A CLOSER LOOK

CARBON DIOXIDE REMOVAL: PATHWAYS AND POLICY NEEDS

C2ES CLIMATE *INNOVATION* 2050

by

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Achieving net-zero emissions will require large scale change across all sectors of the economy, and efforts to drive this transition are intensifying. Over the past several years, through the Climate Innovation 2050 initiative, the Center for Climate and Energy Solutions (C2ES) has engaged closely with leading companies across diverse sectors to examine challenges and solutions to decarbonizing the U.S. economy by 2050. As we laid out in *Getting to Zero: A U.S. Climate Agenda*, reaching net-zero will require this large-scale change, but it will also require us to address a number of discrete and urgent challenges. To inform policymakers considering these near- and long-term questions, C2ES launched a series of "Closer Look" briefs to investigate important facets of the decarbonization challenge, focusing on key technologies, critical policy instruments, and cross-sectoral challenges. These briefs will explore policy implications and outline key steps needed to reach net-zero by mid-century.

EXECUTIVE SUMMARY

Carbon dioxide removal (CDR) solutions will likely be needed to achieve global climate objectives, though deployment of CDR is not a substitute for cutting emissions. For large CDR projects to be realized at scale by mid-century, an unprecedented level of development and deployment must start taking place now. CDR solutions include both nature-based approaches (e.g., afforestation, reforestation, biochar, soil carbon sequestration) and technological and industrial approaches (e.g., bioenergy with carbon capture and storage, direct air capture).

Whether CDR solutions can scale to the levels that studies suggest are needed to have a significant impact on climate mitigation depends on numerous factors, including: the potential a given technique or technology has to remove carbon dioxide from the atmosphere; cost effectiveness; level of readiness to be deployed; scalability; how quickly the carbon sink reaches capacity; permanence of the carbon removals; and other benefits and challenges. Nature-based solutions are largely affordable and ready now and will be of importance in both the near and long term. Technological solutions may be more

scalable and more permanent but must continue to be developed and deployed. Given the variation in removal potential, cost, readiness, and other factors, a portfolio of CDR solutions will be needed to maximize the chances of meeting climate targets. Policy can play a vital role in making such a portfolio a reality.

Policies that can help remove economic and technological barriers for large-scale deployment of CDR solutions include the following:

- **Research, development, and demonstration funding:** Government RD&D funding programs can make a huge difference in the costs and deployment levels of technologies. The size of the federal RD&D budget dedicated to CDR should better reflect its potential economic and climate benefits.
- **Carbon pricing and standards:** Policies that institute a robust carbon price or carbon constraint could boost CDR's cost competitiveness. Additional policy mechanisms will also likely be needed to accelerate the deployment of CDR technologies, such as a federal Clean Energy Standard that permits CDR projects to contribute in limited and targeted ways to an overall clean energy target.
- **Infrastructure:** The need for supporting infrastructure presents a key constraint on the scalability of several CDR approaches, particularly the technological solutions. Federal infrastructure policies should address siting, permitting, and investment needs for carbon dioxide pipelines and sequestration sites.
- **Market creation:** Policies can create demand for CDR technologies (and other carbon capture and storage technologies) by fostering markets for utilization of the captured carbon dioxide, such as through government procurement policies and building codes.
- **Life cycle analysis and environmental monitoring:** To foster public trust and long-term support for CDR, it is critical to establish rigorous and credible life cycle analyses for a variety of removal solutions. Real-world impacts also have to be tracked, which means monitoring, reporting, and verification will be critical.
- **Integrity of storage:** The integrity of geologic storage will be another key enabler for sustained public support for CDR. Policies are needed to ensure secure geologic storage and to reduce uncertainties related to long-term carbon storage and liability.

A continued focus on reducing emissions, paired with policies that can help ensure that CDR solutions are available at the scales necessary, will be critical to meeting the global challenge of climate change.

INTRODUCTION: CARBON DIOXIDE REMOVAL IN A NET-ZERO FUTURE

Given the strong likelihood of continued carbon dioxide emissions from hard-to-decarbonize sectors, carbon dioxide removal (CDR) methods will likely be needed to produce the "negative emissions" required to achieve economy-wide carbon neutrality (and then carbon negativity). A number of recent studies—including the landmark 2018 Intergovernmental Panel on Climate Change (IPCC) special report on global warming of 1.5 degrees C—have emphasized the need for carbon dioxide removal to reach global climate objectives and avoid the most severe consequences of climate change.[1] All IPCC mitigation pathways that limit global warming to 1.5 degrees C by 2100 with no or limited overshoot project the use of on the order of 100–1000 gigatons of carbon dioxide ($GtCO_2$) of CDR by the end of the century. 100 gigatons, or 100 billion tons, of carbon dioxide is almost equivalent to the total U.S. emissions of carbon dioxide from 1990 to 2010.[2] The National Academy of Sciences, in turn, has estimated that to meet the Paris Agreement goals, 10 gigatons of carbon dioxide will need to be removed globally each year through 2050, with 20 gigatons of carbon dioxide removed each year from 2050 to 2100.[3] Likewise, the UN Environment Programme estimated that CDR needs to be deployed with a very rapid scale-up to 8 gigatons of carbon dioxide per year by 2050 with a projected cumulative removal of 810 $GtCO_2$ by 2100 (*see* **Figure 1**).[4]

For large CDR projects to be realized at scale by mid-century, an unprecedented level of development and deployment must start taking place now. This paper focuses on the key categories of potential CDR solutions that are being or need to be deployed in the near term.

