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Policy Incentives to Scale Carbon Dioxide Removal: Analysis and Recommendations

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1. Introduction

Many analysts have concluded that large amounts of atmospheric carbon dioxide (CO_2) must be captured and permanently stored in the coming decades to meet international goals for arresting climate change, even with aggressive measures to limit greenhouse gas (GHG) emissions. The amount of carbon dioxide removal (CDR) needed to achieve net-zero GHG emissions poses a technological challenge, requiring significant advances in CDR capability and deployment. CDR at the needed scale will be expensive, particularly in the near term. It also can pose social and environmental challenges through spillover effects on communities, changes in land use, and major increases in electricity consumption. This report discusses the challenges for the United States in scaling up CDR, recommends immediate policy actions to improve and scale up CDR, and discusses longer-run policy frameworks through which CDR can play its necessary role for achieving net-zero GHG emissions in the United States by midcentury. In particular, we recommend—with important caveats—that CDR incentives be integrated with incentive-based mechanisms for GHG mitigation in the longer term.

The “removal gap” is the amount of CDR needed to achieve policy targets for limiting temperature increase, given trajectories for GHG emissions and policies for their mitigation. As the size of the removal gap becomes clearer, so does the gap in removal policies. As observed in Smith et al. (2023), no countries have yet set removal goals. Current US policies encourage some CDR via subsidies for increased forest carbon storage, carbon capture and storage (CCS) with bioenergy, and direct air capture. A variety of recent policy measures, including financial incentives in the 2022 Inflation Reduction Act, are providing increased CDR stimulus. However, the size of the removal gap and the policy focus on near-term initial investments versus longer-term technological development and scaling up indicate a need to fortify current policies *and* consider longer-term policies to induce the required amounts of CDR capacity.

Notably, the nature and design of policies to motivate and finance the necessary levels of CDR have received little attention, an oversight that is increasingly recognized (Honegger 2023; Meyer-Ohlendorf and Spasova 2022; Schenuit et al. 2021).[1] Recent studies on the need for CDR make these observations:

> “There is an urgent need for comprehensive policy support to spur growth in CDR” (Smith et al. 2023, 39).
>
> “CDR at anywhere approaching the scales projected here would require strong policy incentives … and public investment …” (Fuhrman et al. 2023, 9).

1 An exception focused on BECCS deployment is Zetterberg et al. (2021).

Substantially scaling up global CDR by midcentury will be a technological challenge. It will also be a challenge for climate policy. Core policy questions include the following:

- How can policies create the incentives needed for private provision of CDR at a large scale over the long term?
- If private sector investment in CDR remains limited by high cost or other constraints, what might the government do to scale up CDR?
- What policies would improve CDR technologies and lower their cost over time?
- How do CDR and GHG emissions reduction policies interact, and what are the implications for CDR policy design?

This report also addresses complementary policies to deal with a range of other issues that arise in scaling up different CDR approaches:

- What measures can address the environmental and social consequences of CDR and thus ameliorate the negative community reactions that otherwise may result?
- Beyond technological and economic barriers, what other barriers to CDR deployment need to be addressed? Two examples: health and safety measures, and the siting and regulation of industrial capture facilities, GHG storage facilities, and CO_2 pipelines.

Our focus is US policy, though important aspects of our analysis are also relevant for other countries. In addition, US policy will trigger international questions, such as whether CDR projects abroad can be used by US emitters to offset their emissions. The United States should play a leading role in CDR deployment and policy development because it is the second-largest global GHG emitter, with a correspondingly large need to counteract residual emissions. In addition, the United States is in a strong competitive position to produce CDR, given its wealth, robust institutions, capacity for technological innovation, and large land mass suitable for nature-based removal and storage infrastructure. The United States also has an existing, though limited, suite of removal incentives on which to build.

The report is organized as follows. Section 2 explains the urgent necessity for carbon dioxide removal as a complement to emissions reductions. Section 3 looks at the various technologies that can deliver CDR, their development status, and their costs. Section 4 lays out the criteria by which we analyze current and recommended CDR policies. Section 5 reviews today's US CDR policies and highlights policy gaps, weaknesses, and other barriers to CDR deployment.

Section 6 makes recommendations for new policies and modifications of existing policies to accelerate CDR technology development and larger-scale CDR investments. It also makes recommendations for addressing CDR's environmental and other community effects, and it suggests complementary policies related to, for example, permitting CO_2 pipelines and storage facilities. The recommendations in Section 6 can be thought of as a policy "on-ramp" that can facilitate the transition to a policy architecture consistent with net-zero ambitions. However, the policy steps discussed in Section 6 will not drive sufficient CDR investment to meet net-zero goal.

Section 7 explores the more ambitious midcentury CDR policy architecture needed to continue the transition to net zero and compares the options in terms of cost-effectiveness, equitability, and feasibility. Section 8 concludes with some final observations.

2. Net Zero: The Goal and the Gap

Because growth in GHG emissions has not been curtailed as envisaged in the 2015 Paris Agreement (which itself was only an initial step toward deep cuts in GHG emissions), many observers have concluded that the internationally accepted aim of capping the global average temperature increase at less than 2.0°C, and as close to 1.5°C as possible, is infeasible without major increases in CDR.[2] Net zero requires both deep emissions reductions and emissions removals (the "net" in net zero) to offset residual emissions that are economically or technologically impractical to avoid. Furthermore, net *negative* emissions removal (above and beyond what is achieved by a net-zero economy) will be necessary to reduce the stock of atmospheric CO_2 if emissions "overshoot" the trajectory for achieving the temperature limits.

