A CLOSER LOOK

ENGINEERED CARBON DIOXIDE REMOVAL: SCALABILITY AND DURABILITY

C2ES CLIMATE INNOVATION 2050

by

Mahmoud Abouelnaga,
Center for Climate and Energy Solutions

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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

Given the scale of the climate crisis, the short timeframe for action, and insufficient progress in reducing greenhouse gas emissions, there is broad scientific agreement that large-scale deployment of carbon dioxide removal (CDR) technologies and approaches are needed to counter rising atmospheric concentrations of carbon dioxide. CDR encompasses a suite of solutions, both engineered and nature-based, that remove carbon dioxide from the atmosphere and durably store it.

The climate crisis requires countries to cooperate on developing climate solutions, including engineered CDR technologies, that can be deployed at scale around the world. While nature-based CDR approaches are cheaper and more readily available in the short term, engineered CDR technologies can bring many advantages in addressing the climate crisis, including larger removal potentials, more durable carbon sequestration, greater scalability, and more locational flexibility. At the moment, however, these technologies are constrained by cost, energy needs, and potential land and climate impacts. There are also risks that relying too heavily on the eventual availability and scalability of engineered CDR will lead to delays in other mitigation efforts and

continuation of business-as-usual practices. Advancing CDR technologies must not be used as an excuse for inaction on other carbon mitigation strategies.

Equally important, climate justice must be embedded in strategies to accelerate development and deployment of engineered CDR technologies. Engineered CDR projects could have impacts on local communities—either directly or by extending the lifetime of polluting industries—highlighting the need for robust stakeholder and community engagement. As CDR deployment progresses, there should also be opportunities for community ownership of CDR benefits, as well as efforts to ensure a just and well-managed transition of skills and expertise into new jobs in the emerging carbon removal sector.

A range of policy interventions could accelerate the equitable deployment of engineered CDR technologies, including the following:

- *Infrastructure development*: supporting development of regional carbon dioxide transport networks and accelerating commercial carbon dioxide storage projects.
- *Regulatory framework*: improving the permitting process for Class VI wells (for permanent geologic storage), providing a clear federal regulatory framework for siting of interstate carbon dioxide pipelines, and developing a clear framework for long-term liability related to stored carbon dioxide.
- *Market-based mechanisms*: using carbon price revenues to support carbon removal projects, making CDR projects eligible for credits in clean energy standards, and requiring federal procurement of carbon removals.
- *Financial incentives*: promoting the improved 45Q tax credit and expanding the investment tax credit to support deployment of engineered CDR.
- *Research, development, and demonstration (RD&D)*: directing the Department of Energy to clarify its Carbon Negative Shot plans to help CDR technologies scale and expanding RD&D investments in carbon dioxide utilization technologies.
- *Equitable transition*: establishing requirements for funding applicants to show local economic and social benefits, expanding apprenticeship programs and grants, and modernizing federal environmental justice engagement.

Accelerating the equitable development and deployment of engineered CDR solutions by 2030 creates a greater chance of achieving gigaton-scale removals and ultimately net-zero emissions by 2050.

INTRODUCTION

As global efforts ramp up to reduce greenhouse gas emissions and avoid the most drastic impacts of climate change, humanity faces a dilemma: Current mitigation efforts will not be enough to keep the rise in global temperatures in line with the Paris Agreement's goals (i.e., well below 2 degrees C, preferably below 1.5 degrees C, compared to pre-industrial levels).

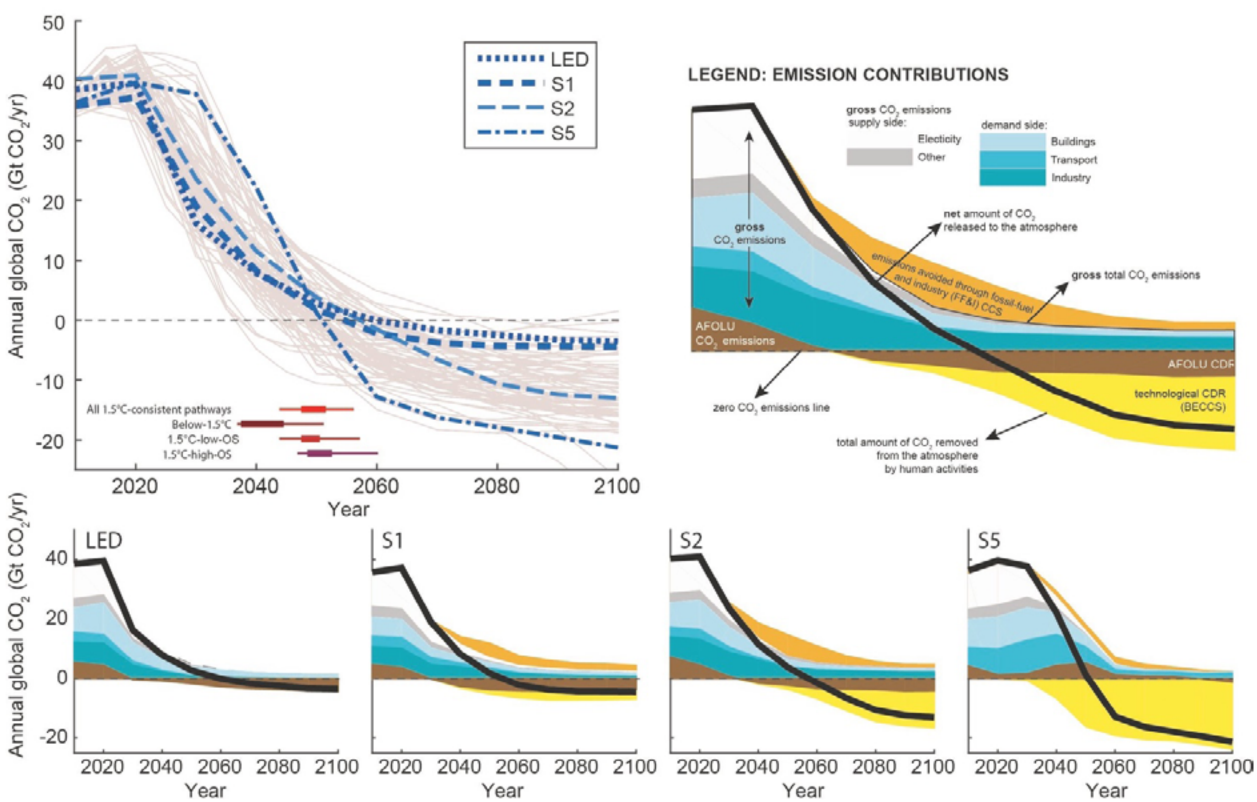
Because emission reduction efforts to date have been insufficient, there is wide agreement across the scientific community on the need for large-scale deployment of carbon dioxide removal (CDR) technologies and approaches in order to substantially reduce emissions and limit global temperature increase to 1.5 degrees C by the end of the century.[1] CDR is of particular importance because emitted carbon dioxide otherwise stays in the atmosphere for hundreds of years.[2] The National Academy of Sciences has estimated that meeting the Paris Agreement's goals will require 10 gigatons (Gt) of carbon dioxide removal globally each year through 2050, with 20 Gt of carbon dioxide removed each year from 2050 to 2100.[3] Likewise, all Intergovernmental Panel on Climate Change (IPCC) mitigation pathways that limit global warming to 1.5 degrees C by 2100, with no or limited overshoot, project the deployment of enough CDR capacity to remove 100–1000 Gt of carbon dioxide over the remainder of the 21st century.