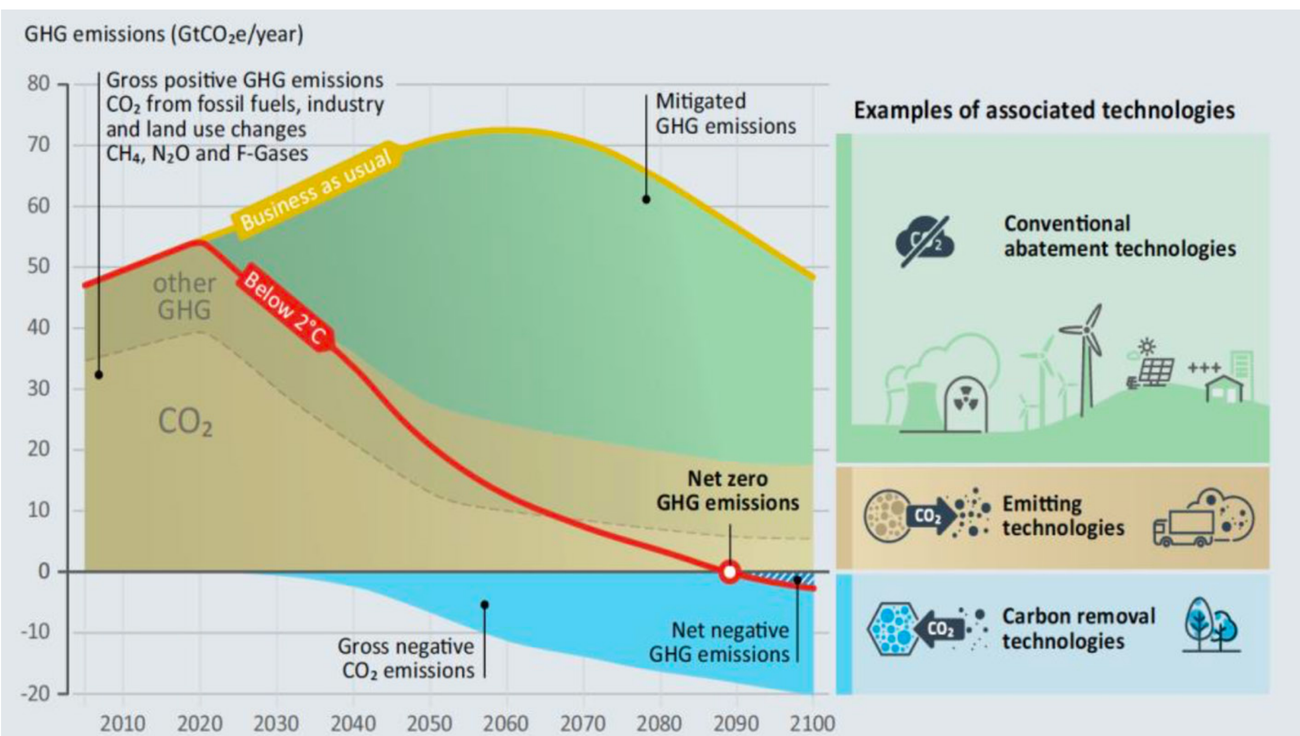
These solutions include both nature-based and technological approaches.

- ***Nature-based solutions*** include afforestation, reforestation, biochar, and soil carbon sequestration. Some nature-based solutions (namely regenerative farming practices that enhance soil carbon sequestration) are already regularly practiced by farmers because of their benefits to soil fertility and productivity. Nature-based solutions can also support resilience efforts in rural communities across the United States. The scale of deployment, though, is still small compared to their removal potentials. Realizing this potential will require clear policy support and significant investment.
- ***Technological and industrial approaches*** include bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC). The scale of the carbon removal challenge in the United States and the rest of the world suggests that developing scalable technological solutions such as BECCS and DAC will be essential to reaching sufficient levels of carbon dioxide removal. Carbon removal technologies will need both policy and public support to reach the needed levels of deployment. Policies that support CDR technologies can boost the competitiveness of U.S. industries while creating opportunities for U.S. companies to develop carbon removal technologies that could be exported across the globe.

Other approaches to remove carbon dioxide such as enhanced weathering and solutions in marine environments (e.g., ocean fertilization, coastal management, wetlands restoration)—which are still in earlier stages of research or are far less commercially viable—are not covered in this paper, though they, too, need greater research and policy support.

Characterizing the variety of CDR approaches is the first step toward developing a fuller understanding of their ramifications and of the policies needed to advance them. This paper examines and characterizes key nature-based and technological CDR solutions as a part of a comprehensive U.S. climate strategy to meet the Paris Agreement goals. Whether CDR solutions can scale to the levels that studies suggest are needed depends on numerous factors. This paper uses several assessment

FIGURE 1. How much carbon removal is needed to meet Paris Agreement goals?



Source: UNEP 2017

criteria—including removal potential, economic costs, level of readiness, and other benefits and challenges—to evaluate the potential role of different CDR technologies and techniques in climate change mitigation. This paper then concludes with policy recommendations that can help remove economic and technological barriers for large-scale deployment of CDR solutions.

While this paper explains the potential and the importance of CDR, it cannot be emphasized enough that deployment of CDR is not a substitute for cutting emissions. Its availability should not justify delaying ongoing decarbonization efforts, which remain an urgent priority. Transformative changes will be needed across the economy and must take place *alongside* CDR to meet long-term climate goals. The scale of the crisis requires utilizing every tool available.

KEY CRITERIA FOR EVALUATING CDR SOLUTIONS

Generally, the process of carbon removal involves two stages:

1. Capture of carbon dioxide from the atmosphere.
2. Storage of the captured carbon dioxide in a way that prevents it from being released back into the atmosphere for an extended period of time.

While there are different ways to categorize CDR solutions, they can be simply categorized according to their capture/removal mechanism—i.e., nature-based solutions and technological solutions. Nature-based solutions—involving trees, plants, and soils—increase the biological uptake of carbon dioxide by increasing natural "sinks" or improving natural processes and practices. Nature-based solutions combine the capture and storage processes within the natural carbon cycle. Technological solutions, in contrast, utilize separate processes to first capture the carbon dioxide and then store it in dedicated geological reservoirs or long-lived materials**. Table 1** shows different CDR pathways with their removal and storage techniques.

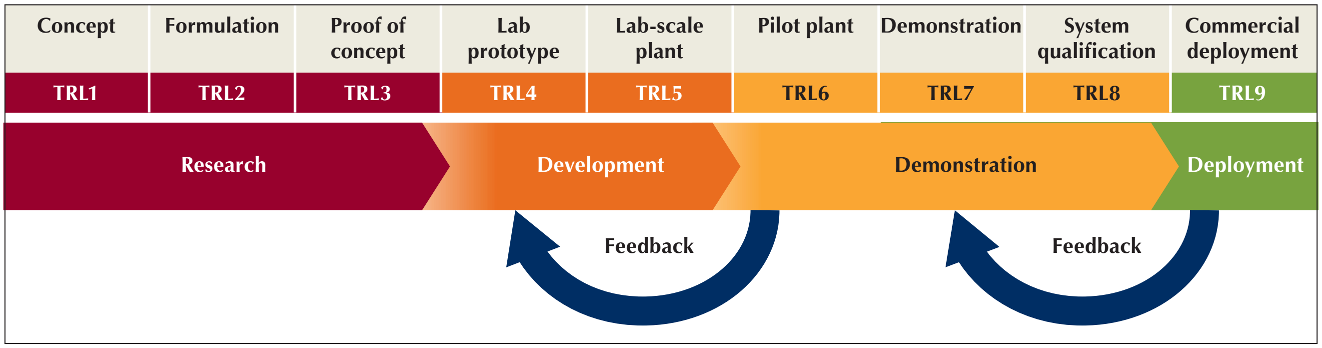
To assess the role of different CDR approaches in a comprehensive decarbonization plan, this paper considers their respective potentials and identifies barriers for large-scale deployment. In particular, specific criteria applied to the different CDR pathways include the following:

- **Removal potential—**How much carbon dioxide a given technique or technology can remove from the atmosphere is vitally important to addressing climate change. Removal potential is generally expressed in megatons of carbon dioxide (or, when other greenhouse gases are also involved, of carbon dioxide equivalents (CO_2e)) that could be removed per year, as well as in terms of the overall capacity (in gigatons) that can be stored by a given date.
- **Economic costs—**The cost-effectiveness of different approaches (i.e., the bang for the buck) is a key consideration. To be able to compare the costs of different approaches, economic costs are generally expressed in terms of dollars per ton of carbon dioxide removed.

TABLE 1. Carbon dioxide removal pathways categorized by their removal and storage techniques

PATHWAY/SOLUTION	REMOVAL TECHNIQUE	STORAGE MECHANISM
NATURE-BASED		
Afforestation/Reforestation	Growth of woody biomass	Standing forests and long-lived wood products
Biochar	Growth of plant biomass or utilization of agricultural waste for pyrolysis and application of char to soils	Black carbon
Soil carbon sequestration	Increase in soil organic carbon content via various land management practices	Soil organic carbon
TECHNOLOGICAL		
BECCS	Growth of plant biomass to generate energy and capture and store the resulting carbon	Geological sequestration
DAC	Chemical reactions employing reversible sorbents to capture carbon dioxide from ambient air, followed by storage	Geological sequestration

FIGURE 2. Flow of technology advancement and the associated Technology Readiness Level (TRL)



Source: U.S. National Aeronautics and Space Administration, Technology Readiness Level, October 2012. Accessed July 14, 2020

- **Level of readiness—**Time is of the essence in addressing climate change, so how ready CDR approaches are to be deployed must be a factor. The readiness criterion is of particular relevance to technological solutions, which are, generally speaking, less widely deployed than some nature-based counterparts. **Figure 2** illustrates the system of technology readiness levels (TRLs) commonly used for technology assessments.
- **Scalability—**CDR approaches do not just have to be deployed quickly; they also have to be deployed at scale in order to remove a sizeable amount of carbon dioxide. It is therefore important to consider how feasible it is for a CDR approach to achieve wide-scale deployment.
- **Sink saturation—**Once a CDR project is deployed, it can achieve carbon removals only until its sink or storage location for the captured carbon dioxide is full. It is helpful to consider how long any given type of CDR project will be providing removal benefits.
- **Permanence—**Removing carbon dioxide from the atmosphere is only part of the challenge; it also has to stay stored/removed from the atmosphere for an extended period of time. The relative permanence of carbon dioxide removals—i.e., how easily removal/storage gains might be reversed—is thus of great relevance in evaluating CDR approaches.
- **Other benefits, co-benefits, and challenges—** Numerous other impacts and considerations can either enhance the appeal of a particular CDR approach or hinder its deployment, and these must be taken into account as well.

CDR SOLUTIONS

NATURE-BASED SOLUTIONS AND ENHANCED NATURAL PROCESSES

As trees and plants grow, they absorb carbon dioxide from the atmosphere and store it as carbon in living biomass and soils. Increasing the biological uptake of carbon dioxide has always been an attractive approach to addressing climate change, especially as it offers a low-cost solution with a range of co-benefits.

Afforestation and Reforestation

Afforestation refers to the process of planting trees and forests in areas that historically did not have forests, while reforestation refers to the process of replanting trees in areas where existing forests have been depleted.

Potential

The removal potential of afforestation and reforestation (AR) is massive, though there is a great degree of variation across studies on AR's projected removal potential in the United States. The variation mainly stems from the underlying assumptions and methodologies in each study, including the impact that carbon prices might have on the deployment of AR. At, for instance, a $50/ ton carbon price, studies estimate forest sequestration ranging from about 73 megatons to 200 megatons to as much as 800 megatons.[5] Most estimates range from 80–390 megatons of carbon dioxide equivalent ($MtCO_2e$) per year (with a carbon price in the range of $25–$50 and a 25% increase in forest area by 2050).[6]

The removal potentials estimated in studies such as these are by no means the same thing as real-world potential, given a range of other factors and considerations (some of which are described further below) that constrain AR's potential. Even studies that consider such constraints suggest substantial removal potential.[7]

Cost

Afforestation and reforestation are low-cost removal solutions, especially when compared to other approaches. Most cost estimates for AR are in the range of $5-50/ton of carbon dioxide.[8]

Readiness

Thanks to a high level of knowledge and experience in their respective practices, afforestation and reforestation are already being deployed and are ready for further adoption. That means these solutions are primed to help now, while work continues to deploy more permanent, engineered solutions at scale.

Scalability

The main limitation on the scalability of afforestation and reforestation is competition for land. Simply put, not everywhere that could be forested will be forested because other competing land uses have value as well, and the economic costs and consequences of a change in land use could be significant. For example, land conversion from agriculture to afforestation could affect food production and result in higher costs for agricultural goods.[9]

Sink saturation

The removal pace of AR will be relatively slow as trees need to grow to their full potential. It takes forests approximately 10 years to ramp up to the maximum sequestration rate. As the trees grow and get closer to maturity (around 20 to 100 years, depending on the species), their biological uptake of carbon dioxide starts to slow down. Once trees reach their saturation level in terms of carbon dioxide, they no longer result in net carbon removal.

Permanence

Trees sequester carbon dioxide in their trunks, roots, and so forth, and it remains there, even if additional removals have ceased. Even if a tree is harvested, the stored carbon remains in the wood or wood product until it is burnt or decays.

There is always a concern, though, over the degradation or destruction of forests due to natural or human disturbances. Fires, in particular, can release much of the carbon that had been stored. The increasing intensity and frequency of wildfires, as well as forest decay due to invasive pests, means management of afforested and reforested areas is essential to retain their carbon capture benefits long-term.

