a portfolio of carbon removal technologies: RD&D, deployment support, and advancements in fossil fuel carbon capture, storage, and utilization. Sustained RD&D and learning-by-doing play significant roles in technology development and cost reduction. Government support and the development of markets for products that utilize CO_2 are likely to be critical in driving early deployment. Accelerating the deployment of CCS in fossil fuel facilities could be catalytic in driving CO_2 transport, storage, and utilization technologies. Adopting CCS in existing biorefineries—a relatively low-cost proposition—could have a similar effect.

Carbon removal technologies are likely to rely on regulatory mandates or carbon pricing mechanisms to be deployed at large scale on a sustained basis. Carbon removal technologies provide a public good. To the extent that they also provide valuable private goods (e.g., energy or products), the goods are not cost-competitive with goods produced by other means without explicit or implicit carbon pricing. Furthermore, although CO_2 utilization markets may play a critical role in supporting near- to medium-term deployment experience, they are unlikely to fully support sustained deployment at the scale envisioned in global climate models. As a result, addressing the needs identified in this paper across the portfolio of carbon removal technologies is essential but insufficient on its own without some form of carbon pricing.

ABBREVIATIONS

ARPA-E	Advanced Research Projects Agency-Energy
BECCS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
CO_2	carbon dioxide
DACS	direct air capture and storage
DOE	Department of Energy
EPA	Environmental Protection Agency
GHG	greenhouse gas
GJ	gigajoules
$GtCO_2$	gigaton (billion metric tons) of carbon dioxide
$MtCO_2$	megaton (million metric tons) of carbon dioxide
NASA	National Aeronautics and Space Administration
R&D	research and development
RD&D	research, development, and demonstration
tCO_2	ton of carbon dioxide
WRI	World Resources Institute

INTRODUCTION

Background on Carbon Removal

The Paris Agreement established a goal of limiting average global temperature rise to well below 2˚C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5˚C. These targets are intended to avoid the worst impacts of climate change. Global scenario planning models are used to identify the pace and scale of mitigation efforts that will be required to meet a target for temperature rise. The large majority of modeled scenarios indicate that ambitious greenhouse gas (GHG) emissions reductions alone will not be enough to have a likely chance of achieving the Paris Agreement targets (Nemet et al. 2018). These models therefore combine ambitious emissions reductions with the *removal of carbon dioxide* (CO_2) from the atmosphere (Minx et al. 2018). However, the approaches and technologies for what is often called *carbon removal* are largely unproven at the scale that appears in these models (Fuss et al. 2018). Modeled scenarios for global emissions pathways consistent with 1.5˚C temperature rise above pre-industrial levels rely on 5–15 $GtCO_2$ (15th and 85th percentiles) of emissions removed per year by 2050 and 10–17 $GtCO_2$ removed per year by 2100 (Fuss et al. 2018). In scenarios consistent with a likely chance of stabilizing at 2˚C, the models rely on 1–7 $GtCO_2$ of emissions removed per year by 2050 and 7–17 $GtCO_2$ removed per year by 2100.

Carbon removal can take a variety of forms, including land management approaches in forests and farms; bioenergy with carbon capture and storage (BECCS); direct air capture with storage (DACS); and several frontier technologies, such as biochar, plant breeding and engineering, enhanced weathering, and seawater capture, among others. Developing capabilities for large-scale technological carbon removal may prove critical for stabilizing global temperatures given limitations on land management approaches to carbon removal. The National Academy of Sciences has suggested that total land use emissions since 1750—660 $GtCO_2e$, give or take 290 $GtCO_2e$—act as a theoretical upper limit on the physical potential for land management–based carbon removal approaches (NRC 2015). The academy further argues that in practice the upper limit will be considerably lower, because the ongoing and increasing need to produce food and fiber prevents the full restoration of lands to the carbon-dense states that existed prior to large-scale human intervention. If 660 $GtCO_2$ is indeed an upper limit to carbon removal from land management, on their own these potentially significant approaches will be insufficient to fulfill the estimated need for carbon removal to meet the temperature targets in the Paris Agreement. Global climate models indicate that carbon removal of roughly 700 $GtCO_2$—and up to 1,000 $GtCO_2$—may be necessary in the 2011–2100 period to stabilize temperatures at either 1.5˚C or 2˚C above pre-industrial levels (Minx et al. 2018).

Objectives of This Paper

The purpose of this working paper is to explore the potential for technological carbon removal in the United States, in order to identify needs likely to arise on the pathway to large-scale deployment and to consider ways to begin addressing those needs. World Resources Institute (WRI), with support from the Linden Trust for Conservation (LTC) and in partnership with the Carbon180 and Carbon Wrangler LLC, surveyed the technical potential, economic dynamics, and uncertainties associated with the approaches identified in Box 1; identified the key needs to facilitate large-scale deployment; and explored possible measures for addressing those needs.

This working paper examines candidate options for technological carbon removal, including BECCS, DACS, and several frontier technologies. Each of the candidate approaches and technologies faces its own set of challenges, potential pitfalls, and limitations (Minx et al. 2018). There are no “silver bullets.” There appears to be a gap between the need for rapid emissions reductions to stabilize the climate at the temperature targets established in the Paris Agreement and the availability of cost-effective measures that can provide those reductions (UNEP 2017). As major emitters like the United States continue to delay action, that gap will only widen, necessitating the creation of *options* for deeper, faster emissions reductions than envisioned in global scenario planning models and for removing CO_2 from the atmosphere at large scale.

Box 1 | WRI Series CarbonShot: Creating Options for Carbon Removal at Scale in the United States

In the publication series CarbonShot: Creating Options for Carbon Removal at Scale in the United States (wri.org/carbonremoval), WRI presents three thematic working papers that outline the findings of an assessment of prospects for carbon removal in the United States:

- Foundational Questions on Carbon Removal in the United States
- Carbon Removal in Forests and Farms in the United States
- Technological Carbon Removal in the United States

These papers cover the key needs facing major carbon removal approaches and technologies and the policies that could begin to address those needs.

The assessment relied on an integrated process of expert consultations and literature review, review of existing policy mechanisms, and the application of a structured assessment framework to guide information collection and synthesis.

The assessment was limited to terrestrial-based and select marine-based carbon removal approaches potentially applicable in the United States. The five carbon removal approaches within the scope of this assessment were forest carbon; soil carbon on agricultural lands; BECCS; DACS; and four frontier technologies (biochar, plant breeding and engineering, enhanced weathering, seawater capture). These approaches were selected because they are most commonly referenced in the literature. Although all carbon removal technologies are arguably emerging, the technologies grouped together as frontier technologies commonly face uncertainties that the authors determined would prohibit a robust evaluation of potential scale and its specific dependencies.

The assessment excluded ocean fertilization because of potential negative effects on ocean ecosystems, associated transboundary effects, and international law complications. Previous studies largely agree that ocean fertilization at large scale poses risks that outweigh potential benefits (NRC 2015). The assessment further excluded wetlands, on the basis of preliminary findings that wetland interventions were more relevant to emissions reduction strategies than carbon removal strategies, although recent studies show mitigation potential for coastal restoration (Griscom et al. 2017), with potential in the United States (Euliss et al. 2006).

To identify key needs for scaling the evaluated approaches and technologies, the team first explored the core parameters of each approach and technology:

- Scale of potential
- Economics
- Co-benefits as well as negative effects related to emissions reductions, environmental resources, and human well-being
- Major areas of uncertainty that may affect deployment

Information collected and synthesized was then used to identify key needs that, if addressed, would facilitate deployment at a large scale: technological maturity; enabling infrastructure and markets; the need for additional knowledge to reduce uncertainty; and the need for dedicated funding mechanisms. The team then judged which of the identified needs to prioritize, setting aside needs that were not clearly essential to deploy a carbon removal approach or technology at a large scale and needs that could be more easily addressed if other needs were addressed first. The needs prioritized through this process were classified as "key needs." The team sought to identify actions by government, civil society, and the private sector that could address those needs. Among the types of actions considered for each key need were

- research, development, and demonstration (RD&D);
- government incentives and regulations;
- government procurement and land management; and
- voluntary action by the private sector.

The papers highlight a preliminary list of actions that could address some of these needs. The actions should not be taken as recommendations; they should be fully evaluated before adoption.

Initial findings related to the carbon removal potential, costs, uncertainties, key needs, and actions for scaling these approaches and technologies were then subjected to external feedback—first in expert interviews, then in an informal review process.

In all, 34 subject matter experts from academia, government, and civil society were consulted. These experts were affiliated with the following institutions: Advanced Research Projects Agency-Energy, American Association for the Advancement of Science, Applied Geospatial Solutions, Carbon180, Clean Air Task Force, Colorado State University, Columbia University, Delta Institute, Duke University, Energy Futures Initiative, Global CO_2 Initiative, Lawrence Livermore National Lab, Massachusetts Institute of Technology, Ohio State University, Oxford University, Pinchot Institute for Conservation, Princeton University, Stanford University, U.S. Department of Agriculture, Office of Fossil Energy of the U.S. Department of Energy (DOE), U.S. Environmental Protection Agency, University of California–Davis, Woods Hole Research Center, and World Resources Institute. Experts were identified on the basis of past publication of relevant literature, past or ongoing assessment work related to one or more carbon removal approach or technology, or deep subject matter expertise in a specific area where the assessment team required insight. Expert consultations were unstructured and tailored to the expertise of each individual. In some cases, the team interacted with a single expert on multiple occasions.

Then, two in-person gatherings with experts and practitioners in the climate community were hosted in San Francisco, California, and Washington, DC. Participants included a subset of the experts that were consulted previously, as well as a number of practitioners from the broader climate change mitigation community of practice. These practitioners included analysts and decision-makers in the nonprofit and philanthropic sectors. Through facilitated discussions at these events, the assessment team affirmed its prioritization of needs, identified additional policy ideas, and gleaned insights about perceptions of carbon removal in the climate community.

Table 1 | **Costs, Potential, and Key Needs of Technological Carbon Removal Approaches in the United States**

CARBON REMOVAL TECHNOLOGY	COST[a]	POTENTIAL IN THE UNITED STATES	KEY NEEDS
Bioenergy with carbon capture and storage (BECCS)	\$15–\$400/tCO_2 (Fuss et al. 2018)[b]	About 85–88 MtCO_2/year in 2020 if only agricultural residues and woody biomass feedstocks co-located with geological storage reservoirs are considered (Baik et al. 2018); additional feedstocks are available	■ Reduction in cost of carbon capture and storage (CCS) technology ■ CO_2 transport, storage, and utilization infrastructure and markets ■ Sustainable waste-derived feedstock supply chains ■ Better understanding of climate benefits and ancillary effects
Direct air capture and storage (DACS)	\$94–\$600/tCO_2 (Keith et al. 2018; APS 2011)[c]	No obvious limitation on technical potential	■ Reduction in cost of DACS systems ■ CO_2 storage and utilization infrastructure and markets ■ Abundant low-cost, carbon-neutral energy
Frontier technologies	Uncertain[d]	Uncertain	■ More RD&D to build sufficient knowledge and create viable technologies

Notes:

[a] Estimates generally reflect current costs. Different metrics are used to describe cost ("capture cost" and "avoided cost"). These metrics and their implications are discussed in the BECCS and DACS sections of this paper. Avoided cost is the most relevant metric for evaluating the cost-effectiveness of climate solutions, as it accounts for broader lifecycle effects on emissions.

[b] The low end of this range reflects capture costs in the transportation sector; the high end reflects capture cost in the power sector. Avoided costs are generally higher than capture costs in the transportation sector, where fuels are generally combusted without capture. Avoided costs can be lower than capture costs in the power sector, where bioenergy can displace emissions from fossil fuels.

[c] The low end of this range (\$94–232/tCO_2) reflects recent estimates of capture cost by company officials in a peer-reviewed study of one system design (Keith et al. 2018). Avoided costs would be somewhat higher, depending on the emissions intensity of energy inputs. House et al. (2011) estimated costs to be \$1,000/tCO_2. They did not examine a particular DACS design but instead theorized costs based on thermodynamic efficiencies. Because more recent estimates are available for specific system designs, we do not include the House et al. estimate.