In its *Special Report: Global Warming of 1.5°C*, the IPCC modeled the evolution and breakdown of global carbon dioxide emissions until 2100. Figure 1 shows the mitigation pathways analyzed in this report and highlights four 1.5 degree C-consistent pathways. These four pathways have some common features: full decarbonization of the power sector by 2050, significant emissions reductions in the transportation and industrial sectors, and contributions from CDR. The contribution from CDR can be limited (low energy demand [LED] and S1 pathways) or more predominant (S2 and S5 pathways).

CDR encompasses a suite of solutions that remove carbon dioxide from the atmosphere and durably store it in geological formations, the biosphere (e.g., plants and soils), or long-lasting products. These solutions include both technological or engineered approaches, as well as nature-based approaches (e.g., afforestation, reforestation, enhanced uptake, and retention of carbon by soils). This paper focuses on engineered carbon removal technologies. In particular, it focuses on bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) because these methods have been included in many integrated assessment models and have gained the most traction in public policy debates and legislation.

- BECCS is the process of using biomass to generate energy, capturing the resultant carbon dioxide, and storing it in underground geologic formations (or potentially utilizing it to make long-lasting products). Biomass can be converted into energy through combustion, biochemical, or thermochemical processes. The combustion process of biomass generates heat or electricity. Biochemical and thermochemical conversion processes produce chemicals and fuels (e.g., ethanol and biodiesel).
- DAC involves direct removal of dilute carbon dioxide from ambient air via chemical bonding.

FIGURE 1: Mitigation pathways compatible with 1.5 degrees C



This figure shows mitigation pathways for carbon dioxide emissions by 2100 and highlights four scenarios (LED, S1, S2, S5) compatible with 1.5 degrees C increase by the end of the century. The top-right panel explains all carbon dioxide emissions from the different sectors, as well as carbon dioxide removals from nature-based CDR approaches (brown) and technological CDR approaches (yellow). The bottom row highlights the different 1.5 degree C-compatible pathways. Some of these pathways (LED and S1) involve global efforts focused on rapidly reducing carbon dioxide emissions from energy end-use sectors, with limited contributions from CDR. Other pathways (S2 and S5) involve delayed global emissions reduction efforts in these sectors and thus higher contributions from CDR.

Source: IPCC Special Report: Global warming of 1.5°C, 2019[1]

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). Once fixated in a carbonate or carbamate bond, the carbon dioxide 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.

Other engineered CDR technologies, such as enhanced weathering and ocean-based approaches, are not addressed in this paper.

It is important to distinguish engineered CDR technologies from solar geoengineering or solar radiation management (SRM). SRM aims to increase reflection of solar radiation back into space, counterbalancing the temperature rise caused by greenhouse gases.[4] SRM includes techniques that increase the reflectiveness of the land surface or clouds (e.g., by injecting aerosols) or that block a small proportion of sunlight. SRM thus seeks to counter some of the effects of climate change via approaches that have risks and uncertainties around potential unintended consequences (e.g., disruption of ecosystems). CDR technologies, in contrast, seek to address the cause of climate change by removing previously emitted carbon dioxide from the atmosphere, with none of the same risks and uncertainties.

While this paper explains the potential role of engineered CDR to meet long-term climate goals, it cannot be emphasized enough that deployment of engineered CDR is not an excuse to delay other carbon mitigation strategies (e.g., deploying more clean electricity, electrifying end uses, developing low- and zero-carbon fuels). However, the scale of the climate crisis and the short timeframe for action require utilizing every tool available to counter persistently high emissions and rising atmospheric concentrations of carbon dioxide.

Similar to other nascent technologies, engineered CDR technologies need supportive policies and regulatory frameworks that can attract investments and push them to market, especially in the early development stages. Strong support today for smaller-scale demonstration projects and investments in innovation are necessary to help deliver cost reductions for gigaton-scale carbon removal projects in the decades ahead.

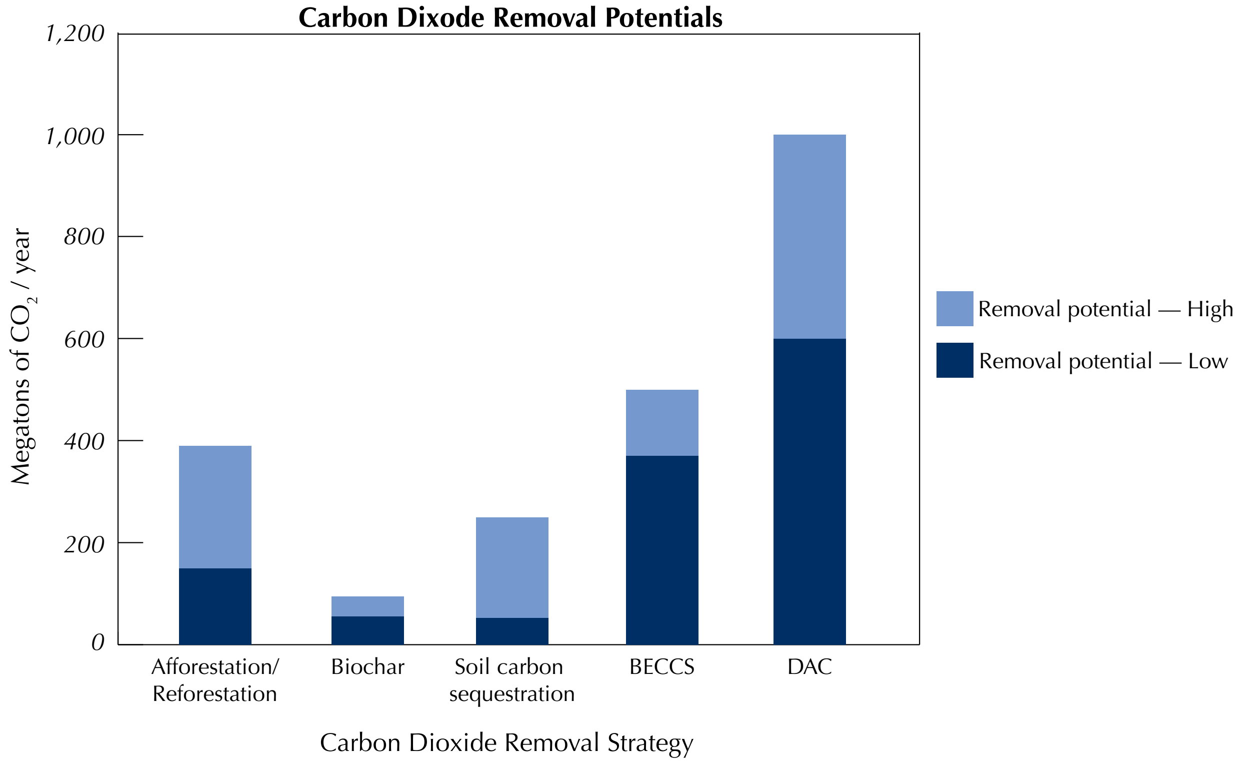
ADVANTAGES OF ENGINEERED CDR TECHNOLOGIES