Benefits and co-benefits

AR can have a range of beneficial impacts on the environment, depending on management practices and local ecosystem conditions. For example, replacing degraded land with forests could enhance biodiversity, improve soil quality, reduce flooding and erosion, and increase ecosystem resilience to climate events.

Challenges

While AR can have environmental benefits, large-scale deployment could also pose potential risks to soil and water. For example, it is uncertain how large AR conversion rates could affect soil organic carbon, nutrient cycling, and water consumption.

Furthermore, for a project to provide true carbon removal benefits, it should be additional to the baseline (i.e., what would have occurred anyway), and this "additionality" presents a key challenge for AR—and, indeed, for all nature-based solutions. For an AR project, additionality implies that a land use transition to forested land would not have occurred under business-as-usual practices, but it can be hard for AR projects to demonstrate this because of the low quality of available data on historic deforestation. Also, previous practices might have included rotational considerations (i.e., planting a sequence of different crops in the same field) that can have removal benefits which makes it harder to estimate the true GHG benefits of AR projects.

Another challenge facing AR is that tree planting does not necessarily equate to creating a biodiverse forest. If not properly designed, incentives for large-scale afforestation and reforestation can result in monoculture plantations designed to sequester as much carbon as possible without considering the importance of diverse forests ecosystems. That may have some climate benefits, but such monoculture plantations might lead to depletion of adjacent water resources due to changes in the hydrological cycle and substantial biodiversity losses. Inadequate management can also lead many planted tree saplings to die; careful forest management is a necessity for a long period after the actual afforestation or reforestation process.

In addition, the land use competition mentioned earlier means that even if an AR project is successfully implemented, it could have negative ramifications on land elsewhere. For example, AR incentives can shift agricultural production to other regions, including potentially clearing forested land elsewhere to create new cropland. This "leakage" problem can reduce or eliminate the removal benefits intended by the original project.[10]

Biochar and soil carbon sequestration

Biochar is a charcoal-like substance produced via pyrolysis (i.e., the thermal decomposition of organic material in the absence of oxygen). Biochar production converts biomass that might otherwise decay into a form that is relatively resistant to decomposition. When added to the soil, biochar stores carbon in a stable form that prevents it from leaking into the atmosphere.

Soil carbon sequestration refers to the process of removing carbon dioxide from the atmosphere by changing land management practices in a way that increases the carbon content of the soil. Since the level of carbon in soil is a balance of carbon inputs (e.g., from leaf litter, residues, roots, manure) and carbon losses (mostly through respiration, increased by soil disturbance), practices that either increase inputs or reduce losses can promote soil carbon sequestration.

Potential

Biochar has the potential to remove up to 95 MtCO_2e per year[11] in the United States, the equivalent of nearly all carbon dioxide emissions from power plants in the New England and Pacific regions combined.[12] This estimate takes into account crop cultivation, biochar production by pyrolysis, and carbon sequestration by biochar used as a soil improver.

The use of cover crops is one of the main strategies to increase soil carbon. Replacing conventional growing practices with cover cropping on the 88 million hectares of land used to cultivate the United States' five primary crops the presents a substantial carbon removal opportunity of 103 MtCO_2e per year.[13] Adoption of no-till or organic farming practices have also been shown to create carbon storage benefits, although it is likely best to consider this storage as a co-benefit of these practices, given challenges with permanence and carbon accounting.[14]

Cost

Cost estimates for biochar vary significantly. Some studies estimate an abatement cost as low as $30/ton of carbon dioxide, while others have higher estimates up to $120/ton of carbon dioxide.[15] It is challenging to estimate abatement cost for soil carbon sequestration since these processes vary greatly by context, type of practice, labor costs, and degree of mechanization. Some studies note that 20 percent of the removal achieved by soil carbon sequestration can even be associated with savings up to $45/t$CO_2$e, while about 80 percent can be realized at costs between $0-10/t$CO_2$e.[16] Other studies have higher estimates for removal potentials assuming higher carbon prices ($20-$100/tCO_2e) that could encourage further adoption of soil carbon sequestration practices.[17]

Readiness

Biochar is an established technology that has been used in some form for thousands of years, but is not yet widely applied.

Soil carbon sequestration is also ready for deployment. Many of the agricultural and land-management practices required are well known by farmers and mostly do not require significant machinery or infrastructure upgrades. Like AR, this makes soil carbon sequestration well-suited to provide near-term climate benefits while work continues to develop engineered solutions at scale.

Scalability

In order for biochar to be deployed at large scale, the infrastructure, especially pyrolysis facilities, will need to ramp up significantly, which would also bring down costs of production. In addition, the quantity of biomass available for biochar production is a limiting factor; biochar competes with other applications (e.g., combined heat and power (CHP), BECCS) for a limited amount of biomass, which can make large-scale deployment of biochar more challenging.

Although regenerative soil management practices are well known, a lack of policy and financial incentives can delay large-scale adoption of practices that could enhance soil carbon sequestration. For example, the annual cover crop survey by the Sustainable Agriculture Research and Education (SARE) program and the Conservation Technology Information Center (CTIC) found that cost share/incentive programs were the top factor non-users said would influence adoption.[18] In addition, there is still a need for large demonstration projects to build confidence that such practices can be adopted without incurring substantial costs.

Sink saturation

Further research is needed to estimate the time needed for biochar to reach saturation, but analysis of various studies on the stability and decomposition of biochar suggests a saturation limit on the scale of several centuries.[19] However, these estimates vary based on soil type and pyrolysis temperature.

Soil carbon sequestration, like AR, locks away carbon until the carbon sink is saturated, which occurs within 10-100 years depending on soil type, climate zone and other factors. The IPCC uses a default saturation time of 20 years.[20]

Permanence

The inert carbon of biochar makes it very stable, which is essential for its longevity in soil after application (more than 100 years).[21] The stability of biochar in the soil provides a greater degree of permanence than many other nature-based solutions because of its extremely slow rate of decomposition.[22] Therefore, biochar should remain in the soil for as long as possible to achieve long-term carbon storage.

The main drawback for soil carbon sequestration is the reversibility of carbon storage if the practices that led to sequestration cease to be utilized. For example, if cover crops are no longer used on a field, soil respiration would ramp up, increasing carbon losses. Soil tillage and erosion may also have negative effects on soil's carbon capture ability, with precise impacts depending on soil type and other environmental factors.[23]

Benefits and co-benefits

Biochar can enhance soil fertility and productivity. Some studies suggest that crop productivity increases by 10 percent on average following biochar soil amendment.[24]

Soil carbon sequestration can also help enhance soil health, crop yields, and yield consistency. In addition, although soil carbon sequestration is applied on large land areas, it can be applied without major concerns over changing land use, as well as with almost negligible water and energy footprints.