[d] The literature provides rough estimates of cost for enhanced weathering and biochar. In some cases it may be feasible to develop reliable cost estimates for specific pilot projects or types of deployment. However, as the pathways to large-scale deployment for these technology categories remain uncertain, cost estimates are not presented here.

This working paper describes these technologies and identifies three types of key needs for large-scale deployment:

- **Technological maturity.** Early-stage technologies are typically associated with high costs. Estimates of current costs and the potential for future cost reduction can be highly uncertain because of a lack of RD&D and deployment and installation experience.
- **Enabling infrastructure.** Deploying technologies at large scale would require a wide range of enabling infrastructure that does not currently exist. This paper defines "enabling infrastructure" to mean more than just roads and bridges. It can include the range of data, systems, tools, and assets a technology requires to operate at large scale. For carbon removal technologies, such infrastructure typically includes supply chains, monitoring systems, CO_2 transport and storage networks, or renewable energy generation capacity.
- **Better understanding of climate benefits or ancillary effects.** Many of the technologies considered have GHG lifecycle impacts that reduce net CO_2 removal below the gross amount. But some could also have ancillary impacts on ecosystems and resource consumption. Poor understanding of lifecycle impacts and ancillary impacts can frustrate prudent deployment and lead to unintended consequences.

Another clear need is a carbon pricing mechanism that would provide incentive for private actors to invest capital in improving or deploying these technologies. Some form of explicit or implicit carbon pricing will be needed no matter how successfully the other needs are addressed. However, because the need for carbon pricing is not unique to carbon removal, it is not a focus of this paper.

This paper also explores policy ideas to help address the identified needs and begin the long-term process likely required to reach large-scale deployment. These actions could help advance carbon removal technologies in the United States. Investing in a portfolio of new and emerging carbon removal technologies, and building the knowledge, systems, frameworks, infrastructure, and finance streams needed to bring them to scale, may be essential steps on the path to stabilizing the climate.

BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS)

BECCS can take many forms. BECCS is a carbon removal approach that captures and stores CO_2 emitted from the conversion of biomass feedstocks (i.e., organic plant matter) into outputs such as power, heat, or biofuels (Minx et al. 2018) (see Figure 1). The CO_2 captured from the biomass operation can be stored underground or in products. BECCS provides a carbon removal function to the extent that it causes "additional" biomass to grow, which otherwise would not have grown, and/or causes the carbon embodied in biomass that would otherwise be released back to the atmosphere to be permanently stored. BECCS can also be used as an emissions reduction measure by displacing GHG-intensive sources of energy.

Despite its prominence in global climate models, BECCS faces significant limitations, related to the availability of biomass feedstocks that could provide climate benefits without displacing food production or natural ecosystems (Muri 2018). Deploying net-negative BECCS at any meaningful scale would require addressing needs related to the costs of CCS technology; the availability of CO_2 transport, storage, and utilization infrastructure and markets; and better understanding of climate benefits and ancillary effects (e.g., on ecosystems and food security) (see Table 2). Scaled deployment would then depend on the development of supply chains for sustainable feedstocks that provide net climate benefits.

How Does BECCS Work?

When biomass grows, it removes CO_2 from the atmosphere via photosynthesis. Typically, whether the biomass is used or not, after it is harvested or dies it eventually releases some or all of its embodied carbon back into the atmosphere through decomposition or combustion.

BECCS is the process of using biomass for energy and capturing and storing the embodied carbon before it is released back into the atmosphere (Sanchez et al. 2015). Biomass feedstocks can include the following:

- Dedicated plants, such as trees, grasses, or other crops, that are grown and harvested exclusively or primarily for energy generation. Examples include switchgrass, energy cane, biomass sorghum, willow, eucalyptus, poplar, and pine (U.S. DOE 2016). Dedicated feedstocks require available land for growing the biomass.
- Organic waste and residues, such as forest byproducts, agricultural residues, municipal solid waste, manure, and other biomass waste. Waste and residue feedstocks do not require dedicating land to produce these feedstocks (Cigolotti 2011).

Once the CO_2 is captured, it can be processed for transport and stored in geological formations or used in multiple economically valuable end uses (see Box 2).

Figure 1 | **Removing Carbon Dioxide from the Atmosphere via Bioenergy with Carbon Capture and Storage**

Table 2 | Costs, Potential, and Key Needs of Bioenergy with Carbon Capture and Storage (BECCS) in the United States

CARBON REMOVAL TECHNOLOGY	COST[a]	POTENTIAL IN THE UNITED STATES	KEY NEEDS
Bioenergy with carbon capture and storage (BECCS)	\$15–\$400/tCO_2 (Fuss et al. 2018)[b]	About 85–88 MtCO_2/year in 2020 if only agricultural residues and woody biomass feedstocks co-located with geological storage reservoirs are considered (Baik et al. 2018); additional feedstocks are available	■ Reduction in cost of carbon capture and storage (CCS) technology ■ CO_2 transport, storage, and utilization infrastructure and markets ■ Sustainable waste-derived feedstock supply chains ■ Better understanding of climate benefits and ancillary effects

Notes:

[a] Estimates generally reflect current costs. Different metrics are used to describe cost ("capture cost" and "avoided cost"). These metrics and their implications are discussed in the BECCS and DACS sections of this paper. Avoided cost is the most relevant metric for evaluating the cost-effectiveness of climate solutions, as it accounts for broader lifecycle effects on emissions.

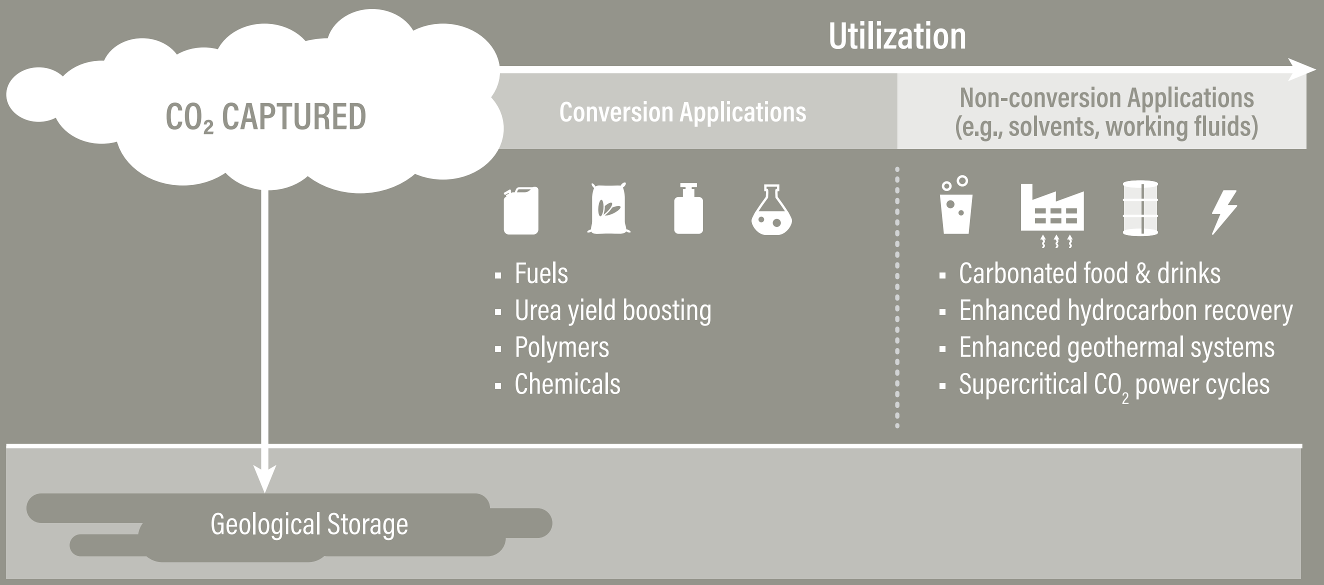
[b] The low end of this range reflects capture costs in the transportation sector; the high end reflects capture cost in the power sector. Avoided costs are generally higher than capture costs in the transportation sector, where fuels are generally combusted without capture. Avoided costs can be lower than capture costs in the power sector, where bioenergy can displace emissions from fossil fuels.

Box 2 | CO_2 Utilization and Geological Storage

Once anthropogenic CO_2 emissions are captured from industrial sources or ambient air, they can be permanently stored in underground geological formations or used in valuable products via conversion or nonconversion processes (Figure B2.1).

Conventional geological storage involves the injection of captured CO_2 into subsurface sedimentary rock formations (NRC 2015; CRS 2013). Once captured, CO_2 is compressed and injected into the subsurface reservoir through a well. The CO_2 is compressed to a form that is less dense than water and therefore can have buoyant properties once underground. It becomes trapped when it encounters a low-permeability overlying rock structure, or permeability seal. Over time, natural secondary

FIGURE B2.1. | WHERE CAN CAPTURED CARBON DIOXIDE GO?



Box 2 | CO_2 Utilization and Geological Storage (continued)

trapping mechanisms further ensure the inability of CO_2 to escape to the surface, thus reducing the dependency on the primary seal. Secondary trapping mechanisms include the following:

- Solubility trapping, whereby the CO_2 dissolves in water or in the residual organic matter (oil, gas) within the reservoir
- Hydrodynamic residual trapping, whereby, after injection, water moves back through porous spaces in the rock, trapping CO_2 in pockets
- Reactive mineralogy, whereby the fraction of reactive minerals within the formation interacts with the CO_2 to form solid carbonates (U.S. DOE NETL 2017).

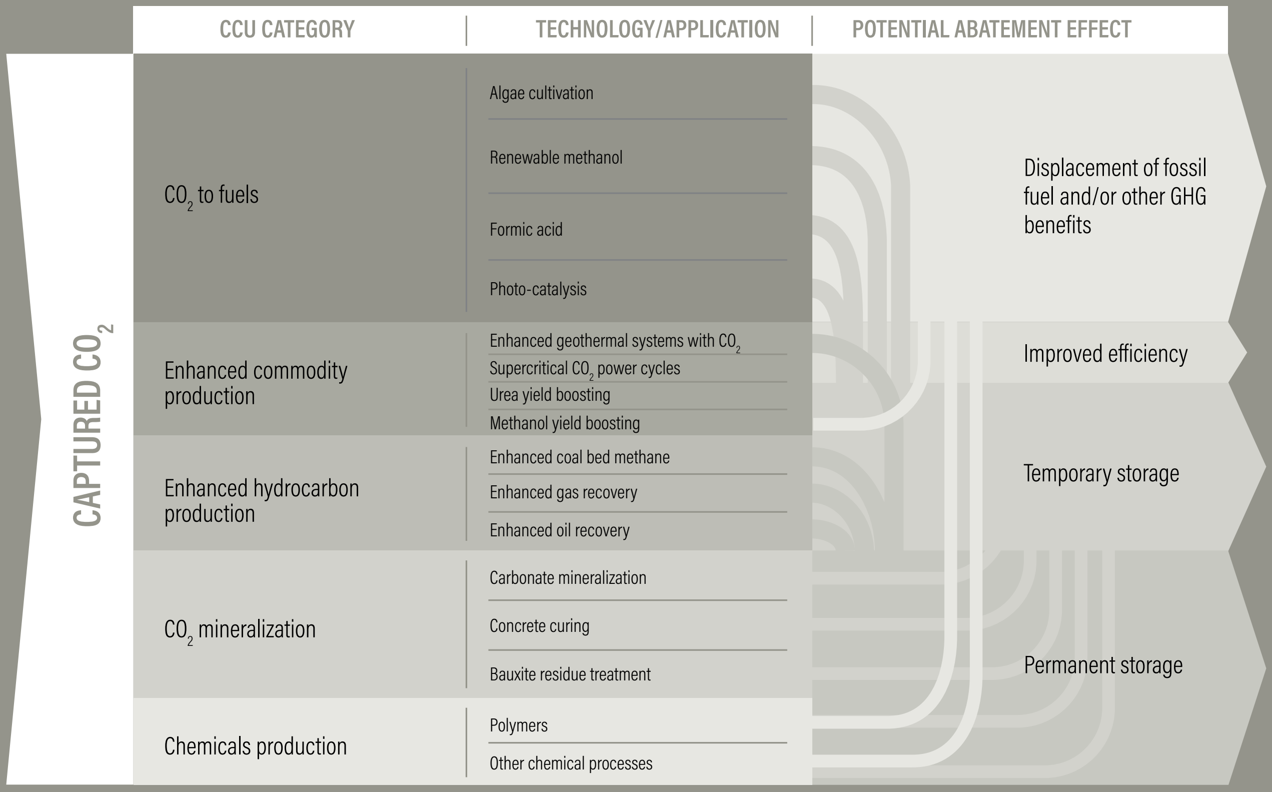
Technically accessible geological storage capacity in the United States is estimated to be 3,000 $GtCO_2$ across 36 formations (USGS 2013). In comparison, total annual U.S. GHG emissions are about 6 $GtCO_2e$. However, site-specific information is needed to determine whether a geological formation has the capacity, injectivity, and storage security parameters required (WRI 2008). For example, a site needs to have a degree of permeability that allows sufficient CO_2 injectivity over a projected project footprint, and it should possess characteristics and confining zones (e.g., thick cap rock) sufficient to prevent injected or displaced fluids from migrating into drinking water or the surface (WRI 2008).