Nature-based CDR approaches are cheaper and more readily available in the short term than engineered technologies, and they will play an important role in meeting midcentury climate goals. However, it is important to recognize the many advantages engineered CDR technologies present in addressing the climate crisis.

LARGE REMOVAL POTENTIAL

One of the main advantages of engineered CDR technologies is that they have much larger removal potentials compared to nature-based solutions. For example, estimates suggest that BECCS could remove around 0.37 Gt of carbon dioxide per year in the United States, which is equivalent to almost 35 percent of carbon dioxide emissions from the U.S. power sector.[5] The main constraints on BECCS are supplies of suitable feedstocks and access to sufficient sequestration sites (or utilization opportunities). DAC facilities have few limits on their removal potential; as long as they have access to low-carbon electricity sources and—again—sufficient geologic sequestration sites (or utilization opportunities), they can remove many Gt of carbon dioxide per year. Conversely, afforestation/reforestation and other forest management practices in the United States only offer around 0.16 Gt of carbon dioxide removals per year, and, like BECCS, they are limited by land availability, demand for wood, and biodiversity challenges. Biochar and soil carbon sequestration have even lower removal potentials. Figure 2 shows the removal potentials of engineered CDR technologies compared to nature-based solutions.

Figure 2: CDR potentials



"Low" corresponds to estimates associated with limited adoption of CDR solutions. "High" corresponds to estimates that model fast technology advancement and strong policy and economic support to scale up CDR solutions.

Source: Carbon Dioxide Removal: Pathways and Policy Needs, (C2ES, 2021)[2]

DURABLE CARBON SEQUESTRATION

Engineered CDR technologies offer durable carbon sequestration, providing effective, permanent carbon removal. Conversely, there are concerns about the potential for reversal of nature-based sequestration. For example, wildfires can release much of the carbon that had been stored during tree growth, negating the removal benefits associated with those forests. In contrast, engineered CDR utilizes separate processes for capturing carbon dioxide and for sequestering it in appropriate geological reservoirs or in long-lived materials (e.g., concrete, aggregate materials). This type of geologic storage has proven to be safe, with decades of experience in carbon dioxide injection and storage operations demonstrating minimal risk of leakage or release.[6]

In geological sequestration, carbon dioxide is injected into the pore space of the rock formation, and it can be kept there in a variety of ways.

- Structural/Buoyant trapping: Similar to the way that naturally occurring oil and gas are trapped underground, the sequestered carbon dioxide can be held in place by layers of low-permeability rock ("caprock") on the top that prevent upward leakage, with porous rock on the sides and below containing fluid that is denser than the carbon dioxide, thereby trapping the carbon dioxide in between.
- Residual Trapping: Injected carbon dioxide initially displaces fluid in the rock formations, but as the carbon dioxide moves through the formation, the fluid returns, and some of the carbon dioxide is left behind and trapped in place by surface tension in the pore spaces.[7]
- Solubility trapping: When carbon dioxide contacts with the formation fluids, mass transfer occurs as carbon dioxide dissolves into these fluids until equilibrium is reached.
- Mineral trapping: The injected carbon dioxide reacts with minerals in the rock and solidifies into carbonates over time, locking the carbon dioxide into the rock formation.

FIGURE 3: A schematic illustration of the different trapping techniques in geological carbon storage

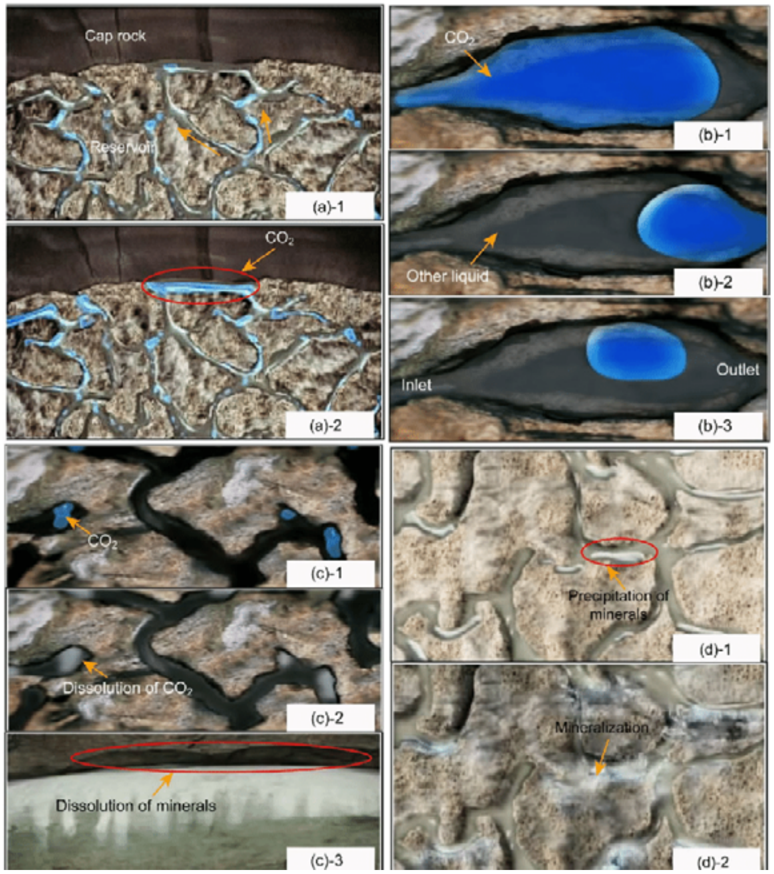


Illustration of geological carbon storage mechanisms. a: structural trapping; b: residual trapping; c: solubility trapping; and d: mineral trapping.