Challenges

Since biomass can be used as a fuel, its conversion to biochar and burial forgoes some of the potential energy uses available. In addition, large-scale biochar application can darken the soil surface, which will decrease the amount of sunlight reflected from the soil without being absorbed (i.e., surface albedo) and lead to changes in the land surface radiation balance.

As noted earlier, soil carbon sequestration projects can cease any new carbon removal after 20 years of implementation, but they will need to be maintained indefinitely, considering the reversible nature of soil carbon sequestration.

TECHNOLOGICAL SOLUTIONS

Bioenergy with carbon capture and storage (BECCS)

Bioenergy with carbon capture and storage (BECCS) is the process of using biomass to generate energy, capturing the released carbon dioxide, and storing it in underground geologic formations (or potentially utilizing it to make long-lasting products). Biomass includes both dedicated energy crops and waste (e.g., from forestry, agricultural, and municipal sources). CCS refers to the suite of technologies that capture carbon dioxide from the exhaust of power plants or industrial sources, transport it in dedicated pipelines, and store it in deep geologic formations. (When considering captured carbon that is utilized rather than stored, a "U" is sometimes added into the acronym: CCUS.)

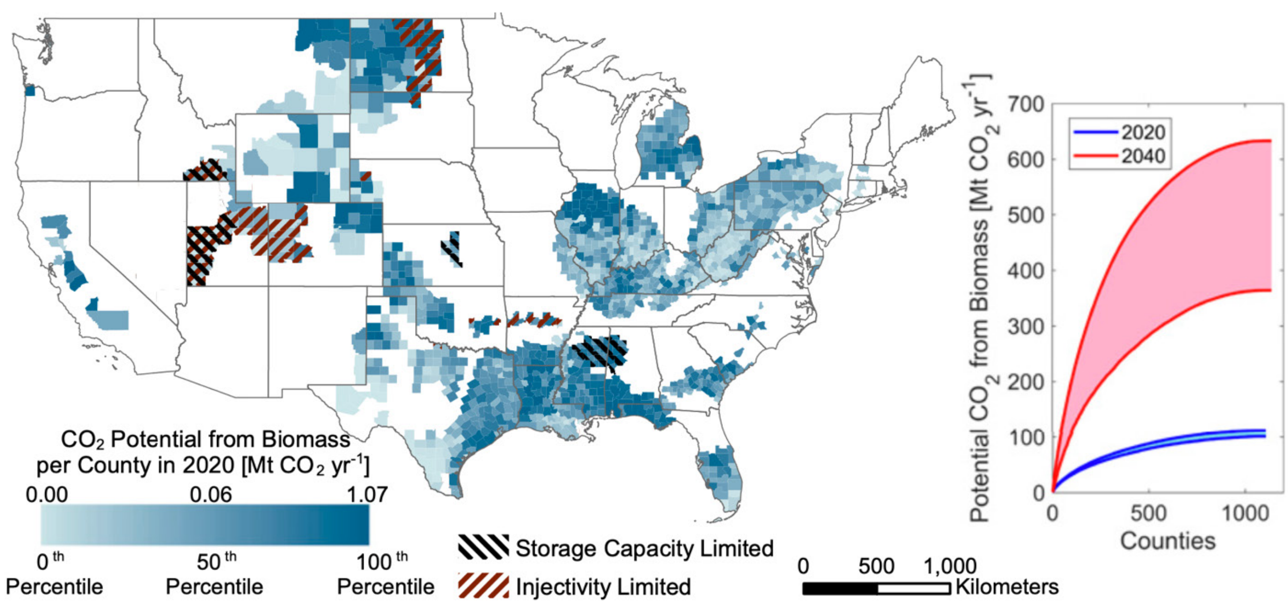
Potential

Fully realized, the total biomass currently available in the United States could result in removal of 370–400 $MtCO_2e$ per year.[25] However, the carbon removal potential of BECCS in the United States is constrained by the absence of transportation networks between sourced carbon dioxide and storage sites. A near-term solution could be to focus on regions where biomass resources are co-located with storage basins that have suitable storage and injection rate capacities. This could result in the removal of 100–110 $MtCO_2e$ per year with the possibility of expanding that to 360–630 $MtCO_2e$ per year by 2040. Regions with highest CO_2 potential and co-located suitable storage sites are the northern Illinois basin, the Gulf region, and western North Dakota (see **Figure 3** below).[26]

Cost

Cost estimates of BECCS vary widely depending on the accessibility of biomass, the suitability of various types of industrial plants, and the distance to storage sites. For example, cost estimates for carbon dioxide capture from ethanol fermentation in a typical plant in the Midwest can be as low as $14–$30/ton of carbon dioxide, but the majority of midwestern biorefineries are not co-located with suitable sites for geologic sequestration.

FIGURE 3. Distribution of technical potential of BECCS in the US



Left: carbon dioxide availability from U.S. biomass in 2020, Right: Cumulative sum of the potential carbon dioxide removal in counties with a suitable storage site for 2020 and 2040. While storage capacity is generally considered abundant, injection rate capacity is an important limiting factor to consider for geologic storage. Injection rates should not exceed the injectivity limit of a particular geologic formation to avoid creating fractures in the confining formation which can lead to leakage.
Source: Baik et al., 2018

Sixty percent of current nationwide biorefinery capacity requires pipeline transport to basins in Illinois, the Dakotas, Wyoming, or Kansas.[27] Combustion BECCS has higher cost estimates ranging from $88–$288/ton of carbon dioxide.[28] Transport costs, in turn, could be in the range of $10-$20/ton of carbon dioxide depending carbon dioxide transport networks' capacity and length.[29] Estimates for the overall net removal costs for different BECCS technologies, including land requirements for biomass, transport, and storage, are generally in the range of $40-$130/ton of carbon dioxide.[30]

Readiness

Although bioenergy and CCS are each relatively mature technologies, in combination they have seen very little demonstration at commercial scale (e.g., the Illinois Basin-Decatur Project, described below). BECCS technologies currently have TRLs ranging from 3-7.[31] While BECCS for combustion and co-firing (i.e., a power plant) is associated with a TRL of 3-6, BECCS for ethanol fermentation has a TRL value of 5-7. (See Figure 2, earlier, for a review of the TRLs.)