Additional storage capacity could be created by accelerating the natural reactive mineralogy process—known as in situ enhanced weathering—by actively increasing the surface area of reactive minerals (e.g., silicates) within geological formations exposed to CO_2. This can be achieved through methods such as drilling, hydrofracturing, or thermal fracturing host rocks (U.S. DOE NETL 2017). However, the technique is still in its infancy and very few injection-test projects or feasibility studies have been conducted, making it difficult to assess the storage potential and cost of in situ carbonation domestically (Sanna et al. 2014).

CO_2 is also a chemical feedstock capable of being converted and/or used in many commercial applications, including conventional products, such as beverages and enhanced oil recovery operations, and emerging products, such as commodity chemicals and fuels or durable carbon materials like carbon fiber (Wilcox et al. 2014; Dairanieh et al. 2016; Sandalow et al. 2017). CO_2 utilization can

- provide storage for CO_2 captured via carbon removal technologies such as BECCS or DACS;
- help create market demand (niche and commodity market opportunities) for carbon capture, producing revenues to offset carbon capture costs and facilitate deployment experience;
- generate new industries and jobs and help increase the security of supply chains and energy; and

FIGURE B2.2 | POTENTIAL EMISSIONS ABATEMENT ILLUSTRATED BY EXAMPLES OF CO_2 UTILIZATION APPLICATIONS



Note: This figure provides an illustrative, not exhaustive, list of CO_2 utilization applications. CO_2 utilization applications can have multiple abatement effects.
Source: Hendriks et al. 2013.

Box 2 | CO_2 Utilization and Geological Storage (continued)

- displace emissions-intensive fossil fuel–derived feedstocks and materials such as steel or other liquid fuels (APS 2011; Dairanieh et al. 2016).

CO_2 utilization integrates captured CO_2 into products through various applications that have the potential to be carbon neutral or negative. Not all CO_2 utilization applications result in permanent sequestration of CO_2 (see Figure B2.2).

A range of factors affects prospects for CO_2 utilization, including the size and value of prospective markets, technological maturity, and costs. Relatively little is known about the current or likely costs or carbon lifecycles of various CO_2 utilization conversion approaches, because of the wide range of technological methods (e.g., direct utilization, carbonate mineralization, thermocatalytic separation, electrochemical separation), the dearth of scientific studies, and company confidentiality (Sandalow et al. 2017; NRC 2015).

Greater understanding is also needed regarding the lifecycle impact on net GHG emissions to identify the climate benefit of particular CO_2 utilization products. It is affected by factors such as the transport needs of captured CO_2, the energy and resource intensity of production processes, and the longevity of the CO_2 utilization product.

Globally, markets for concrete and aggregate could present a large-scale opportunity for utilizing captured CO_2 in forms that would provide long-term storage. For example, applying direct utilization of CO_2 into all concrete produced in 2030 could provide a market for up to 1.2 $GtCO_2$ (Sandalow et al. 2017). Several billion additional tons of CO_2 could potentially be sequestered by making aggregates partially with CO_2 as well. At least a dozen start-up companies are already bringing CO_2 utilization to the cement, concrete, and aggregate markets. However, these materials are inexpensive and provide small margins.

Durable carbon materials such as carbon fibers and nanotubes are another pathway for utilizing captured CO_2 in forms that would provide long-term storage, but these markets are small today. Global potential has been estimated to be the equivalent of approximately 1 percent of net annual global carbon emissions, using the current and projected state of the market for these materials (Douglas and Pint 2017).

Other nondurable products, such as fuels, polymers and chemicals, present market opportunities for carbon removal technologies like direct air capture. They are not avenues for permanent storage, however, unless fuels are combusted with CCS.

Geological storage and CO_2 utilization present options for storage of CO_2 captured from BECCS, DACS, and future carbon removal technologies. Expanding U.S. CO_2 transport networks—pipeline, truck, rail—from anthropogenic sources to storage sites and accelerating the validation of geological storage sites are critical enabling infrastructure requirements for these technologies. Although the United States is home to the world's largest CO_2 pipeline network (with roughly 4,500 miles of pipeline), this infrastructure is focused primarily on linking sites for enhanced oil recovery with CO_2 from natural geologic reservoir sources rather than anthropogenic sources (Sandalow et al. 2017).

Which Sectors Can Apply BECCS?

Biomass can be converted for energy in different sectors, including industry, transport, and power:

- In the industrial sector, biomass can be combusted to provide heat for industrial processes, such as pulp and paper production
- In the transportation sector, biomass can be converted into biofuel at dedicated refineries
- In the power sector, biomass can be gasified or converted into renewable natural gas and combusted alone or co-fired with natural gas; pelletized biomass can also be co-fired with coal or waste

For these processes to qualify as BECCS, the industrial facilities, biorefineries, and power plants must be equipped with CCS systems. Where biomass is used for biofuels production, the CO_2 released by biomass conversion is only partially captured for storage (during the fermentation process); the resulting fuels are ultimately combusted by vehicles without capture. Therefore, the biofuels application of BECCS may not be net-carbon-negative, although it can displace the use of fossil-based liquid fuels.

In the power sector, because of generally higher costs of biomass power compared with gas-fired power, CCS technology is likely to be applied to gas-fired plants first, given adequate incentives (NRC 2015).

Worldwide, at least 15 pilot-scale BECCS operations and one large-scale project (in Decatur, Illinois) are in demonstration phase (Gough and Vaughan 2015).[5]

Is BECCS Cost-Effective?

Costs cited in the literature range between US\$15 and \$400/tCO_2 (Fuss et al. 2018). They vary widely depending on several factors. Several metrics are used to describe cost. The simplest is capture cost, which divides the added cost of energy from a BECCS facility by the total CO_2 captured. Capture costs can vary significantly, depending on the feedstock used and the capture technology applied, even within a sector. BECCS in biorefineries generally appears at the low end of the cost range—less than \$50/tCO_2 capture cost (Sanchez et al. 2015; Sanchez et al. 2018; Johnson et al. 2014)—because the fermentation process generates a near-pure stream of CO_2 that is easily captured. Capture costs are higher in the power and industrial sectors.

A more relevant cost metric for climate mitigation efforts is avoided cost, which reflects capture cost net of lifecycle emissions. The GHG intensity of the sources of energy assumed to be displaced by BECCS can significantly affect total avoided cost. Sanchez and Callaway (2016) estimate that a biopower facility in Illinois would cost \$80/tCO_2 if it displaced an efficient gas-fired power plant but just \$60/tCO_2 if it displaced a coal plant instead. This effect will tend to cause total avoided costs of BECCS to rise as the emissions intensity of the economy declines over the coming decades.

The literature inconsistently accounts for full lifecycle emissions (e.g., from the production and gathering of biomass feedstocks) in the calculation of avoided costs. Especially where the production of feedstocks causes direct and indirect land use change (see Box 3), proper accounting of these lifecycle emissions could dramatically increase total avoided costs.

What Are the Global Land Use and Land Management Implications of Scaling BECCS?

A salient trend affecting land use is the need to feed a growing population. WRI estimates that calorie availability will need to increase 40 percent between 2018 and 2050 (Searchinger et al. Forthcoming). Closing this gap by boosting crop yields or limiting growth in crop demand will be important but difficult to achieve; pressure to convert more land to produce more crops and sustain livestock will thus remain high (Hanson and Searchinger 2015).

The conversion of forests or grasslands to agricultural uses is a major source of land sector emissions (IPCC 2014). Converting natural ecosystems and farmland in order to grow dedicated feedstock plants for BECCS instead of food or maintaining lands for their carbon benefits could thus have significant negative impacts on food security, natural ecosystems, and the terrestrial carbon sink (see Box 3) (Searchinger and Heimlich 2015) .

Evidence of these effects is already apparent from past policy interventions. In the United States, for example, more than 4 million acres of arable grassland, forestland, shrubland, and wetlands were converted to cropland within 100 miles of ethanol refineries during the first implementation period of the expanded Renewable Fuel Standard (2008–12) (Wright et al. 2017).

BECCS can leverage feedstocks that do not require converting lands for the growth of dedicated feedstock plants, such as forest by-products, agricultural residues, and municipal solid waste. Feedstocks that do not require land conversion are more limited in supply, however, and may require collection from more sources and more diverse feedstocks, increasing processing costs and requiring further transport. There is also emerging interest in other forms of bioenergy, such as aquatic biomass and biomass that can grow on marginal lands not suitable for food production (e.g., agave) (Mielenz et al. 2015). Further research on potential and impacts is needed (Robledo-Abad et al. 2017).

How Much Carbon Removal Can BECCS Provide?

Further research that incorporates full lifecycle accounting and safeguards for additionality and sustainability is needed to adequately determine the potential of BECCS in the United States.[6] Using dedicated plants or by-products and waste residues for BECCS feedstocks presents difficult GHG lifecycle accounting considerations that affect the level of net carbon removal potential. Accurate accounting for total lifecycle emissions of bioenergy remains a substantial challenge, given the need to account for the carbon opportunity cost of land dedicated to bioenergy

Box 3 | Potential Impacts of Dedicated Bioenergy Crops on Arable Land

If dedicated bioenergy crops displace other land uses, such as forests or farms, the production of food or fiber would be reduced. As the supply of food or fiber is reduced, all else being equal, the prices of those commodities will increase, and at least some portion of the lost supply will be replaced from elsewhere. As a result, previously undisturbed land could be converted to food production, leading to losses in biodiversity and ecosystem services and potentially offsetting the carbon benefits of bioenergy, even with CCS (Gough and Vaughan 2015). To the extent that lost supply is not replaced from elsewhere, prices will remain higher, which could affect food security for vulnerable populations.

Growing dedicated bioenergy plants on abandoned agricultural lands, marginal lands, or degraded lands could still lead to competition with other land uses. These lands are often treated as a "free" reserve for various future uses, from food production to feed a growing population to reforestation to store more carbon to bioenergy to power the economy. But these uses would be in conflict (Tilman et al. 2009; Gough and Vaughan 2015). Dedicated bioenergy production also requires using water for feedstocks and for power generation, and it can scale faster if agricultural yields are higher. Using large-scale irrigation and higher rates of fertilizer use can help boost production yields. These efforts would have implications for water conflict in water-stressed regions, degradation of freshwater ecosystems, and increased emissions from higher rates of fertilizer use (Gough and Vaughan 2015).

production; emissions associated with cultivating and combusting biomass, including from fertilizer use; the transportation of biomass; and whether feedstocks can be regrown on a meaningful timeline (Global CCS Institute 2018). Searchinger and Heimlich (2015) reveal errors in accounting in which emissions reductions from biomass electricity generation are double counted. Leakage from land use change can also result in reductions in climate benefits.