Source: Wu and Li Geothermal Energy, (2020)[3]

SCALABLE TECHNOLOGIES

In addition to needing to be deployed safely and quickly, CDR solutions also need to be deployed at scale in order to sequester a sufficient amount of carbon dioxide to help stabilize global temperatures. While nature-based removals have limitations on scalability due to competition with other land uses, engineered CDR technologies (e.g., DAC) are generally more scalable due to their ability to remove additional emissions without necessarily requiring a significantly greater land footprint at the facility level.

Companies looking to reduce their emissions, especially in hard-to-abate sectors (e.g., cement, steel, chemicals, heavy transport), can benefit from the scalability of engineered CDR technologies to reduce emissions that cannot be addressed through other mitigation efforts (e.g., cleaner energy substitution, energy efficiency, electrification of industrial processes) and reach their carbon-neutrality goals through high-quality, certified carbon offsets. Emissions from these hard-to-abate sectors account for more than 30 percent of global annual carbon dioxide emissions—representing almost 11 Gt of carbon dioxide.[8] Much of the infrastructure needed to build the future's decarbonized economy will still depend on cement and steel. While efforts to decarbonize these industries are critical, investments that help advance the commercial viability of scalable carbon removal technologies can provide an additional avenue for these industries to contribute to a low-carbon economy.

LOCATIONAL FLEXIBILITY

Engineered CDR technologies benefit from having locational flexibility, which enables project development at locations that avoid competition with other land uses. For example, DAC plants can be sited in any location where there is inexpensive, low-carbon electricity and a suitable carbon storage site or carbon utilization opportunity (or transport to those). Low-carbon electricity sources and suitable geological storage sites are geographically dispersed enough to allow project developers to site their DAC facilities where both operational efficiency and economic opportunity can be maximized.

LIMITATIONS OF ENGINEERED CDR TECHNOLOGIES

COST

Engineered CDR technologies are currently considerably more expensive than nature-based solutions. These technologies have transportation and storage costs that nature-based solutions do not, but the cost of capturing the carbon dioxide is the most significant factor in the overall cost.

In general, the more concentrated carbon dioxide is at the capture point, the less expensive it is to capture. That is why the majority of existing BECCS facilities worldwide capture carbon dioxide from fermentation at ethanol plants: The high purity of the flue gas stream (nearly 100 percent carbon dioxide, with a small fraction of water) typically requires only dehydration before the carbon dioxide can be compressed for transport and storage. 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. On the other hand, carbon dioxide from combustion in a BECCS facility is released in diluted form in the exhaust gas and needs further separation and energy use, which leads to higher estimated capture costs of \$88–\$288/ton of carbon dioxide.[9]

In the case of DAC, atmospheric carbon dioxide is much more dilute (412 parts per million, or 0.04 percent) than any industrial point source (e.g., 4–5 percent for natural gas combined-cycle flue gas, 12–15 percent for coal-fired flue gas, 14–33 percent for cement production).[10] This extremely low concentration of carbon dioxide makes the cost of DAC higher compared to other capture/removal technologies. DAC cost estimates vary widely across the literature, typically ranging from \$600–\$1,000/ton of carbon dioxide captured.[11] A 2021 assessment by the International Energy Agency, however, estimates the cost of DAC projects to range from \$400–\$700/ton.[12] Additional deep cost reductions are expected with technological improvements, large-scale deployment, and increasing availability of low-cost, clean electricity. These developments could conceivably reduce the cost of early commercially viable DAC projects to \$190–\$230/ton.[13] Additionally, locational flexibility allows CDR facilities to reduce costs by co-locating with existing or planned carbon transport (i.e., pipelines) and storage infrastructure.

ENERGY NEEDS

Engineered CDR facilities can require very large quantities of low-carbon energy (electricity and heat). While this is less of a concern for BECCS, since it can generate its own energy, it is a key hurdle for large-scale deployment of DAC.

The energy needs of the different DAC technologies vary greatly, with liquid solvent technologies requiring a higher operating temperature than solid-based DAC technologies. The liquid solvent system requires heat up to nearly 900 degrees C (1,652 degrees F) for the calcination process— the decomposition of calcium carbonate into calcium oxide and carbon dioxide. The solid sorbent system, in contrast, only requires an operating temperature of 80–130 degrees C (176–266 degrees F).[14] The high temperature requirements of liquid-based DAC mean only a few technologies (e.g., natural gas with carbon capture, nuclear) can provide an adequate amount of clean heat, whereas solid-based DAC's lower heat requirements can be powered by several clean energy technologies (e.g., heat pumps, solar thermal, geothermal).

LAND AND CLIMATE IMPACTS

While the footprint of removal facilities is usually small, the footprint of the necessary low-carbon energy sources could be substantial. For example, data from the National Academy of Sciences indicate that gigaton-scale DAC powered solely by solar energy would require a land area of almost 14.5 million acres, ten times the size of the state of Delaware.[15] Other technologies, however, such as advanced nuclear, might be able to provide clean electricity for DAC facilities with a relatively small land footprint.

With respect to BECCS, the reliance on biomass creates land-use challenges. Scaling up BECCS requires increasing supplies of biomass. Competing uses for cropland, switching to energy crops, or creating pressure to convert other land uses to cropland could impact food prices, food availability, and biodiversity. While potential upstream climate impacts from growing and harvesting biomass must be considered, there are many uncertainties related to the accounting of land-use change emissions and their impact on the actual lifecycle climate benefits of BECCS.

Some experts argue the term BECCS provides inadequate emphasis on the carbon removal aspect and too much emphasis on energy generation. Consider the example of municipal solid waste (MSW) incineration plants as an analogy. While MSW incineration plants can generate energy, their main purpose is to get rid of waste. They are not energy-efficient compared to other energy generation options. Likewise, most biomass has high carbon value but poor energy value, and carbon dioxide emissions are the waste that needs to be managed. BECCS facilities should be designed and optimized for carbon removal purposes, to avoid locking in bioenergy projects without a robust economic model for removing considerable levels of carbon dioxide emissions. Indeed, some researchers argue that biomass with carbon removal and storage (BiCRS) would be a better, more accurate term.[16] BiCRS would involve clear parameters for bioenergy-based carbon removal solutions, including using biomass to remove carbon dioxide from the atmosphere, storing the carbon dioxide underground or in long-lived products (e.g., concrete, aggregate materials), and preserving food security, rural livelihood, and biodiversity.