Scalability

The scalability of BECCS faces two main challenges—the need for ramping up production of biomass to be used as a feedstock and the need to accelerate deployment of carbon dioxide transport and storage infrastructure.[32]

With regard to biomass production, most of the total potential biomass available for BECCS in the United States is agricultural residue or harvested and residual woody biomass.[33] There are other uses (e.g., biochar, ecosystem services) competing for that biomass. Likewise, to the extent BECCS relies on energy crops, there are other competing uses for that cropland, and switching to energy crops or creating pressure to convert other land uses to cropland could have impacts on food prices and biodiversity.

The lack of spatial co-location of biomass availability and suitable carbon dioxide storage basins, as noted earlier, could also constrain the deployment of BECCS. Scaling BECCS will require long-distance biomass and/or carbon dioxide transport systems—to move biomass to the bioenergy facility and to move carbon dioxide from a capture facility to a storage facility—as well as further development of carbon dioxide geologic sequestration sites.

Sink saturation

The United States has at least 2,600 billion metric tons of possible carbon dioxide storage resource in saline formations, oil and gas reservoirs, and unmineable coal seams. [34] This translates into potentially storing hundreds of years' worth of industrial greenhouse gas emissions.

Permanence

Assuming suitable storage sites, the carbon dioxide captured from BECCS facilities can be permanently stored in deep geologic formations. Decades of experience with geologic sequestration of carbon dioxide have demonstrated that injected carbon dioxide can be safely stored at suitable sites, essentially in perpetuity, with minimal risk of leakage or release.[35] Injection rates must be considered and closely monitored during carbon dioxide operations, as carbon dioxide injection pressure needs to remain lower than the fracture pressure of the underground storage reservoir to avoid creating fractures or activating faults that might lead to carbon dioxide leakage. Still, project developers need to continue to develop technical capacity in geologic storage site characterization and reservoir monitoring. For instance, the Illinois Basin-Decatur Project (IBDP) injected approximately 1 million metric tons of carbon dioxide derived from biofuel production into the Mt. Simon Sandstone Saline Reservoir, in Decatur, Illinois. Operational injection started in November 2011 and was completed in November 2014. The IBDP effort is currently conducting post-injection monitoring.[36]

Benefits and co-benefits

BECCS is a unique CDR solution as it can be utilized to generate energy—such as ethanol, electricity, or potentially hydrogen—while also removing carbon from the atmosphere. BECCS creates the possibility of producing carbon-negative energy.

In addition, captured carbon dioxide can be utilized in different industrial applications. Fermentation from corn ethanol in the United States is already a large source of carbon dioxide for use in a number of consumer products, such as food, beverage, and dry ice.[37]

Challenges

Putting CCS on a bioenergy facility can address the emissions from that facility, but there are still the upstream climate impacts from the growing and harvesting of biomass to consider. There are many uncertainties related to the accounting of land-use change emissions and their impact on the actual life cycle climate benefits of BECCS.

Direct air capture (DAC)

Carbon dioxide in the ambient air is at about 400 parts per million, which is 100-300 times more dilute than the concentration of carbon dioxide in the emissions stream from a gas- or coal-fired power plant. Direct air capture (DAC) involves direct removal of dilute carbon dioxide from ambient air via chemical bonding. Currently, there are two types of DAC being scaled as CDR solutions: chemical liquid solvent DAC and chemical solid sorbent DAC. While there are technical differences between the two methods, they operate under a similar concept: removal of carbon dioxide from ambient air by contact with a basic solution (chemical liquid solvents) or a basic modified surface (chemical solid sorbents). The carbon dioxide, now fixated in a carbonate or carbamate bond, can then be liberated from the capture media through the application of heat, producing a high-purity carbon dioxide stream that can be transported to storage sites or industrial plants for utilization.

Potential

DAC demonstration projects and activities have received a great deal of attention of late relative to other CDR technologies, but there has been very little focus on the removal potentials of DAC compared to its cost-related barriers.[38] Theoretically, DAC may be able to capture extremely large amounts of carbon dioxide (up to several gigatons), which could then be sequestered in geologic formations that also have enormous storage potential.

Cost

The economic cost has been the main factor determining the viability of DAC. Costs of DAC include: capital investment in equipment and facilities, energy costs associated with capture and operation, energy costs of regeneration, and sorbent loss and maintenance. Additional costs related to carbon dioxide compression, transportation, and storage are similar to other CCS technologies. Because of the high energy requirements of removing dilute atmospheric carbon dioxide and releasing the captured carbon dioxide from the capture media (particularly for solvents), the type and cost of energy utilized by DAC plants will determine the cost and emissions reduction potential of a given DAC facility.

Studies report that first-generation, near-term DAC plants may have carbon removal costs on the order of $600–$1,000/ton of carbon dioxide initially, but this cost could decrease to US$100-$300/ton of carbon dioxide with technological improvements, large-scale deployment, and increasing availability of low-cost clean electricity.[39]

Readiness

There are different DAC processes at various levels of maturity. On a commercial scale, there are a few companies that have started to develop commercial models for DAC, including Carbon Engineering, who uses a chemical liquid solvent, and Global Thermostat and Climeworks, who use a chemical solid sorbent. Currently, DAC technologies have a TRL value of 4-7.[40]

Scalability

Economic costs, rather than biophysical limitations, remain the main barrier for scaling up DAC, though mass production of air capture devices could lead to cost estimates dropping by orders of magnitude.[41] The deployment of DAC at large scale also depends on access to sufficient low-cost, low-carbon energy and water to drive capture and regeneration. While DAC's ability to be located more or less anywhere can reduce the obstacle to scaling posed by the need for extensive carbon dioxide transport infrastructure, it is essential to scale up storage infrastructure so project developers can be certain of their ability to permanently sequester the captured carbon dioxide.

Sink saturation

As noted with respect to BECCS, the United States has at least 2,600 billion tons of possible carbon dioxide storage resource in saline formations, oil and gas reservoirs, and unmineable coal seams.[42] This equates to hundreds of years' worth of industrial greenhouse gas emissions.

Permanence

Like BECCS, the permanent sequestration of carbon dioxide captured by DAC is mostly subject to the nature of underground geological storage. Assuming suitable storage sites, the carbon dioxide captured from BECCS facilities can be permanently stored in deep geologic formations, with minimal risk of leakage or release.