Adequate safeguards and accurate lifecycle accounting are needed to ensure that carbon removal from BECCS is additional and sustainable, and to gauge its true potential. Economically viable biomass production in 2040 at $60 per dry ton has been estimated to embody the equivalent of 1,040–1,780 million metric tons of CO_2 ($MtCO_2$) per year (Baik et al. 2018). The actual net additional carbon removal achieved by producing that level of biomass for energy is unclear, however, especially as a significant portion would require dedicated energy crops. Less than 400 $MtCO_2$ would be available if biomass supply were limited to the entire available supply of agricultural residues and forest by-products.

Baik et al. (2018) assess the constraints on BECCS in the United States posed by transportation radius boundaries for the shelf-life of biomass and co-location of existing geological storage sites with sufficient injection capacities. These constraints reduce the potential of agricultural residues and forest by-products to about 104–111 $MtCO_2$ per year in 2040. The co-location constraint could be partly alleviated by constructing pipelines for the transportation of captured CO_2. Additional benefit could be generated by displacing emissions-intensive sources of energy. The use of other feedstocks (e.g., municipal waste or algae) could also increase potential.

What Key Needs Must Be Addressed to Deploy BECCS at a Large Scale?

Scaling up net-negative BECCS deployment would require a large effort to address key needs.

Need for cost-effective CCS technology

First and foremost, advancing net-negative BECCS at scale is contingent upon the viability and widespread deployment of CCS technology in the power and industrial sectors, where CO_2 emissions from converting biomass to energy could be more fully captured. Reducing capture costs in these applications could help accelerate the deployment of CCS, with either biomass or fossil fuel feedstocks. Researchers have identified pathways for how CCS could be scaled specifically for BECCS (Vergragt et al. 2011).

Need for CO_2 transport, storage, and utilization infrastructure and markets

Successfully deploying BECCS at large scale would require significant supporting infrastructure. CO_2 transport networks (e.g., pipelines for CO_2 transport)may be essential for BECCS, because a relatively small share of total available biomass feedstocks are co-located with potential geological sequestration sites (Baik et al. 2018). Today, limited CO_2 transportation infrastructure exists.

Captured CO_2 must also be stored. Although significant geological storage capacity in the United States is technically accessible, individual sites must be validated to determine their true potential. CO_2 utilization markets could also provide some storage capacity while offsetting some costs of deployment. However, the net lifecycle impacts of CO_2 utilization products require further study, and not all utilization applications lead to permanent storage of CO_2 used, such as fuels and chemicals (see Box 2).

Need for better understanding of climate benefits and ancillary effects

Persistent knowledge gaps surrounding the net climate benefits and sustainability of BECCS in its various forms include land competition implications, the additionality of bioenergy feedstocks, negative impacts on ecosystems and their services, and GHG lifecycle accounting. An accounting framework, coupled with landscape-scale monitoring, could help enable differentiation between additional/sustainable and nonadditional/nonsustainable feedstocks to safeguard BECCS processes. Addressing this need could help focus public and private investments on arrangements of BECCS that are most beneficial while enabling greater public support for those investments.

Need for sustainable waste feedstock supply chains

Assuming that needs related to the cost of deployment of CO_2 transport and storage infrastructure can be addressed, scaling deployment would then rely on further investments in infrastructure to gather, process, and transport biomass feedstocks. Given competition for land for food production, carbon storage, and other ecosystem services, this effort could focus on feedstocks that do not require dedicated land use, including forest by-products, agricultural residues, municipal waste, and other potential sources. Advanced technology for drying biomass at the collection site could also reduce transport costs.[7]

Summary

BECCS can take many forms. They vary widely in viability, cost-effectiveness, technical scale of potential, climate benefits, and detrimental effects. Perhaps the most viable and cost-effective form of BECCS in the production of fuels could reduce emissions, but it may not provide net carbon removal.

Several needs would have to be addressed to bring BECCS to its potential scale as a carbon removal technology in the United States. They relate to capture costs in the industrial and power sectors, enabling infrastructure and markets, and the need for better understanding of net climate benefits and ancillary effects across the many forms and configurations of BECCS. Scaling BECCS will ultimately depend on the availability of additional and sustainable bioenergy feedstock supply chains. Developing those supply chains would yield fewer mitigation benefits in the absence of widespread CCS, however, because collected biomass would be converted to energy without capturing the embodied CO_2.

DIRECT AIR CAPTURE AND STORAGE (DACS)

DACS is a carbon removal approach that captures CO_2 directly from ambient air through a chemical scrubbing process (Minx et al. 2018) (see Figure 2). The CO_2 is then compressed and stored either underground or in products (see Box 2) (NRC 2015).

Currently, there are three major working demonstrations of direct air capture by ClimeWorks, Carbon Engineering, and Global Thermostat.[8] DACS technology has significant technical carbon removal potential, but deploying DACS at a large scale will require addressing needs related to the high costs of the technology, the availability of CO_2 storage and utilization infrastructure and markets, and the availability of low-cost low-carbon, energy inputs (see Table 3).

Figure 2 | **Removing Carbon Dioxide from the Atmosphere via Direct Air Capture and Storage**

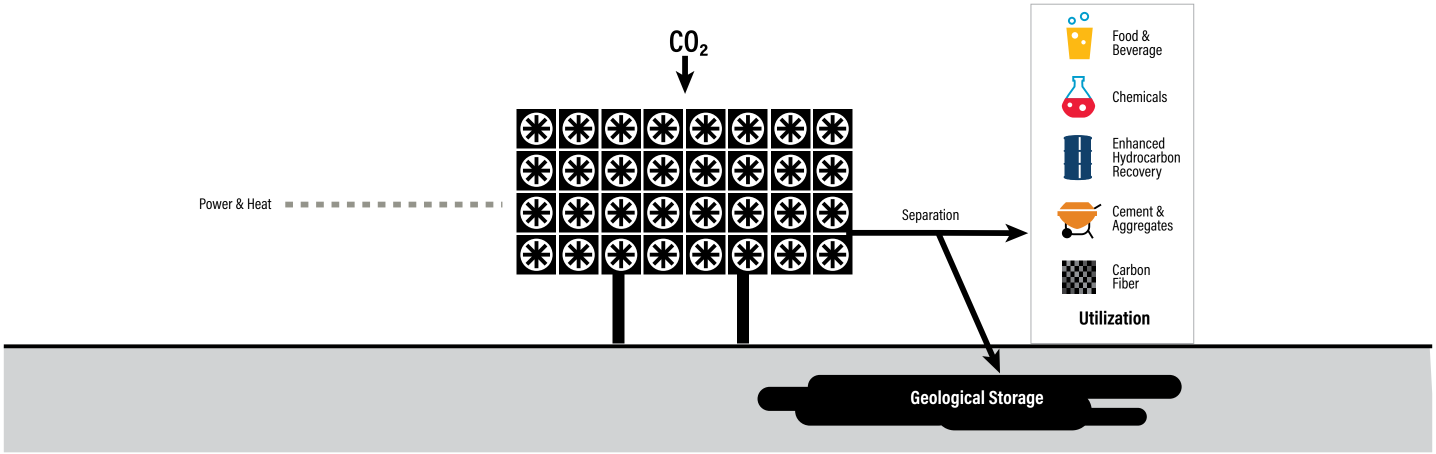


Table 3 | **Costs, Potential, and Key Needs of Direct Air Capture and Storage (DACS) in the United States**

CARBON REMOVAL TECHNOLOGY	COST[a]	POTENTIAL IN THE UNITED STATES	KEY NEEDS
Direct air capture and storage (DACS)	\$94–\$600/tCO_2 (Keith et al. 2018; APS 2011)[b]	No obvious limitation on technical potential	■ Reduction in cost of DACS systems ■ CO_2 storage and utilization infrastructure and markets ■ Abundant low-cost, carbon-neutral energy

Notes:

[a] Estimates generally reflect current costs. Different metrics are used to describe cost ("capture cost" and "avoided cost"). These metrics and their implications are discussed in the BECCS and DACS sections of this paper. Avoided cost is the most relevant metric for evaluating the cost-effectiveness of climate solutions, as it accounts for broader lifecycle effects on emissions.

[b] The low end of this range (\$94–\$232/tCO_2) reflects recent estimates of capture cost by company officials in a peer-reviewed study of one system design (Keith et al. 2018). Avoided costs would be somewhat higher, depending on the emissions intensity of energy inputs. House et al. (2011), estimated costs to be \$1,000/tCO_2. They did not examine a particular DACS design but instead theorized costs based on thermodynamic efficiencies. Because more recent estimates are available for specific system designs, we do not include the House et al. estimate.

How Does DACS Work?

DACS captures CO_2 directly from the ambient air and moves it through a chemical sorbent or solvent—an aqueous solution, amine adsorbent, or solid sorbent (Sanz-Pérez et al. 2016)—that binds the CO_2, separating it from other gases in the air. Once the sorbent is saturated, the collected CO_2 is then released via vacuum swing, temperature swing, or a combined process. Depending on the end-fate of the CO_2, it may be converted to a useful product on-site or pressurized for transport to either a geological formation for storage or a utilization site (APS 2011; Wilcox et al. 2017; Keith et al. 2018; Stolaroff et al. 2008). The chemical process used to capture CO_2 can be similar to point-source CCS. However, DACS captures CO_2 from ambient air, which is approximately 100 times more diffuse than CO_2 in gas-fired power plant flue gas, increasing its energy requirements (NRC 2015). The minimum amount of energy required to capture CO_2 from ambient air is 2–10 times the amount required to capture CO_2 from point sources (NRC 2015).

Is DACS Cost-Effective?

The cost of DACS per ton of CO_2 removed remains high, albeit not as high as previously estimated. Costs associated with DACS involve those related to capital investment; energy required for capture, regeneration of the sorbent or solvent, and operation of the system; and the sorbent or solvent, including its loss and maintenance (Fuss et al. 2018).

Similar to BECCS, two cost metrics are used to describe the cost of DACS: capture cost and avoided cost. Whereas the avoided costs of BECCS can be lower than capture costs if other sources of emissions are displaced, the avoided costs of DACS tend to be higher than its capture costs because additional lifecycle emissions are accounted for, particularly from energy inputs and post-capture transport and storage (Keith et al. 2018; APS 2011). The literature reports a significant range of cost estimates (Realff and Eisenberger 2012; Herzog et al. 2012; APS 2011; Keith et al. 2018):

- A 2018 peer-reviewed study by researchers at Carbon Engineering (one of the three major direct air capture companies) provides system designs and financial estimates that would yield capture costs of \$94–\$232 per tCO_2, depending on design options and assumptions (Keith et al. 2018). Avoided costs would be higher, depending on the GHG intensity of energy inputs. The estimates also assumed contingency costs reflective of an “nth” plant rather than a first-of-a-kind demonstration facility.
- APS (2011) estimates total avoided costs—the average cost of avoiding a ton of CO_2—to be \$400–\$600/tCO_2, assuming carbon-neutral energy sources. The energy input costs used in the study are out of date, however, as the cost of solar energy and natural gas has fallen considerably since it was published. Furthermore, the study did not account for cost reductions associated with different DACS designs, continued technological advances over time, or even reduced contingency costs achieved through deployment experience. For example, Keith et al. (2018) point to several design choices that reduce capital costs relative to the hypothetical system assessed in the APS study.[9]
- A growing number of start-up companies have initiated small-scale pilots and claim potential costs that could be significantly lower (Ishimoto et al. 2017; Keith et al. 2018). The true costs and long-term potential can be difficult to gauge, however, given the proprietary nature of existing deployment data.

What Are the Energy Requirements of DACS?

DACS requires a significant level of heat and power inputs (APS 2011; Fuss et al. 2018), estimated to be at least 0.5 gigajoules (GJ)/tCO_2 for capturing the CO_2 and up to 12.3 GJ/tCO_2 for the entire DACS process (APS 2011). The system posited in Keith et al. (2018) would require 8.81 GJ/tCO_2 (2.45 megawatt-hours). For perspective, the average annual electricity consumption for a residential utility customer in the United States was 38.8 GJ in 2016 (U.S. EIA 2017).