DELAYED EMISSIONS CUTS

Engineered CDR technologies are not silver bullets, and the fact that many CDR technologies currently are relatively nascent, costly, and small-scale highlights the need for some caution. There are risks associated with developing climate policies and practices based on the assumption that engineered CDR will be available and can scale up relatively quickly. Such an assumption can lead to delays in other mitigation efforts and continuation of business-as-usual practices. An overreliance on fossil fuels in the near term makes climate targets harder and much more costly to achieve should engineered CDR fail to deliver in the long term. Engineered CDR must be part of a comprehensive mitigation strategy rather than a reason to avoid significant, immediate emission reductions.

EMBEDDING CLIMATE JUSTICE IN ENGINEERED CARBON REMOVAL STRATEGIES

FRONTLINE COMMUNITY CONCERNS

Engineered CDR projects could have impacts on local communities in at least two ways. First, these technologies could extend the lifetime of polluting industries and perpetuate business-as-usual practices that adversely impact local communities. Second, it is possible that the CDR facilities themselves could have impacts. While there have been studies on the overall implications of engineered CDR deployment on carbon cycles, global temperature rise, and other topics, there has not been enough research exploring the local impacts of engineered CDR projects.

These concerns about impacts are legitimate and highlight the need for stakeholder and community engagement on deployment of carbon removal strategies. Successful CDR project development must engage local communities in the decision-making process from inception, including with regard to siting. Community engagement helps ensure that local concerns are heard and considered during every stage of development and

BOX 1: A 2030 roadmap for engineered CDR solutions

Supporting CDR technologies this decade is critical for reaching gigaton-scale deployment by 2050.

While engineered CDR solutions are expected to play a small role in reaching the country's 2030 emissions reduction target—also known as the nationally determined contribution (NDC) under the Paris Agreement—they are essential in enabling almost every climate action plan for 2050 and beyond.[1] There are several interventions that can accelerate the rate of deployment of engineered CDR during the 2020s and facilitate the transition to net-zero. These interventions could reduce the levelized cost of engineered CDR solutions within a decade to $100 per ton of carbon dioxide, at which point most projects could break even or be profitable enough to sustain CDR businesses as incentives scale down.

Policy and financial incentives

The future of CDR technologies relies mainly on policy support. Building from an increasingly strong policy base, additional targeted carbon removal policies, regulations, and implementation practices would further facilitate the deployment of CDR projects. This would provide clear signals for the market, establish public-private partnerships that can scale up the technology faster, provide the necessary funding for RD&D activities, create demand for carbon removals through procurement programs, and facilitate stakeholder engagement activities that can establish public trust in the climate and community benefits of carbon removal projects.

Like any new technology, CDR requires flexible financing tools that can minimize the investment risks for early adopters and project developers and allow the first generation of these projects to be deployed on time. This includes adopting an economy-wide carbon pricing mechanism that includes complementary crediting for carbon removal technologies. Additionally, expanding programs like California's LCFS on a regional or national scale can further incentivize the rapid deployment of low-carbon fuels in end-use sectors (e.g., heavy-duty trucking, aviation) using carbon captured by CDR technologies. Other new financing tools can also create a sustainable market for engineered CDR solutions and support the procurement of carbon removal credits (as proposed in the Federal Carbon Dioxide Removal Leadership Act).[2]

Research, development, and demonstration

RD&D activities play an essential role in bringing down the cost of CDR projects and enhancing capture/removal process efficiency. These RD&D activities should focus on solvent/sorbent performance to increase capture capacity over their lifetime, which would reduce materials manufacturing costs and lower the capital expenditures (capex) and operating expenditures (opex) of DAC systems. Another important area for research is the potential of utilizing thermal energy from nuclear power plants to provide the energy needed for low-temperature solid sorbent DAC facilities. There is also a need to harmonize lifecycle analysis methodologies for carbon utilization pathways to provide clarity around crediting of their removal benefits.

Carbon removal targets

The U.S. government should establish national carbon removal targets for 2030 and 2050 that are additional to the carbon reduction goals in the NDC. This would give more direction to CDR investments and streamline project timelines to align with these targets.

Community engagement

CDR technologies cannot be part of comprehensive decarbonization strategies unless they are supported by local communities. The development process of CDR projects should include input from local communities, environmental justice organizations, and other stakeholders. These stakeholders should also have access to the benefits of CDR projects (e.g., air quality, employment, carbon credits).

Accelerating the development and deployment of engineered CDR solutions by 2030 creates a greater chance of putting the United States—and the world—on track to reach gigaton-scale carbon dioxide removal and ultimately achieve net-zero emissions by 2050.

that necessary safeguards are put in place. It also fosters greater community understanding of the purpose and impacts of CDR projects. In a recent survey on public perception of CDR technologies in the United States and the United Kingdom, fewer than 10 percent of survey respondents said they knew at least "a fair amount" about CDR.[17] Establishing a solid degree of public understanding of CDR technologies' benefits, trade-offs, risks, and opportunities will be crucial to scaling the deployment of these technologies.

Unlike more established industries, the nascent engineered CDR sector has an opportunity to establish itself as a sector that considers frontline communities from the start. Engaging local communities and understanding their needs from the beginning can help build the necessary trust.

COMMUNITY OWNERSHIP OF REMOVAL BENEFITS

Granting local communities access to the benefits of clean energy projects is often talked about as a way to ensure that benefits are shared. This approach has proven successful over the last decade with community solar projects in 39 states and Washington, DC.[18] As more states adopted policies supportive of community solar programs, the installed capacity of community solar projects increased from less than 2 megawatts (MW) in 2010 to 3,253 MW in 2020.[19] This rapid growth is a testament to the role of community ownership role in advancing innovative technologies in an equitable way.

Additionally, ownership of CDR benefits should not be restricted to corporates and big investors with minimum purchase requirements of thousands or hundreds of thousands of carbon removal credits. Similar to the community solar model, local communities could subscribe to or own shares of carbon removal credits from CDR projects. Project developers could structure their business models to allow for ownership of smaller amounts of credits so that local communities and other small investors can benefit directly from these projects. Doing so could also provide opportunities to redress historic and ongoing harms by enabling pollution-burdened communities to utilize CDR project benefits to invest in community growth and economic prosperity.

PREPARING & TRANSFERRING WORKFORCE SKILLS

As the low-carbon transition progresses, it is critical to prepare the workforce for changes in skills and competencies required in emerging industries, including engineered CDR. These training opportunities must be made available to local communities, particularly those most heavily burdened by historic pollution and/or most heavily impacted by the low-carbon transition.