Benefits and co-benefits

The locational flexibility of DAC—the air is everywhere—makes it a particularly promising CDR approach, as does the fact that DAC facilities have small land and water footprint (not conisdering the land footprint of associated energy sources). In addition, carbon dioxide sequestered from ambient air can be accurately and precisely accounted for, which enables DAC to offer significantly greater investment safety and confidence compared to other CDR solutions, many of which face carbon accounting challenges related to the variability associated with land-use change emissions.

Challenges

The main challenge for DAC is cost, especially in the absence of a price or constraint on carbon that would help justify the costs of DAC. The high energy requirements for large-scale DAC facilities would also require an extraordinary increase in low-carbon energy capacity, beyond what will already be needed to decarbonize the energy system.

TABLE 2. A summary of removals potentials, costs, and readiness levels of different CDR solutions in the US

PATHWAY/ SOLUTION	POTENTIAL REMOVAL RATE BY 2050 ($MTCO_2$/YR)	COST ($/$TCO_2$)	READINESS/ TRL	REMOVAL/ STORAGE RANGE	PERMANENCE EFFECTIVENESS
NATURE-BASED					
Afforestation/ Reforestation	80–390	5–50	Deployment	Decades to centuries	Low
Biochar	55–95	20–130	Demonstration	Years to decades	Low
Soil carbon sequestration	52–103	45 (profit)–10 (cost)	Demonstration	Years to decades	Low
TECHNOLOGICAL					
BECCS	370–400	40–130	5–7	Millennia	High
DAC	No fundamental limitation on technical potential, but mainly limited by financial and low-carbon energy requirements	600+ (early stage) 100–300 (longer term)	4–7	Millennia	High

POLICY RECOMMENDATIONS

The world will need CDR solutions at large scale in order to limit global temperature increases to 1.5 degrees C. At the current rate of emissions reductions, the world is on pace to "overshoot", or exceed, that 1.5-degree threshold. The ability of CDR solutions to achieve "negative emissions" to address overshoot makes them a critical addition to the climate solutions toolkit. (Again, the potential of CDR solutions should not be overstated and will mean little if there are not simultaneous efforts to reduce emissions across the economy.) Given the variation in removal potentials, risks, costs, and uncertainties described earlier, a portfolio of CDR solutions will be needed in order to maximize the chances of limiting warming to 1.5 degrees C. Policy can play a vital role in making such a portfolio a reality.

Policy can accelerate deployment of CDR solutions and the associated learning-by-doing, which can drive down the costs of the solutions. Early assessments of technologies sometimes fail to consider the potential for such policies and thus overestimate the solutions' economic costs. For example, after sulfur dioxide emission trading was enacted, sulfur reduction technologies at power plants proved within a few years to be 10 times cheaper than experts had predicted shortly before trading began.[43] In the case of CDR, the hope is that policy incentives can lead to similar results. Ramping up deployment of removal solutions can help assess and demonstrate their true economic costs and carbon reduction potentials.

Some CDR solutions—primarily nature-based solutions—are already being deployed and, either because of low cost or substantial co-benefits, could be scaled through modest carbon rules or incentives. However, these solutions only go so far. Other CDR solutions have even larger removal potentials but need more robust policy support—ideally from a combination of "technology-push" and "demand-pull" policies—to be brought to scale. Technology-push policies can foster further innovation in CDR solutions, attract investment, and support the development of carbon dioxide infrastructure, while demand-pull policies can accelerate market creation for CDR solutions. Some of these policies are described in more detail below.

In addition, there is a need for other types of policies to foster trust and long-term support for CDR solutions. For example, it is critical to establish rigorous life cycle analyses (LCAs) for a variety of removal technologies. Credible assessment frameworks need to be widely adopted by project developers to demonstrate and verify the net carbon removal associated with their CDR efforts. Likewise, the integrity of geologic storage will be a key enabler for sustained public support for CDR. These are described more below as well.

RD&D

Government funding for research, development, and demonstration (RD&D) programs can make a huge difference in the costs and deployment levels of technologies. For example, federal RD&D funding has played a pivotal role in scaling up renewable energy resources and driving down their costs over the last several decades. The U.S. Department of Energy (DOE) spent $9.37 billion for renewable energy research and development from 2009 to 2018.[44] These investments, paired with other complementary policies, managed to steadily decrease costs and double U.S. renewable energy generation since 2008.[45] In contrast, federal RD&D funding for CDR-related projects has only amounted to nearly $3 billion over the same period. Nearly half of this was dedicated to geologic sequestration projects, 26 percent was dedicated to terrestrial and bioenergy projects, while DAC received barely $10.9 million (less than 1 percent).[46] Higher levels were recently authorized in the Consolidated Appropriations Act, 2021, though funding for these programs at those levels has yet to be appropriated. Still, the current size of the federal RD&D budget dedicated to CDR does not reflect its potential economic or climate benefits.

Given the importance and potential of CDR solutions, there is a need for strong RD&D programs to support the development and demonstration of large-scale removal capabilities. The National Academies of Sciences, Engineering, and Medicine (NASEM) recommended funding the research of CDR technologies such as BECCS and DAC at an annual average of $217 and $240 million respectively over the next 10 years.[47] NASEM also recommended increased funding for AR research over the next three years and the development of a national monitoring system for forest carbon that would complement the U.S. Forest Service forest inventory.[48] In addition, it will be important for DOE to coordinate with the U.S. Department of Agriculture and industry to assess the carbon removal potential of biomass approaches, including BECCS and biochar, and to develop carbon-negative fuel pathways that are cost-competitive. CDR research budgets and programs should better reflect the opportunities that these solutions present for climate mitigation and economic growth.

CARBON PRICING AND STANDARDS

Cost is currently a hurdle for many carbon removal solutions, particularly as costs associated with greenhouse gas emissions are not fully incorporated into economic activities. Policies that institute a robust carbon price or carbon constraint could boost CDR's cost competitiveness, which in turn could increase investments in CDR solutions. Several legislative approaches have been proposed recently to establish a carbon tax or a cap-and-trade program, proposing prices in the range of $15-$52 per ton in the early 2020s and escalating at different rates to $30-$135 per ton by 2030.[49] The higher the carbon price, the more potential for CDR solutions to be deployed at scale.