For DACS to cost-effectively provide net carbon removal, its energy inputs must be carbon neutral or near carbon neutral. Comprehensive lifecycle accounting of net GHG removal includes the CO_2 embodied in energy used for air capture and separation, CO_2 purification and compression, and storage or utilization processes (APS 2011). If grid energy is used, the net emissions effects of adding DACS to the grid must be accounted for.

The amount of energy needed to support DACS at a large scale, the requirement for low or zero GHG energy, and the need for both heat and power likely have important implications for the desired future composition of the energy sector if DACS is to play a significant role in mitigating climate change. Powering 1 $GtCO_2$ per year at the energy intensity of the system design in Keith et al. (2018) would require the equivalent of 43 percent of all carbon-neutral energy (renewable energy and nuclear electric power) consumed in the United States in 2017.[10] Continued improvements in system efficiency could reduce energy requirements. DACS could significantly increase the need to build out renewable energy sources such as solar photovoltaics and wind power. The requirement for high-intensity heat may necessitate other forms of low- and zero-carbon energy, such as geothermal, hydrogen, solar thermal, fossil CCS, BECCS, and nuclear. However, the energy sector implications of DACS have not been modeled.

Where Can DACS Be Sited?

DACS has flexibility in its design and siting. Its feed gas (the air) is everywhere and unlimited. DACS systems can therefore be co-located with sequestration sites or CO_2 utilization sites, minimizing or eliminating the need for CO_2 transportation infrastructure (Wilcox et al. 2017) and avoiding the higher costs of generating high-purity streams of CO_2 required to use CO_2 pipeline networks in some cases.

Other siting considerations include the availability of low-carbon energy inputs and conditions such as temperature, wind, humidity, and pollution, which can affect technology performance and costs (APS 2011). Some system designs could also affect the growth of downwind vegetation as the air is depleted of CO_2 (Johnston et al. 2003; Broehm et al. 2015).

What Are the Land Use Requirements of DACS?

The land footprint of a DACS system includes the structures through which air flows for direct capture as well as the sites providing electricity and thermal energy inputs. Although the direct land footprint of the capture structure itself is relatively small, at 67,000 acres per 100 $MtCO_2$ per year (Smith et al. 2016), the source of energy inputs could have substantial land use requirements. For example, relying on solar photovoltaics for energy inputs could significantly increase the land footprint of DACS. The National Academies of Sciences estimates that powering 13 $GtCO_2$ per year from DACS would require 100 million acres of solar energy (NRC 2015). Other low-carbon energy sources used to power and capture 13 $GtCO_2$ per year from DACS could potentially have smaller land footprints.

How Much Carbon Removal Can DACS Provide?

There is no obvious way to bound an estimate of the full potential of DACS. However, its accessibility as a large-scale carbon removal strategy is linked primarily to its cost. DACS will come online at a large scale only if its cost is competitive with other options for removing CO_2 or reducing emissions. The pace and possibilities of technological innovation and cost reduction remain uncertain. If technology costs do become competitive, the availability of low-carbon energy inputs could become the constraining factor. Geological storage capacity in the United States appears to be sufficiently large to support large-scale deployment. Few studies include DACS in global climate models, and the ones that do assume DACS becomes profitable only for very stringent climate policies post-2065, with rapid scale-up thereafter (Fuss et al. 2018).

What Key Needs Must Be Addressed to Deploy DACS at a Large Scale?

Need to drive down the costs of DACS systems

Current estimated system costs are the primary hurdle for DACS. DACS must be cost-competitive with other carbon removal or emissions reduction measures in order to be deployed at a large scale. RD&D investments in second-generation and beyond DACS technologies and systems, in combination with incentives to spur learning-by-doing and build economies of scale, could help reduce costs and spur innovation. Experience with research and development (R&D) support to renewable energy technologies, for example, shows that significant technological improvements can occur rapidly and costs can drop exponentially (Landberg and Eckhouse 2018). To date there has been relatively little effort to improve DACS technology, with essentially no federal R&D support (Sanchez et al. 2018) and limited private sector investment.

Reviews have begun examining the technological pathways to reduce DACS costs (NRC 2015) and identify specific research needs and R&D priorities (NAS 2017; ASU 2018; Dairanieh et al. 2016), including system design, integration, and improved capture and separation technologies (APS 2011). Research on the ancillary impacts of DACS is also needed to shed light on energy needs, the implications of different energy sources, the impacts on land uses and ecosystems, and to identify optimal siting criteria, such as locations where waste heat and low-carbon electricity are co-located with geological storage or CO_2 offtake opportunities.

Need for abundant low-cost, low-carbon energy

If DACS became cost-competitive, scaling its deployment would depend on the availability of low-cost, low- or zero-GHG energy inputs. Clean energy is making progress in the United States. Net electricity generation from fossil fuels declined over the past two decades as renewable generation increased (U.S. EIA 2018). Renewable energy is becoming profitable in more locations than ever before as its costs decline. In 2017 both unsubsidized onshore wind and utility-scale solar became cheaper than new coal in many parts of the United States and cost-competitive with new combined-cycle natural gas on a levelized cost basis (Lazard 2017).[11] However, fossil fuels continue to dominate the U.S. energy portfolio. Deploying DACS at scale will be contingent on continued progress in transitioning the energy sector toward low-carbon energy.

DACS could use renewable energy that would otherwise be curtailed in an electricity system with high penetration of variable renewable energy resources. This could be a source of very low- or even zero-cost electricity, but it would not be available at all hours. Future cost reductions in energy storage technology may also affect the rationale for using otherwise curtailed energy to power DACS.

Need for CO_2 storage and utilization infrastructure and markets

Immense, inexpensive CO_2 storage capacity is an essential requirement for both BECCS and DACS (APS 2011). However, addressing this need in the near-term would do little to catalyze DACS deployment at scale, given its high cost and energy requirements.

Technically accessible geological storage capacity in the United States appears to be sufficiently large (USGS 2013). Sites need to be individually validated, but this need may be addressed for lower-cost carbon capture technologies (fossil CCS and BECCS) before DACS becomes cost-effective at a large scale. In contrast to BECCS, DACS systems can be sited to minimize the need for CO_2 transport and associated infrastructure. Still, mapping the co-location of carbon-neutral energy development sites and geological formations could be useful in planning future deployment.

Captured CO_2 can also be stored in useful products. The development of CO_2 utilization markets could help provide some storage capacity in long-lived products such as concrete and could provide a revenue stream in the near term to address DACS cost hurdles. However, the potential for long-term CO_2 storage in useful products, although meaningful, appears to fall short of the total storage need if DACS were to be deployed at a large scale in the United States (see Box 2) (Broehm et al. 2015). Moreover, several forms of utilization, such as beverages, chemicals, and fuels, do not provide long-term storage.

Summary

The technical potential of DACS is significant. However, several needs would have to be addressed to bring DACS to scale in the United States. Reducing costs through technological development and leveraging CO_2 utilization markets to offset costs may be the most critical needs to address. DACS would also rely on the widespread availability of low-cost, carbon-neutral energy; storage solutions at immense scale; and ultimately a carbon pricing mechanism with a meaningful price that can drive investments and deployment.

FRONTIER TECHNOLOGIES

Many other technologies could potentially play a role in carbon removal. However, they are in the very early stages of development and/or their utility and efficacy for carbon removal is nascent. Some of the more explored frontier technologies include biochar, plant breeding and engineering, enhanced weathering, and seawater capture (see Figure 3). Other frontier technologies exist, as well as some less advanced concepts, including diverting waste wood from landfills to facilities designed for near-permanent storage and the use of synthetic hydrocarbons produced via renewable energy for electricity generation in CCS-equipped power plants.

With the exception of biochar, these technologies are categorized as frontier technologies because they are in the early stages of development. Biochar is included in this category because, although it is established as a soil-additive technology, its use for carbon removal is nascent. These technologies face uncertainties that frustrate a robust evaluation of potential scale and the investments needed to reach it. These uncertainties include potential costs,[12] resource intensity and climate footprints, and the scale of carbon potentially removed. Scientific and technological development could help build sufficient knowledge and identify frontier technologies that may be viable for carbon removal (see Table 4).

Biochar

Biochar is charred biomass that can be applied to soils of agricultural and forested lands through plowing or spread as a mixture with manure or as a powder. It can potentially increase soil carbon pools by slowing the decomposition of biomass and stabilizing existing carbon in the soil, thereby mitigating the release of CO_2 into the atmosphere (NRC 2015).

Figure 3 | **Frontier Technologies for Removing Carbon from the Atmosphere**

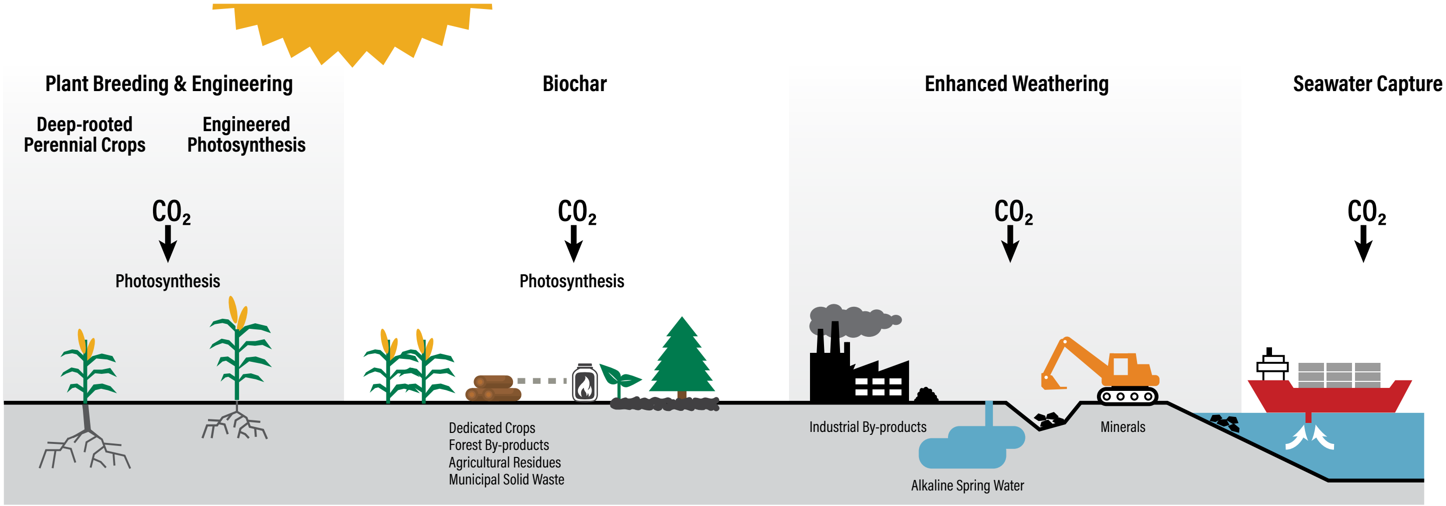


Table 4 | **Costs, Potential, and Key Needs of Frontier Technologies in the United States**

CARBON REMOVAL TECHNOLOGY	COST[a]	POTENTIAL IN THE UNITED STATES	KEY NEEDS
Frontier technologies	Uncertain[b]	Uncertain	■ More RD&D to build sufficient knowledge and create viable technologies

Notes:

[a] Estimates generally reflect current costs. Different metrics are used to describe cost ("capture cost" and "avoided cost"). These metrics and their implications are discussed in the BECCS and DACS sections of this paper. Avoided cost is the most relevant metric for evaluating the cost-effectiveness of climate solutions, as it accounts for broader lifecycle effects on emissions.

[b] The literature provides rough estimates of cost for enhanced weathering and biochar. In some cases it may be feasible to develop reliable cost estimates for specific pilot projects or types of deployment. However, as the pathways to large-scale deployment for these technology categories remain uncertain, cost estimates are not presented here.

Biochar is the solid product of pyrolysis, which occurs through heating biomass in the absence of, or with limited levels of, oxygen at relatively low temperatures compared with combustion or gasification processes (Lehmann and Joseph 2015). Possible biomass sources include plants grown for the dedicated purpose of pyrolysis, as well as crop residues, municipal waste, animal manure, and woody residues (Eagle et al. 2012). Processing methodologies include inducing pyrolysis at different speeds in a range of technologies, including various-sized kilns made of different material (e.g., concrete, brick, metal); retorts; and converters (Garcia-Nunez et al. 2017; Lehmann and Joseph 2015).