It is equally important to ensure that the active workforce can utilize and transfer relevant skills and competencies into new jobs in these emerging industries. Many of the skills in the oil and gas workforce, for example, could be put to good use in the carbon removal sector, including with respect to operation and maintenance of carbon dioxide pipelines, drilling and completion of injection wells, geological surveying and sampling, and monitoring and safety of geologic sequestration. Engineered CDR projects could thus facilitate a transition that utilizes existing knowledge and capacity building. It is essential that state and local governments and CDR project developers work together to ensure a just and well-managed transition of skills and expertise to ensure the skilled workforce can participate in building a net-zero (or even net-negative) future.

ENABLING GLOBAL DEPLOYMENT OF REMOVAL TECHNOLOGIES

Wildfires, extreme weather, sea-level rise, heavy precipitation events, droughts, and other climate impacts are affecting all regions and countries with increasing frequency. The global nature of the climate crisis requires countries to cooperate on developing climate solutions that can be deployed at scale globally. Engineered CDR technologies can be deployed in any country or region where they have access to clean energy sources, carbon dioxide pipelines, and suitable sequestration sites and/or facilities that utilize carbon dioxide as a product input (e.g., sustainable aviation fuel production).

BOOSTING DEPLOYMENT IN THE GLOBAL SOUTH

Deployment of carbon removal technologies in developed countries—those mostly responsible for the climate crisis—could give developing countries more flexibility to realize their economic development targets without sacrificing global climate targets. At the same time, international cooperation on facilitating the transfer of CDR technologies to the Global South will be essential in supporting just and equitable CDR development globally. A potential model of global cooperation is the Just Energy Transition Partnership between the United States, France, Germany, the United Kingdom, and the European Union to support South Africa's decarbonization and coal transition efforts.[20] With adequate support and guidance, developing countries in some regions (e.g., North Africa, the Gulf, South America) could be good candidates for the deployment of CDR technologies, given their large potential renewable energy sources, low energy prices, and suitable geologic formations.

International climate agreements and frameworks need to incorporate engineered CDR solutions, particularly with respect to carbon removal research, development, and demonstration (RD&D) collaboration with the Global South.[21] This would facilitate the transfer of technology, the development and implementation of enabling policies, and funding opportunities. CDR project development in these regions could also support local capacity building and economic development.

Global transfer and deployment of low-carbon technologies from developed to developing countries, however, has been very limited due to concerns over intellectual property rights and constrained production inputs (e.g., limited capital investments, outsourced labor) in developing countries. Almost 71 percent of all patent transfers occurred between countries in the Global North between 2010 and 2015. During the same period, almost no low-carbon technology patents were transferred to low-income countries, and only 23 percent went from high-income to middle-income countries.[22] To enhance the transfer of clean technologies such as engineered CDR, there is a need for patent reform, local capacity building, and regulatory updates to allow patent holders to grant licenses or require royalties.

COOPERATION AND KNOWLEDGE SHARING AMONG EARLY ADOPTERS IN THE GLOBAL NORTH

As governments, mainly in the Global North, establish or expand their carbon removal programs, it is important that they cooperate with each other to help accelerate the scaling of CDR technologies during this decade. For instance, they could establish joint R&D investment programs to build on their domestic programs; these joint initiatives could help identify technical barriers to deployment, create business opportunities, and increase the flow of funds for the first generation of CDR projects. A good example of this sort of collaboration is the Memorandum of Cooperation between U.S. and Japanese government agencies and research institutions in the field of carbon recycling and carbon removal.[23]

Large-scale deployment of innovative technologies requires not just cooperation on the technical aspects of these technologies, but also cooperation to develop supportive economic and policy levers to push new technologies to market and create demand for them. Sharing knowledge about policy interventions (e.g., tax credits, procurement programs, low-carbon standards) to support CDR technologies will be critical in building a supportive environment for projects in different countries. It will also help validate CDR technologies as part of coordinated global efforts to combat the climate crisis, thereby providing more of the certainty needed to attract private investment in CDR.

POLICY INTERVENTIONS TO ACCELERATE DEPLOYMENT OF ENGINEERED CDR TECHNOLOGIES

INFRASTRUCTURE DEVELOPMENT

Developing regional carbon dioxide transport networks

Infrastructure is needed to support the gigaton-scale carbon removal envisioned by the IPCC's 1.5-degree C mitigation pathways. This includes creating carbon dioxide transport networks (e.g., pipelines) to connect captured carbon dioxide (e.g., from DAC facilities) with commercial-scale carbon storage sites and/or industries that utilize the captured carbon dioxide as an input (i.e., for carbon-based products).

The 2021 Infrastructure Investment and Jobs Act (IIJA) incorporated the Storing CO_2 and Lowering

Emissions (SCALE) Act, which included key policies that can support carbon dioxide infrastructure deployment in the United States.[24] For instance, the law established a new Carbon Dioxide Transportation Infrastructure Finance and Innovation program, known as CIFIA, to provide financial assistance for shared carbon dioxide transport projects with anticipated costs that equal or exceed $100 million. This type of shared infrastructure will reduce the overall cost for new CDR projects by allowing them to benefit from shared transport networks. Additional guidance on CIFIA and the application process should be communicated to project developers in a timely manner to support efficient implementation of the program.

Accelerating carbon storage commercialization

Carbon transport infrastructure needs a destination. Before CDR project developers can make their final investment decision (FID), they need certainty that the captured or removed carbon dioxide will have an available and safe storage site. There is an abundance of geologic storage capacity in the United States, with a potential capacity of more than 2,600 billion tons of carbon dioxide (more than 400 times U.S. annual emissions and 70 times global annual emissions). However, potential capacity and commercial-ready storage sites are very different things, and commercial storage sites remain a key limiting factor for capture and removal projects.[25]

The SCALE Act in the IIJA provides $2.5 billion for carbon storage validation and testing, through the establishment of a large-scale carbon storage commercialization program.[26] Considering the complex and lengthy nature of developing carbon storage projects, there is a need for proper and timely implementation of this commercialization program. The U.S. Department of Energy (DOE) will have to expand its staff to enable them to accelerate their efforts and release the first major federal funding opportunities for front-end engineering design (FEED) of carbon dioxide storage projects.

EFFICIENT REGULATORY FRAMEWORK

Improving the permitting process for Class VI wells for permanent geologic storage

One of the main roadblocks for developing permanent carbon storage projects in the United States is the uncertain and lengthy permitting process for Class VI injection wells. Class VI permits refer to those required by the U.S. Environmental Protection Agency (EPA), under its Underground Injection Control (UIC) program, for the underground injection of carbon dioxide for the purpose of permanent geologic sequestration.