However, a price alone might not be sufficient. Additional policy mechanisms will likely be needed to accelerate the deployment of CDR technologies. For example, a federal Clean Energy Standard (CES) that permits CDR projects to contribute in limited and targeted ways to an overall clean energy target could increase the deployment of CDR and provide the certainty necessary for large capital investments. CDR projects could be made eligible for CES credits based on the net carbon dioxide removed from the atmosphere. California has already adopted a similar approach in its Low Carbon Fuel Standard (LCFS) by allowing CCS and DAC projects to be eligible for credits under the LCFS, provided they meet the requirements specified in the CCS Protocol. The inclusion of CDR in a variety of policy contexts, including in the power and fuels sectors, could unlock a massive amount of investment and help CDR solutions reach their removal potentials.

INFRASTRUCTURE

As described earlier, the need for supporting infrastructure presents a key constraint on the scalability of several CDR approaches, particularly the technological solutions. Like other CCS technologies, both BECCS and DAC rely on accelerated deployment of carbon dioxide transport and storage infrastructure (though DAC could be less reliant on the transport infrastructure, given its siting flexibility). Federal infrastructure policies should address siting, permitting, and investment needs for carbon dioxide pipelines and sequestration sites.

MARKET CREATION

A common challenge for new technologies and approaches is the way that risks—real and perceived—affect the market's willingness to pay for them, and CDR solutions are no exception. Policies can create demand-pull for CDR technologies (and other CCS technologies) by fostering markets for utilization of the captured carbon dioxide. For example, government procurement policies can commit to purchasing (and set requirements for) materials that begin to utilize captured carbon dioxide in their production, such as cement, concrete, and aggregate, for use in constructing new state and federal buildings. Similarly, building codes could be updated to set maximum life-cycle emission limits for building and construction materials, and material standards and certifications need to be updated to allow for carbon dioxide-based products to be used. Policies could also help support existing niche markets that have a higher-than-average current willingness to pay for using captured carbon dioxide, (e.g., enhanced oil recovery (EOR)), which can help drive more early deployment and bring costs down. Although these niche markets are miniscule compared to the gigatons required for climate stabilization, this early market creation can help CDR technologies grow and begin to achieve some scale.[50]

LIFE CYCLE ANALYSIS (LCA) AND ENVIRONMENTAL MONITORING

The credibility and smart deployment of CDR solutions will always be tied to how accurately their life cycle emissions are identified and accounted for. Large-scale deployment of CDR solutions (and of carbon dioxide-based materials) will therefore require rigorous and credible life cycle assessment (LCA). LCA analyses will also have to go beyond consideration of only emissions, as large-scale deployment of CDR solutions will have impacts on energy, food, water, and land systems. Furthermore, analyses will have to consider not only the impacts of individual solutions, but also the impacts of deployment of multiple CDR solutions, as some could create additional pressures on the same systems. For example, afforestation and BECCS might compete over land, and biochar and BECCS might compete over biomass feedstocks. EPA should establish a life-cycle GHG accounting framework for CDR solutions that can enable carbon removal projects to be accurately credited for net carbon dioxide removed from the atmosphere.

Beyond LCAs, real-world impacts have to be tracked. Monitoring, reporting, and verification (MRV) will therefore also be critical in establishing public acceptance of large-scale deployment of nature-based and technological CDR solutions (and carbon dioxide-based materials). While MRV guidelines for emissions are well established, guidelines for CDR are not as fully developed. Reporting of carbon removal in nature-based solutions can be particularly challenging because the land is simultaneously a source and sink of greenhouse gases due to both natural and anthropogenic processes that are hard to disentangle. While there are different available approaches for forest carbon accounting (e.g., land-based, activity-based), limitations in these approaches such as measurement uncertainties, data quality issues, and required monitoring still need to be addressed. Ensuring the additionality of nature-based solutions is also a challenge. Reporting guidelines will need to be specific to each CDR methodology to offer rigorous frameworks for the different approaches.

INTEGRITY OF STORAGE

Policies are also needed to ensure secure geologic storage and to reduce uncertainties related to long-term carbon storage and liability. There is high confidence that secure geologic storage is abundant, but liability for stored carbon dioxide is a significant barrier for large-scale deployment of carbon storage projects and infrastructure. However low the probability of carbon dioxide leakage from geologic storage may be, policy should address these concerns to ensure project developers and operators are responsible for reasonable environmental and economic consequences. Although geologically sequestered carbon dioxide is intended to stay underground permanently, it is challenging for project developers and operators to commit to legal liability over geologic timescales; the prospect of thousands of years of liability is a significant deterrent. A potential solution could be a nationally determined minimum period for stored carbon dioxide liability. After meeting a minimum number of years stored and satisfying specific performance criteria, regulatory frameworks would enable the transfer of liability for a storage site or stored carbon dioxide, to an appropriate government agency. There have been examples of this approach implemented in Canada, Australia, Netherlands, and the UK.[51]

CONCLUSION

Carbon dioxide removal will be an important and necessary complement to emissions reduction efforts, which should remain a top priority. The gravity of our challenge to reduce emissions must also recognize that some sectors of the economy like industry and aviation will require CDR and negative emissions solutions as part of their decarbonization. In other cases, the last few percentages of emission reductions may create economic hardships for businesses and consumers due to cost. Compensating for those emissions with CDR, when part of a clear net-zero mandate can provide environmental and economic benefits. CDR solutions currently vary considerably in terms of removal potential, costs, readiness, scalability, permanence, benefits, and challenges. Nature-based solutions are largely affordable and ready now and will be of particular importance in both the near- and long-term. Meanwhile, complementary, scalable, more permanent technological solutions must continue to be developed and deployed. A combination of CDR solutions will be critical in meeting both domestic and international emissions goals. In addition to developing domestic technologies and expertise that can be exported globally, U.S. leadership will be critical to ensuring that CDR solutions are available at the scales necessary to meet the global challenge of climate change. Policy is needed to address numerous technological, economic, and regulatory barriers and enable CDR technologies to contribute meaningfully to a comprehensive decarbonization strategy.

Other Climate Innovation 2050 Resources:

Getting to Zero: A U.S. Climate Agenda
https://www.c2es.org/document/getting-to-zero-a-u-s-climate-agenda/

Pathways to 2050: Scenarios for Decarbonizing the U.S. Economy
https://www.c2es.org/document/pathways-to-2050-scenarios-for-decarbonizing-the-u-s-economy/

Restoring the Economy with Climate Solutions: Recommendations to Congress
https://www.c2es.org/document/restoring-the-economy-with-climate-solutions-recommendations-to-congress/

Climate Policy Priorities for the New Administration and Congress
https://www.c2es.org/document/climate-policy-priorities-for-the-new-administration-and-congress/

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