What Are the Challenges Facing Biochar?

Although it is an established soil-additive technology, biochar is not widely applied, and its climate benefits are debated. A lack of data and well-designed long-term studies limit current understanding of biochar's effectiveness and scalability (Gurwick et al. 2013; Zhang et al. 2013).

The effects of biochar on carbon stabilization or storage are affected by the particular feedstock, soil application, and pyrolysis method used (Gaunt and Driver 2010), and the rate of decay is variable by ecosystem. Much is understood about how production processes yield different biochar types and properties. Better understanding of the relationships between feedstock compositions, processing methodologies, and their impact on soil properties is needed to determine net GHG impacts (Kambo and Dutta 2015; Manyà 2012). Additionally, biochar production units can be modular, but their limited mobility requires harvesting and transporting biomass feedstocks to some extent, which has implications for costs and net GHG effects that are not well understood.

Plant Breeding and Engineering for Carbon Removal

Selective plant breeding and engineering are forms of biotechnology that use biological systems and living organisms to modify processes for a specific use (UNCBD 2010). Engineering or selectively breeding plants to develop particular traits (e.g., enhanced photosynthesis or longer root structures) could potentially harness the natural carbon cycle to increase the level of carbon stored in soils and biomass. This approach captures and stores CO_2 together in a single step, obviating the need for additional investments in CO_2 transportation and storage operations.

When a plant performs photosynthesis, it consumes CO_2 from the atmosphere and fixes it in the plant biomass. CO_2 becomes stored in the soil carbon pool through the growth and death of plant roots and from transfers of compounds between roots and soil microbes (Ontl and Schulte 2012). Some carbon is lost to the atmosphere through respiration; the rest is stored in the biomass of the plant. Engineering the photosynthetic efficiency of plants and crops could drive greater flux of carbon from the atmosphere into biomass and land than achieved with natural photosynthesis. Additionally, engineering or selectively breeding plants to develop particular traits, like deep roots or longer lifecycles (e.g., perennial crops, which are productive for more than one season and penetrate deeper into soil profiles), could increase carbon deposits in agricultural soils. Today, major crops used in large-scale agricultural enterprises are shallow-root, annual crops that have a single-season lifespan.

What Are the Challenges Facing Plant Breeding and Engineering?

Plant breeding and engineering efforts are primarily in the laboratory phase, alongside various types of biotechnology under development (Eagle et al. 2012). Although research is greatly expanding the understanding of plant growth and photosynthetic efficiency, many questions remain unanswered (U.S. DOE 2017). These technologies could sequester more carbon and reduce on-farm emissions (e.g., reduced fuel use by switching to perennial crops from annual). Other implications and potential unintended consequences remain unclear.

Enhanced Weathering

Enhanced weathering consists of a range of processes that encourage the acceleration of the natural reaction between CO_2 in the atmosphere and reactive sources (e.g., silicate minerals or alkaline industrial by-products) (NRC 2015).[13] The accelerated reactions speed the formation of solid carbonates on land or dissolved bicarbonate in the ocean, sequestering more CO_2 from the atmosphere. Enhanced weathering captures and stores CO_2 in a single step, obviating the need for investments in CO_2 transportation and storage operations.

A major approach involves the mining and distribution of reactive minerals (e.g., silicates, carbonates) across landscapes or into the ocean (Minx et al. 2018; Kirchofer et al. 2012). The minerals are crushed or broken down using enzymes, increasing the reactive surface area exposed to CO_2.

Other approaches involve speeding the reaction of CO_2 from the atmosphere with alternative reactive or alkaline sources, including the following:

- **Mine tailings:** Reactive mineral materials left over from asbestos, nickel, or other mining operations that contain calcium or magnesium, such as silicates like olivine or serpentine (Harrison et al. 2013)
- **Industrial by-products:** Alkaline industrial wastes such as fly ash, cement kiln dust, or iron and steel slag (Kirchofer et al. 2013)
- **Alkaline spring water:** Pumped spring water with an alkalinity higher than drinking water.

What Are the Challenges Facing Enhanced Weathering?

Enhanced weathering approaches are the result of limited laboratory and small-scale field testing or theoretical explorations (NRC 2015). Understanding of the cost-effectiveness and environmental or net GHG impacts of various approaches is limited. Requirements for these approaches could include the collection and transport of viable natural or industrial sources of reactive materials as well as potentially substantial resource inputs, such as water and heat (Kirchofer et al. 2013, 2012). More needs to be learned about the application of these processes outside controlled laboratory environments and their environmental impacts.

Ocean and terrestrial approaches that involve crushing and distributing minerals to expand reactive surface areas are highly contested because of their unknown environmental impacts. Ocean-based applications also face legal challenges under the London Protocol and London Convention, which prohibits dumping into the ocean (U.S. EPA 2015).

Seawater Capture

Seawater capture is the extraction of CO_2 from seawater. The process can be done via a modular unit attached to a ship or docking platform at sea or at a facility on land. The CO_2 is extracted by heat, vacuum, purging with a non-CO_2 gas, or by shifts in pH achieved through electrochemical approaches (NRC 2015). Following extraction, the partial pressure of CO_2 in remaining seawater is reduced, which could draw CO_2 from the atmosphere into the ocean.

Seawater extraction processes require the use and movement of large volumes of seawater to avoid recycling material that has been depleted of CO_2, as well as energy. However, because seawater has a concentration of carbon that is 100 times greater per unit volume than carbon in the air, sequestering CO_2 from seawater capture has the potential to require less energy consumption than capturing CO_2 from ambient air (Eisaman et al. 2011). Seawater capture technology is at working prototype demonstration scale in modular form for the production of fuels on at-sea vessels (DiMascio et al. 2017).

What Are the Challenges Facing Seawater Capture?

Many aspects of seawater capture technologies require further investigation. They include energy intensity, effective system design approaches to minimize energy requirements for moving seawater while also withstanding harsh maritime environments, and the potential scale of deployment (NRC 2015). Greater understanding of the potential environmental impacts of this technology, including potential localized benefits for ocean acidification, is also needed.

Summary

Each frontier technology has unique needs and challenges, but all need further technological development. More RD&D is needed to build sufficient knowledge and create viable technologies, from technological development and related scientific inquiry, to GHG lifecycle impact analyses and small-scale demonstration efforts. It can shed light on which frontier technologies can be emissions negative and reveal challenges related to enabling infrastructure and deployment of these technologies.

POLICY IDEAS FOR PROGRESS

Advancing carbon removal is an exercise in creating options. This paper explores emerging carbon removal technologies and identifies key needs for deploying these technologies at scale in the United States. These needs relate to technology maturity and cost reduction, enabling infrastructure and markets, and uncertain climate benefits and ancillary impacts (e.g., of land conversion or unsustainable biomass production). Deploying these approaches at scale would require addressing these needs through significant and sustained policy investments.

Three broad categories of potential policy action could help begin to address them:

- Launching a federal cross-cutting RD&D program for carbon removal
- Applying federal and state deployment-support policies to enable learning-by-doing
- Advancing fossil fuel carbon capture, storage, and utilization technologies that are synergistic with carbon removal efforts

Within these categories (examined below) fall several individual policy measures for consideration (see Box 4). Additional analysis is needed to create a prioritization roadmap, identify the most impactful measures, and estimate the cost of these prospective public investments.

These actions are critical for setting the stage for large-scale technological carbon removal but insufficient on their own without some form of carbon pricing mechanism that provides sufficient incentive for deployment by the private sector.

Box 4 | Potential Policy Measures

Individual policy measures for consideration include the following:

Federal Cross-Cutting RD&D Program for Carbon Removal

- Establish and fund a cross-cutting federal RD&D program for carbon removal.
- Develop a coordination mechanism for federal RD&D on carbon removal and related technologies.
- Invest in GHG lifecycle assessment and related policy development across the full set of carbon removal technologies.

Federal and State Deployment Support

- Provide tax incentives—such as credits, deductions, investment or production credits, or accelerated depreciation—for carbon removal and related technologies.
- Incorporate carbon removal and related technologies into existing state programs that incentivize reductions in GHG emissions.
- Develop federal, state, and corporate procurement policies for CO_2 utilization products.

Support for Carbon Capture, Storage, and CO_2 Utilization

- Lift constraints on the DOE's Office of Fossil Energy to direct R&D efforts across technologies and fuel types beyond coal CCS technology.
- Pursue legislative or regulatory changes that can mobilize CCS in existing biorefineries.
- Secure increased funding for federal RD&D for CO_2 utilization technologies and fossil CCS technologies.
- Utilize the Clean Air Act to accelerate deployment of CCS in fossil fuel facilities.

Federal Cross-Cutting Research, Development, and Demonstration Program for Carbon Removal

Why Is it Needed?

To date there have not been concerted federal efforts to invest in technological development for carbon removal (Sanchez et al. 2018). Establishing and funding a significant, multiagency federal RD&D program could help bring carbon removal technologies to maturity in the United States by creating new technology pathways—such as novel materials, system designs, or operating procedures—that could drive down the full installed system cost per tCO_2 removed and stored.

What Would It Look Like?

A federal RD&D initiative for carbon removal could do the following:

- **Set a target to help propel progress.** Setting one or more ambitious but achievable long-term targets (e.g., over a 10-year horizon) could help direct programmatic investments strategically, avoid poor internal management of RD&D, and prevent lapsing into research for research's sake. Some notable examples of target-driven program design are the SunShot program's \$1 per watt target for utility-scale solar PV and the drop-in biofuel target of \$3/gasoline gallon equivalent set by the DOE's Bioenergy Technologies Office (U.S. DOE EERE 2016). A carbon removal RD&D initiative could set targets for technology cost, installed capacity for removal, or cumulative removal achieved (Box 5). Clear, understandable targets of this nature are important in technology development programs, which can otherwise seem opaque or poorly motivated to nontechnical stakeholders—particularly Congress—making sustained federal funding difficult.
- **Run the gamut from basic science to demonstration, with ongoing and detailed lifecycle assessment.** Key dimensions include basic science, lifecycle assessment, technology development, pilot demonstrations, and tech-to-market efforts. Forthcoming reports by the National Academies of Sciences and other experts will address the specific contours and priorities of technology development roadmaps for carbon removal technologies. Ongoing and detailed lifecycle assessment analysis, with frequent updates and close integration with RD&D planning, can be a guide, emphasizing technology pathways that have a higher likelihood of delivering better overall lifecycle GHG emissions reductions (Wender et al. 2014). Lifecycle assessment for BECSS, DACS, and frontier technologies is not yet mature. Federal agencies should make specific investments to develop guidelines, common datasets, and expert communities.
- **Focus on cost reduction.** Detailed cost modeling can help establish cost benchmarks and develop practical metrics for estimating current and future system costs. In the course of allocating limited program dollars, cost reduction potential is an important guide for prioritizing research topics. A second area of techno-economic analysis would be understanding possible supply constraints for technologies that

depend on critical materials or materials that could be rendered critical if demand grew dramatically. Cost analysis should also include the potential role of waste heat and curtailed renewable energy, which might reduce the operational costs of some carbon removal technologies.