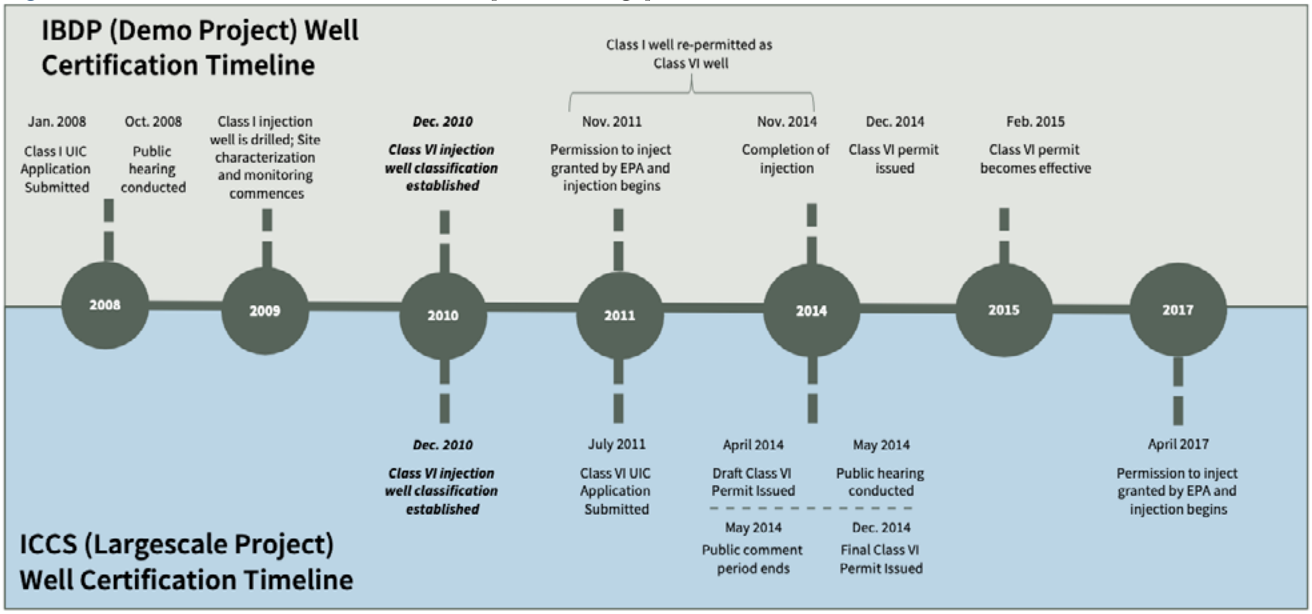
As required by the Safe Drinking Water Act, EPA developed UIC program requirements to be adopted by states, territories, and tribes to protect underground sources of drinking water. However, only two states (North Dakota and Wyoming) currently have primary enforcement authority ("primacy") to permit Class VI wells under the UIC program; the EPA must review Class VI efforts anywhere else.[27] The IIJA includes increased funding for Class VI permitting capacity to support state primacy efforts, but there is no clear guidance on the available grants for states to seek EPA approval for a state Class VI program. EPA should provide this clear guidance promptly to allow states to establish rigorous Class VI permitting programs. In addition, as state-level Class VI primacy efforts advance, it will be important for those states to establish a transparent process that offers opportunities for community engagement early and often.

Figure 4 provides an overview of the permitting process timeline for one set of projects in Illinois. After the successful demonstration of the Illinois Basin – Decatur Project (IBDP) that stored 1 Mt of carbon dixode from 2011 to 2014, it was extended to be the Illinois Industrial Carbon Capture and Storage (ICCS) project which started injection operations in April 2017 after receiving the Class VI permit. ICCS took almost six years to complete before it could begin injecting carbon dioxide.[28] Currently, ICCS remains the only project that has managed to complete the permitting process for a Class VI well. With the main tax incentive (45Q) for this kind of project effective for 12 years, such a long permitting process could jeopardize the development of many projects. It will be critical to accelerate the permitting process for permanent geologic sequestration, while preserving the environmental and community safeguards the process is intended to ensure.

Providing a clear regulatory framework for federal agencies to facilitate interstate carbon dioxide pipeline deployments

To support large-scale deployment of carbon removal technologies, the IIJA authorizes the development of four regional DAC hubs with a removal capacity of at

Figure 4: A timeline of the Class VI permitting process



Source: Energy Futures Initiative and Stanford University, 2020[4]

least 1 Mt of carbon dioxide per year each. This scale of carbon removal would require building a regional/national carbon dioxide pipeline system to connect removal facilities with storage sites. However, federal jurisdiction over siting of inter- or intra-state carbon dioxide pipelines remains unclear.[29] The Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) regulates carbon dioxide pipeline safety, but siting oversight is more ambiguous. [30] Neither the Federal Energy Regulatory Commission (FERC) per the Natural Gas Act nor the Surface Transportation Board (STB) per the Interstate Commerce Act has clear authority or previous rulings that indicate jurisdiction over carbon dioxide pipelines.

One possible solution would be for Congress to grant a federal agency (e.g., STB) the authority to issue the needed siting permits, including the use of eminent domain. Other aspects of the pipeline regulatory process (e.g., inspection, carbon dioxide stream composition) would be exercised at the state level. This cooperative model between federal and state agencies would provide some of the regulatory clarity needed for carbon dioxide pipeline projects to proceed.[31]

Developing a clear framework for long-term liability of stored carbon dioxide

Geological sequestration projects inject carbon dioxide underground with the intent of it staying there safely and permanently, but 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 few states have established regulatory approaches to address this issue, such as by ultimately having the state assume long-term responsibility for the stored carbon dioxide.

These states are not letting project developers and operators off the hook. They would have liability for a set number of years at the outset. However, after meeting a minimum number of years of storage and satisfying specific performance criteria, regulatory frameworks would transfer liability to an appropriate state agency. Montana (30 years post-injection), Louisiana, and North Dakota (10 years post-injection) are examples of states that have adopted this approach, and there have also been examples of this approach implemented in Canada, Australia, Netherlands, and the UK.[32]More states should think about adopting similar approaches for long-term liability (e.g., creating liability funds, dedicating a certain percentage of storage volume to reserve accounts in the case of future leaks)

MARKET-BASED MECHANISMS

Carbon pricing and revenue use

Carbon pricing is a policy instrument (which can take various forms) that creates a financial incentive to reduce carbon dioxide (and other greenhouse gas) emissions. Policies that institute a robust carbon price could help drive demand for engineered CDR solutions, which in turn could increase investments in CDR technologies.