- **Seek to advance a suite of carbon removal technologies in an integrated way.** Linking focus areas, targets, and timelines of the RD&D programs across carbon removal technologies can help ensure coordination and learning while recognizing the unique needs of different technologies. For example, if disruptive technical pathways emerged from RD&D on one of the frontier technologies, it would be important to update or evolve the planned directions of research for BECCS and DACS. Doing so can be difficult given bureaucratic inertia, researcher biases, and sunk costs in technology development. Embracing truly disruptive technologies would call for effective management and a commitment to an overall program target rather than technology-specific allegiances within the various RD&D program offices.
- **Balance steady progress with investment in disruptive pathways.** The bulk of program resources in federal RD&D initiatives are generally dedicated to achieving relatively steady but incremental progress toward established technical goals along conventional and well-mapped technology roadmaps. However, good applied RD&D program design generally includes a small investment in disruptive technical pathways that are unconventional and may prove to be technologically infeasible (i.e. have high technical risk) but whose potential payoff in terms of technology advancement and/or cost reduction is high (Azoulay et al. 2018). If successful, disruptive research can change entire technology roadmaps and open new pathways that had previously not been considered or had been examined and rejected as technically unviable. The original model for this form of RD&D is the Defense Advanced Research Projects Agency (DARPA). The Advanced Research Projects Agency-Energy (ARPA-E), the U.S. government agency tasked with promoting and funding R&D on advanced energy technologies, uses this model for energy technologies.
- **Involve multiple agencies.** The DOE could be the primary agency for an RD&D program on carbon removal, given its expertise in CCS technology and implementation of small projects on DACS and BECCS. Other agencies—including the National Science Foundation, the Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), the National Institute of Standards and Technology, the Department of Defense, the Department of Agriculture, the U.S. Geological Survey, and the U.S. Department of the Interior have relevant expertise and have supported or conducted related RD&D in the past (see Box 6). They could also play roles as appropriate within the broader program. The limited and scattered RD&D efforts that are currently under way could be expanded and brought under this larger effort.

Box 5 | Target Setting to Help Drive Progress

Modeled scenarios for global emissions pathways consistent with 1.5˚C temperature rise above pre-industrial levels rely on 5–15 $GtCO_2$ (15th and 85th percentiles) of emissions removed per year by 2050, and 10–17 $GtCO_2$ removed per year by 2100 (Fuss et al. 2018). In scenarios consistent with a likely chance of stabilizing at 2˚C, the models rely on 1–7 $GtCO_2$ of emissions removed per year by 2050 and 7–17 $GtCO_2$ removed per year by 2100.

The global need for carbon removal at the scale highlighted sets the ultimate scale for carbon removal technologies. However, it would be unrealistic to attempt to design a U.S. federal program to achieve these levels in the span of one decade. Instead, an interim target could be set of sufficient magnitude to demonstrate the viability of further scaling of technological approaches to carbon removal as a substantial component of global climate strategy. Possible approaches to setting this target include the following:

- **Technology cost,** expressed as a levelized cost per tCO_2 removed. This cost parallels the levelized cost of electricity generation, which is used as a target for renewable technology and provides a basis for cost comparison of generation technologies. However, a technology cost would be meaningful only if it were based on net CO_2 removal, which often depends on lifecycle factors outside the removal technology itself (e.g., the carbon intensity of a supply chain).
- **Total deployment amount,** expressed as a total capacity for removal (tCO_2/yr) installed. This would measure the potential for removing CO_2 but would not necessarily indicate actual removal if duty cycles or capacity factors were low (similar to the situation with solar and wind capacity).
- **Cumulative amount of CO_2 removed using technological methods,** expressed in tCO_2, would directly demonstrate the capability of carbon removal technology. However, it would not include a cost metric, meaning that it would not necessarily focus attention on achieving economical operation of carbon removal technology.

All three options would need to be considered carefully and the appropriate quantitative values of each parameter set to reflect a threshold likely to lead to the deployment of carbon removal technology at scale.

- **Require a formal coordination structure.** Frequent and substantial interagency coordination would be needed to manage a cross-cutting RD&D initiative. A coordinating authority would help ensure communication among participating agencies and serve as a conduit for interested parties outside the federal government that want to identify opportunities for RD&D funding, federal partnerships on technology demonstration, technology investment opportunities, or policy or analytical input on the overall role of these technologies within broader climate and technology innovation policy. This role could potentially be performed by the Office of Science and Technology Policy (part of the Executive Office of the President) or a dedicated interagency task force.

As with all major federal RD&D, an initiative of this sort would need Congressional authorization for the appropriation of sufficient funds over a sustained period. Several agencies may already have sufficient authorization under their existing statutory language. Explicit congressional authorization to direct relevant agencies to implement specific programs or components would help make carbon removal a priority.

Federal and State Deployment Support

Why Is It Needed?

Many hardware technologies, particularly in energy-related applications, display strong learning effects with deployment, known as "learning-by-doing" (McDonald and Schrattenholzer 2001). For every doubling of the total cumulative amount of deployed systems (measured in megawatts of generation, tCO_2 removal/year, or other appropriate metric), the marginal cost of producing the

Box 6 | Federal Agencies That Could Support Research Related to Carbon Removal

Federal research on CCS and CO_2 utilization technology is housed in the DOE's Office of Fossil Energy. A substantial portion of a federal RD&D initiative on carbon removal technologies could be housed there as well, given the office's expertise in industrial chemistry and CO_2 management.

Several other offices within DOE and other federal agencies have substantial capabilities that are relevant to these technologies and could also be included in such an initiative. Within DOE, they include the Advanced Manufacturing Office (AMO) and the Bioenergy Technologies Office (BETO). AMO has expertise in the scaling of prototypes for manufacturability and knowledge of materials availability issues, and it is familiar with industries (such as pulp and paper) using closely related chemical processes. BETO has expertise in hydrocarbon fuels and chemical separations. ARPA-E is a natural home for disruptive energy-relevant RD&D. The National Laboratories host several tech-to-market programs funded by DOE, such as Cyclotron Road (Lawrence Berkeley National Laboratory), Chain Reaction (Argonne National Laboratory), and Innovation Crossroads (Oak Ridge National Laboratory).

Several DOE Office of Science programs are supporting research that seeks to harness the photosynthetic connection between atmospheric carbon, plants, microbes, and soil (U.S. DOE 2017). For example, ARPA-E recently launched the Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) program, which is developing advanced technologies and deep-root crop cultivars that enable a 50 percent increase in soil carbon accumulation (U.S. DOE 2017).

Ongoing carbonate mineralization–related research cuts across multiple DOE programs, including the Office of Science Geosciences Program; three CCS-focused Energy Frontier Research Centers (U.S. DOE 2017); and the Office of Fossil Energy's Carbon Storage Program Carbon Use and Reuse core program technology area (U.S. DOE NETL 2018).

Outside DOE, many agencies are conducting relevant research:

- NASA is conducting substantial research on CO_2 capture for space applications, including air scrubbing on spacecraft and in situ resource use on Mars (whose atmosphere is 95 percent CO_2).
- The Department of Defense uses CO_2 separation technology for air cleaning on board submarines and has engineering expertise in this application at the Naval Surface Warfare Division (U.S. DOE PNNL 2018).
- The U.S. Navy is conducting research on direct seawater capture of CO_2 (Parry 2016). The U.S. Naval Research Laboratory has developed a research prototype that can simultaneously extract CO_2 and hydrogen from seawater—a process that provides all raw materials needed for the production of synthetic liquid hydrocarbon fuels. The prototype gives the navy the ability to produce fuel stock at sea or in remote locations and has propelled its research into the development of a second-generation prototype (DiMascio et al. 2017).
- The National Institute of Standards and Technology conducts a range of relevant activities, including standards-setting and direct materials research.
- The National Science Foundation supports basic science and engineering research related to CSS, particularly in its Division of Chemical, Bioengineering, Environmental and Transport Systems (NSF 2018).
- The U.S. Department of Agriculture's Agricultural Research Service (ARS) supports a range of research efforts that are relevant to biological carbon removal (particularly BECCS). Scientists from ARS and EPA have also been collaboratively evaluating the potential of biochar to improve degraded soil quality characteristics and impact soil carbon sequestration, plant growth, crop yields, and microbial movement (Novak et al. 2016).
- EPA's Office of Research and Development conducts research on environmental chemistry, ecosystem impacts, and related topics.
- The U.S. Geological Survey's Energy Resources Program conducts research on geological CO_2 utilization and sequestration.

next unit falls by a fraction known as the “learning rate” (Rubin et al. 2015). The decline reflects a complicated interaction of factors, including increased manufacturing experience, the aggregation of many minor innovations, and the standardization and commoditization of supply chains (Kavlak et al. 2017). Government subsidies to support early deployment of target technologies essentially pay for the first few doublings of the total deployed amount, driving down the marginal system costs in accordance with the learning rate (Bollinger and Gillingham 2014). Ultimately, this leads to “Nth-of-a-kind” plant designs that are significantly cheaper than “first-of-a-kind” plants.

This effect could occur for the carbon removal technologies described, because they are based on hardware systems or have components similar to those of other technologies that have displayed learning-by-doing effects. An important unknown is the extent of the learning rate, which strongly influences how rapidly costs can fall in response to deployment-support policies. Determining this would require empirical evidence over at least several doublings of total deployed system size.

Providing federal or state support to drive early deployment of carbon removal technologies would be important, because these technologies generally do not produce a revenue stream, making them unattractive for most private investment. Lack of investment limits deployment and prevents the technologies from beginning to move down the learning curve and benefiting from learning-by-doing effects.

What Would It Look Like?

Transferring the results of RD&D on carbon removal technologies into the market would require a range of policies to support deployment, such as expanded tax incentives (building on the existing Section 45Q Tax Credit), incorporation into existing emissions reduction mechanisms (such as the California Low-Carbon Fuel Standard), and inclusion in federal and state procurement. Nonsubsidy policies, such as the development of interoperability standards and testing protocols, would also be necessary. Supporting deployment through these policies could lead to learning-by-doing, which could drive down technology costs.

The costs of many carbon removal technologies will initially be significantly higher than any potential revenues from selling CO_2 or other products, strongly discouraging private investment. Federal and state policies could reverse this calculus by providing subsidies in various forms to incentivize private investment. Some of the types of policies that could be considered include the following:

- **Federal tax incentives, such as credits, deductions, or accelerated depreciation.** Although these and many other instruments could potentially be useful, the only existing federal tax incentive for carbon removal technologies is the Section 45Q Tax Credit, which provides a credit per tCO_2 captured and used or stored. The provision was expanded in 2018 to include DACS technology in addition to CCS and CO_2 utilization. However, its value is still well below the estimated costs of DACS technologies, and its impact on incentivizing private investment is unclear. Expanding the size, scope, and type of tax incentives on carbon removal technologies could potentially provide important incentives to encourage private investment (see Box 7).
- **Incorporating carbon removal technologies into programs that promote GHG reductions.** Programs that promote GHG reductions—such as cap-and-trade programs, carbon taxes, low carbon fuel standards, and procurement standards—could be designed to recognize the climate benefits certain carbon removal technologies provide. This could help promote private investment for deployment of carbon removal technologies if prices or other incentives are high enough. This could be done at the federal level, or at the state level if states see this as a way to help attract early deployment or in-state investment in these technologies.

Box 7 | Designing Successful Tax Incentives

Designing successful tax incentives would require a careful analysis of the factors that shape investment decisions around these technologies, including the ease of access to capital, the potential for revenue from installed equipment, and the tax appetite of the tax-paying entity. Tax incentives for energy technologies—such as the Section 179D Commercial Buildings Energy Efficiency Tax Deduction (U.S. DOE 2018a), the Business Energy Investment Tax Credit (U.S. DOE 2018b), and the Renewable Electricity Production Tax Credit (U.S. DOE 2018e) have had a variety of impacts and can be studied for insights.

Another factor in federal tax incentives is their longevity. Uncertainty about whether they will be renewed has a major effect on the willingness of private actors to invest capital (Barradale 2010).

Support for Carbon Capture, Storage, and CO_2 Utilization

Why Is It Needed?

Carbon capture technology could be deployed in the near term—including point-source CCS in the power and industrial sectors and in biorefineries. Generally speaking, these technologies would reduce emissions rather than remove CO_2 from the atmosphere. Nonetheless, advancing point-source CCS, including in fossil fuel facilities, could be catalytic for technological carbon removal in several ways:

- Widespread deployment of fossil CCS systems could help reduce CCS technology costs—a crucial initial step for the long-term prospects of deploying BECCS.
- Improvements in sequestration technology, geological site validation, and CO_2 transportation networks to support the deployment of fossil CCS address the same transportation and storage challenges that will affect BECCS and DACS, including permitting for underground injection.[14]
- Fossil CCS deployment could spur learning-by-doing deployment experience for emerging technologies to utilize CO_2. These technologies could provide vital early revenue streams to help offset the cost of CO_2 capture equipment for either point-source or ambient air capture systems.

Achieving the Paris targets will require both point-source CCS and carbon removal (UNEP 2017). CCS technology is more mature than most carbon removal technologies and has received more RD&D funding, but the widespread deployment that would lead to learning-by-doing has not yet begun. It must therefore continue to be a key focus of RD&D and deployment-support policies, in parallel with carbon removal.

CO_2 utilization technologies are relatively immature and have not entered widespread deployment. As they will likely underpin the economic case for some private investment in carbon removal technologies, it will be important to continue to support their development and deployment.

What Would It Look Like?

The primary deployment-support policy for CCS and CO_2 utilization in the United States is the Section 45Q Tax Credit. In addition, as of July 2018, California's low-carbon fuel standard was undergoing revisions that are likely to include CCS. Other areas for additional policy consideration include the following:

- **Continued RD&D on core capture and storage technology.** The DOE RD&D program on CCS would need continued funding support to bring CCS to scale. Research focal points could include advanced catalytic materials, sequestration-site characterization techniques and demonstration of secure storage areas, and enhanced storage techniques (e.g., in situ reactive mineralization).
- **Expansion of the DOE CCS program beyond coal-fired flue gas.** Congressional appropriations language restricts DOE's CCS program to focusing exclusively on coal-fired plants. Given the growth of natural gas in the U.S. fuel mix, CCS for natural gas–fired plants, as well as advanced thermodynamic cycles, is increasingly important and could benefit from enhanced RD&D. Similarly, exploring CCS for biomass-fired or co-fired plants will also be important once fossil CCS becomes more cost-effective. Lifting the congressional restriction and giving the DOE CCS program a fuel-neutral mandate for RD&D could enable better prioritization of effort across the most promising technologies. DOE proposed this change in the FY17 budget request, but it was rejected by Congress.
- **Analysis of the potential for CCS as best system of emission reduction (BSER) at fossil fuel power plants.** In accordance with the Clean Air Act, EPA could analyze whether CCS technology is the BSER for natural gas and/or coal-generating units. If it finds that CCS has been "adequately demonstrated," it could then issue a new source performance standard (NSPS) requiring that all new or modified plants be equipped with CCS technology. A new rule could also then be promulgated to cover existing plants. Individual states could potentially adopt similar standards.
- **Deploy CCS in biorefineries and other industrial facilities.** Carbon capture at ethanol biorefineries presents a potentially lower-cost opportunity for CCS deployment in the United States because the fermentation process produces a near-pure stream of CO_2. Other industrial processes also offer relatively low-cost capture opportunities. CCS in ethanol refineries reduces GHG emissions from the fuel production site but does not necessarily provide net carbon removal, because the biofuel is then combusted without capture. However, mobilizing CCS in these kinds of facilities could catalyze private investment in enabling infrastructure such as CO_2 pipelines and validated sequestration sites, which could facilitate both fossil

CCS as well as BECCS. Congress could achieve this result with a variety of legislative provisions. Additional policy analysis could help identify viable options within the Clean Air Act.

- **Fold CO_2 utilization into cross-cutting federal RD&D and deployment support initiatives for carbon removal.** Although CO_2 utilization does not directly remove CO_2 from the atmosphere, markets for captured CO_2 can help support fossil CCS and carbon removal alike. Although most CO_2 utilization technologies remain immature, some—such as cement, aggregates, and certain chemicals—have reached the early stages of commercial introduction. If utilization opportunities for CO_2 can be expanded, the resulting markets for CO_2 could be beneficial for the development of carbon removal technologies by providing revenue streams for CO_2 removed from the atmosphere. Although the maximum amount of CO_2 that could be utilized across all sectors is much smaller than the total amount of carbon removal that global climate models indicate may be needed, even small amounts of revenue from CO_2 sales could help incentivize important early-stage investments of private capital to drive deployment. Potential priority areas for CO_2 utilization policy include technological development through RD&D, expansion of CO_2 utilization lifecycle assessment studies and standardization, and deployment support using pre-market government procurement and purchasing standards (see Box 8).
- **Establish federal incentives for the construction of CO_2 pipelines.** An extensive network of CO_2 pipelines would be important for both transporting CO_2 to storage sites and enabling a robust CO_2 market for utilization. A variety of policies could support the development of CO_2 pipeline infrastructure, including tax credits, federal loans and loan guarantees, private activity bonds, and related instruments (State CO_2-EOR Deployment Work Group 2017).

Summary

The needs identified for technological carbon removal at scale can begin to be addressed by large-scale RD&D at the federal level; deployment-support policies at the state and federal levels; and renewed efforts to deploy carbon capture, storage, and CO_2 utilization with fossil energy sources. Additional analysis of individual policy measures for consideration could help create a prioritization roadmap and identify the most impactful measures. Although

Box 8 | Potential CO_2 Utilization Policies for Consideration

CO_2 Utilization RD&D

DOE's Carbon Storage Program has four main CO_2 utilization research focus areas: cements/carbonate mineralization, polycarbonate plastics, chemicals, and enhanced hydrocarbon recovery. In 2017 DOE added 12 new projects, at a total funding of approximately $10 million, to investigate novel uses of CO_2 captured from coal-fired power plants (U.S. DOE 2018c, 2018d). DOE could expand these focus areas to include improved catalytic materials and process integration to reduce overall energy requirements and capital costs. It could also add a focus area to support applied research on utilizing CO_2 to produce durable carbon materials such as carbon fibers. These materials offer long-term carbon storage solutions and are very high value, but they are at least a decade away from being technologically mature enough for commercialized market deployment. DOE could also expand RD&D into CO_2 utilization technologies that can accept lower-purity CO_2 streams. Doing so could create markets for CO_2 removed from the atmosphere that are mixed with other gases, significantly lowering energy requirements for DACS.

Lifecycle Assessment

CO_2 utilization processes consume energy and in most cases additional feedstocks beyond CO_2. As a result, the net emissions reduction could be less than the amount of CO_2 utilized and can even result in a net increase of emissions relative to simply forgoing capture and utilization altogether. GHG lifecycle impacts are, however, distinct for each CO_2 utilization process, as well as the marginal CO_2-intensity of the energy used to drive it, and are not well understood. Although International Organization for Standardization (ISO) standards and guidance for lifecycle assessments exist, there is no universally accepted evaluation approach (Sandalow et al. 2017). A robust framework could help determine whether a certain use of CO_2 could bring about an overall reduction in emissions, or net-negative emissions, relative to an alternative and to quantify those benefits. Federal support could be used for lifecycle analysis research and the development and harmonization of standardized lifecycle analysis methods. DOE and the National Institute of Standards and Technology could be the lead agencies.

Pre-market Government Procurement and Purchasing Standards

Some CO_2 utilization products, particularly building materials, have entered early commercialization. Federal and/or state governments could provide deployment support for these products by mandating that products made with captured CO_2 be included in procurement for construction projects supported with public funds. Doing so would require that these products be included in the standards developed by various certification bodies (e.g., ASTM) and that a sufficient supply chain exists, to avoid creating mandates that cannot be fulfilled. If these preconditions are established, this form of purchasing requirement could support the growth of companies using CO_2 utilization technologies and signal to developers and manufacturers of products that there is an assured market. It could also help encourage the development of technical standards and regulatory evaluations for acceptance of innovative materials into the market.

these measures could help advance the maturity of carbon removal technologies and develop the needed initial scale of experience to help them reach more cost-effective thresholds, government subsidies alone are likely to be insufficient. Policies such as broader regulatory mandates or carbon pricing mechanisms for incentivizing private capital are also likely to be needed to deploy carbon removal technologies at meaningful scale on a sustained basis.

CONCLUSION

The large majority of modeled scenarios indicate that ambitious emissions reductions alone will not be enough to have a likely chance of achieving the Paris Agreement targets, which aim to avoid the worst impacts of climate change. These models illustrate that not only ambitious emissions reductions but also the removal of CO_2 from the atmosphere is needed. A wide set of natural and technological carbon removal approaches are being explored for their ability to remove CO_2 from the atmosphere at large scale.

This working paper examines candidate options for technological carbon removal in the United States, including BECCS, DACS, and frontier technologies. Its main findings can be summarized as follows:

- **BECCS.** BECCS can take many forms. Some of them (e.g., using waste feedstocks) could provide net carbon removal in a way that safeguards food security and natural ecosystems. However, its prudent deployment is likely to be significantly constrained with appropriate safeguards in place. Developing capabilities for deploying BECCS at a large scale would require addressing needs related to the cost of CCS technology, CO_2 transport and storage infrastructure, and better understanding climate benefits and ancillary effects.
- **DACS**. The technical potential of DACS is significant, but its potential is limited by current costs and intensive energy requirements. Deploying DACS at a large scale would require addressing needs related to the cost of the technology, CO_2 storage infrastructure and utilization markets, and the availability of low-carbon energy.
- **Frontier technologies.** Frontier technologies could potentially play a role in carbon removal, but their utility and efficacy for carbon removal is nascent. Additional RD&D are needed to help build sufficient knowledge, uncover frontier technologies that may be viable for carbon removal, and identify new technologies.

Deploying these approaches at scale would require addressing these needs through significant and sustained policy investments. Three broad categories of action could begin to do so:

- RD&D
- Deployment-support policies
- Advancements in fossil fuel carbon capture, storage, and CO_2 utilization technologies that could be catalytic for carbon removal technologies

Additional analysis would be needed to create a prioritization roadmap to identify the most impactful measures and estimate the cost of these prospective public investments.

ENDNOTES

1 Net-zero emissions is achieved when there is a balance between anthropogenic GHG emissions and removals of GHG emissions from the atmosphere by enhanced action to sequester it in carbon sinks (e.g., increased reforestation to sequester more CO_2 in vegetation).

2 For simplicity, this paper uses "carbon removal" to mean removal of carbon dioxide.

3 In many ways BECCS is a hybrid approach, with natural and technological aspects, as it involves converting biomass to energy and capturing and storing the carbon emissions. This paper treats it as a technological approach to carbon removal.

4 These approaches have been classified as technological because they are biotechnological manipulations.

5 The Decatur facility makes a variety of products out of corn, including ethanol and other products that rely on fermentation. If BECCS is defined as including capture from ethanol, this facility could be classified as BECCS.

6 It would also be beneficial for further research to account for the distance to use and implications of remote harvesting.

7 The Department of Energy's Billion-Ton Report explores potentially available biomass feedstocks in the United States (https://www.energy.gov/eere/bioenergy/2016-billion-ton-report).

8 Climeworks is working on combining direct air capture and storage; the other companies are not storing the carbon and are instead using it in other applications. There are also some smaller companies and research units that are pursuing early DACS research efforts.

9 House et al. (2011) estimated the costs to be \$1,000/tCO_2. They did not examine a particular DACS design but instead theorized costs based on thermodynamic efficiencies. Because more recent estimates are available for specific system designs, we do not include the House et al. estimate.

10 1 $GtCO_2$ is 1 billion tCO_2. At 8.81 GJ/tCO_2, total energy requirements would be 8.81 billion GJ. Total U.S. primary energy consumption in 2017 from renewable energy and nuclear electric power was 11.0 and 8.4 quadrillion British thermal units (Btu), respectively, or roughly 20.4 billion GJ (combined); 8.81 divided by 20.4 is equal to 0.43 (i.e., 8.81/20.4 = 0.43).

11 The levelized cost of electricity (LCOE) is the net present value of the total cost of building and operating a power plant over its lifetime.

12 The literature provides rough estimates of cost for enhanced weathering and biochar (Minx et al. 2018). In some cases it may be feasible to develop reliable cost estimates for specific pilot projects or types of deployment. However, as the pathways to large-scale deployment for these technology categories remain uncertain, cost estimates are not presented here. Instead, this chapter focuses on the needs for continued technological development and study.

13 Enhanced weathering processes are also known as accelerated weathering, mineral carbonation, and reactive minerology.

14 EPA is tasked with permitting all Class VI wells (injection wells intended for geological storage of CO_2). The application process for acquiring a Class VI permit at the federal level is lengthy, creating regulatory risk.

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.