Even with higher carbon prices, though, a recent study showed that reaching long-term mitigation goals requires dedicating some of the proceeds of these carbon pricing mechanisms to support CDR technologies.[33] The complement to placing a price on emitting carbon is rewarding the removal of carbon. However, there are currently no implemented carbon pricing models that use the proceeds to fund carbon removal projects. For example, cap-and-trade programs, such as the Regional Greenhouse Gas Initiative (RGGI) and California–Quebec Agreement, use the proceeds to support renewable energy and energy efficiency projects, direct bill assistance, and other measures, but they do not incorporate CDR in the distribution of their proceeds. Given its importance to meeting climate goals, CDR should be a supported eligible technology in those programs.

Credits for removals

Other policy mechanisms, such as clean energy standards, could also support deployment of engineered CDR as a contributor to an overall clean energy target, receiving credits based on the carbon dioxide removed. California has already adopted a similar approach in its low-carbon fuel standard (LCFS), under which carbon capture and storage (CCS) and DAC projects are eligible for credits, provided they meet various requirements (e.g., geologic and hydrologic evaluation, permanence, injection monitoring, post-injection closure). The inclusion of CDR in such policy instruments could unlock significant investments and help CDR solutions reach their removal potentials.

Procurement programs

Procurement programs can also create sustainable demand for carbon removals by requiring a share of the federal procurement capacity to be used for removing carbon from the atmosphere. For example, the recently proposed Federal Carbon Dioxide Removal Leadership Act would require DOE to enter contracts to remove an increasing amount of carbon dioxide emissions—reaching 10 million tons per year—by 2035, using direct air capture or other technology-based removal solutions.[34] This would provide a clear market signal and reliable demand for the emerging carbon removal sector and accelerate the deployment of large-scale removal projects.

Additionally, the U.S. government should establish national 2030 and 2050 carbon removal targets in addition to the carbon reduction goals in the U.S. Nationally Determined Contribution (NDC) under the Paris Agreement. While CDR technologies are not expected to play a significant role in achieving the 2030 emissions reduction target, these technologies need to be deployed at-scale by 2030 to enable substantial cost reductions and emissions removal by mid-century and beyond.

FINANCIAL INCENTIVES

Improving the 45Q tax credit

Since the Section 45Q performance-based tax credit was first enacted in 2008, it has proven to be the most influential incentive for the deployment of CCS projects, with almost half of all global projects since 2008 located in the United States. Section 45Q was reformed as part of the Bipartisan Budget Act of 2018 to allow DAC projects to qualify for the credit. Since DAC is not at the same level of development as point-source capture technologies, it needed a higher credit level per ton of carbon dioxide.

The Inflation Reduction Act of 2022 includes further enhancements of 45Q that will allow rapid scale-up of DAC projects, including increasing the credit value to $180/ton for permanent geologic storage.[35] It also substantially reduces the capture thresholds for DAC facilities from 100,000 tons/year to 1,000 tons/year. This will allow smaller projects to benefit from the tax credit, increase the number of projects, and eventually drive down the costs of future projects through learning and economies of scale.

Expanding the Investment Tax Credit

The Investment Tax Credit (ITC) has proven to be one of the most effective policy mechanisms for supporting the growth of solar energy in the United States, with more than 50 percent average annual growth in solar since the ITC was enacted.[36] The ITC has also been critical in promoting the continued development of many other clean energy technologies (e.g., combined heat and power, fuel cells, geothermal heat pumps, offshore wind) through recent legislative updates (e.g., the Emergency Economic Stabilization Act of 2008, the Consolidated Appropriations Act of 2016, the Taxpayer Certainty and Disaster Tax Relief Act of 2020).[37] The ITC could likewise be expanded to support deployment of engineered CDR.

RESEARCH, DEVELOPMENT, AND DEMONSTRATION

Directing DOE to clarify Carbon Negative Shot plans

In November 2021, DOE announced its Carbon Negative Shot initiative to help CDR technologies scale and contribute to the target of net-zero emissions in the United States by 2050.[38] This research initiative aims to reduce the cost of carbon removal to less than $100 per ton of carbon dioxide equivalent; ensure robust accounting of lifecycle emissions; facilitate monitoring, reporting, and verification (MRV) of at least 100 years of durable storage; and enable gigaton-scale removal. While the Carbon Negative Shot represents a significant step forward, there is a need for additional details on the different types of projects that will be supported, funding timelines, stakeholder engagement requirements, and other specifications for successful projects. The sooner these details are clarified and communicated, the greater the opportunity for CDR technologies to be deployed at scale and in time to contribute to U.S. climate targets.

Expanding research into utilization technologies

There is also a need to increase RD&D investments in carbon dioxide utilization technologies that can contribute to net-negative products and materials. This includes using captured carbon in long-lasting materials (e.g., concrete). Captured carbon could also be used to create products, such as fuels, that will re-release the carbon when combusted, creating a net-zero cycle. Using carbon dioxide from either BECCS or DAC facilities to create these fuels creates opportunities for decarbonizing hard-to-abate sectors. For example, hydrogen and CDR-derived carbon dioxide can be combined to create synthetic, drop-in sustainable aviation fuels for the aviation sector.

EQUITABLE TRANSITION

Establishing requirements for local economic and social benefits

As engineered CDR projects scale, it is essential to make sure that projects are tailored to meet the environmental, social, and economic needs of communities where they will be located. Project developers should be required to demonstrate and commit to local benefits when they apply for DOE or other governmental funding opportunities.

Expanding apprenticeship programs and grants

The U.S. Department of Labor should expand its apprenticeship programs and grants to support the transition of traditional fossil energy workers to carbon removal jobs. It would be unfortunate and inefficient to miss the opportunity to utilize the skills of fossil energy workers and enable them to participate in building a decarbonized future. Failing to maximize this opportunity risks slowing the clean transition, both because of increased political and community pushback from potentially displaced workers and because of the significant need for skilled workers in the emerging carbon removal sector.

Modernizing environmental justice tools

Historically, environmental justice (EJ) programs have received far less funding than would be commensurate with the environmental and economic burdens of frontline communities.[39] While there have been renewed efforts to increase funding for environmental justice programs and create novel initiatives (e.g., Justice40, the Climate and Economic Justice Screening Tool), there is still a need to update the traditional process of engaging EJ communities. For example, federal agencies can provide training on EJ tools and resources so that local communities and EJ groups can make better informed decisions about whether to support CDR projects and can be confident about the value proposition for their communities from projects that move ahead.[40]

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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