For those reasons, the need for large-scale increases in CDR is urgent. How much new CO_2 removal is needed depends on the timing of global emissions pathways. However, the National Academy of Sciences (2019) estimates that worldwide, 10 Gt of CDR will be needed annually by 2050, and 20 Gt annually by 2100.[3] These numbers are consistent with a more detailed range of scenarios reported in Smith et al. (2023), who report a range of 6.8 Gt to 16 Gt annually by the time net zero is achieved, and larger amounts in the final decades of the century.

Smith et al. (2023) also report that about 2 Gt is removed annually worldwide. This implies the need to quintuple annual global removal by 2050 and increase it by a factor of 10 by 2100. Although quintupling global removal over the next 27 years may not seem challenging, 99.99 percent of the current 2 Gt of CDR comes from afforestation, reforestation, and carbon-oriented forest management practices. This form of removal faces natural biophysical limits (available land area, suitable climatic and soil conditions), not to mention the social and economic trade-offs associated with massive conversion of agricultural and range lands to forest. This means most new CDR must come from novel technology that has not yet been deployed at scale.

The 2015 Paris Agreement reflects voluntary national commitments to GHG mitigation, which in turn reflect countries' state of economic development. Article 3 of the 1992 United Nations Framework Convention on Climate Change also allows for "common but differentiated responsibilities." Looking ahead to midcentury, how

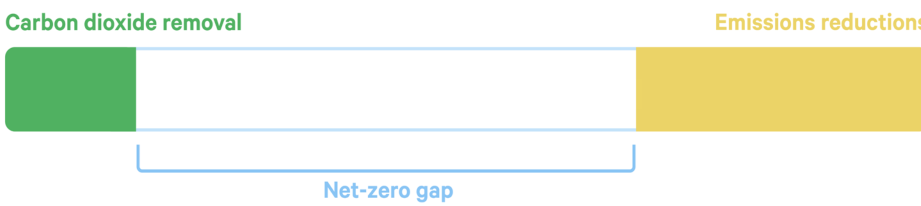
2 Smith et al. (2023); Coalition for Negative Emissions (2021); Environmental Defense Fund (2021); Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration et al. (2019); IPCC (2018); World Resources Institute (n.d.). These sources also provide background on the temperature goals; in addition, see IPCC (2018).

3 For reference, the United States currently emits roughly 5 Gt annually.

much decarbonization by (current) lower- and lower-middle-income countries could be expected? For the world to achieve global net-zero emissions by midcentury, advanced-economy countries must aim for negative net emissions to offset continuing emissions elsewhere.

In Figure 1, the bar represents the total amount of emissions reduction (ER) and CDR needed to achieve net zero emissions. In the status quo, there is not enough of either to meet the net-zero goal—that is, CDR is insufficient to counteract residual emissions. The net-zero gap must be addressed by expanding both ER and CDR.

Figure 1. Status Quo: Not Enough CDR or ER



In a net-zero economy, the gap is filled by expanded ER and CDR. All residual emissions remaining after ER measures are implemented are counteracted by CDR (Figure 2).

Figure 2. Midcentury Net Zero: CDR Removes Residual Emissions

The stylized graphs raise two important policy questions. What is the right balance of ER and CDR in a net-zero economy, and what policy mechanisms will best achieve that balance? In Sections 6–7, we address different policy approaches.

3. Carbon Dioxide Removal Technologies and Costs

3.1. Technological Options

CDR comprises several processes by which CO_2 is deliberately removed from the atmosphere and durably stored in land, ocean, geologic, or product reservoirs (IPCC 2022a).[4]

ARI (afforestation, reforestation, and improved forest management) consists of actions taken to expand the forest carbon sink (including carbon stored in soils); it includes harvested carbon stored in wood-based products.[5] We refer to this collection of activities as simply afforestation because the distinction between afforestation (the conversion of land to forest) and reforestation (the replanting of forest after harvest or disturbance from fire, disease, or pests) is not important to our recommendations.

BC (biochar) is a carbon-dense material formed when plant biomass is heated to a high temperature with limited oxygen. Applying it to soils or burying it increases carbon sequestration in soils.

BiCRS (biomass carbon removal and storage) involves the capture of atmospheric carbon by plants followed by the disposal of that plant biomass in ways that inhibit decomposition, such as underground or deep in the ocean. Another BiCRS approach is ocean iron fertilization to promote phytoplankton CO_2 uptake; the storage occurs when the phytoplankton die and fall to the ocean floor.

BEC (bioenergy with carbon capture) is the production and use of plant biomass as a feedstock for supplying energy, through either combustion or fermentation and refining into fuel; **BECCS** (bioenergy with carbon capture and storage) adds transportation (by pipeline or other means) and long-term underground storage of the CO_2.[6]

DAC (direct air capture) uses chemical processes to remove CO_2 directly from the air; DACCS (direct air capture with carbon storage) adds transportation if needed (by pipeline or other means) and long-term underground storage of the CO_2. Because DAC facilities are designed to remove CO_2 in concentrations found in the air, they do not have to be located near sources of CO_2 emissions but could be located near storage facilities.

4 Depending on the technology, the duration of storage varies and may be uncertain—clearly important factors.

5 Additional carbon could also be stored in agricultural soils, but both the amount of feasible storage and its permanence remain unclear (Toman et al. 2022).

6 BiCRS is sometimes defined in a way that includes both BECCS and storage in wood products (Sandalow et al. 2021). We choose to define it as a set of approaches distinct from those sequestration options.

EW (enhanced weathering) involves pulverizing silicate rock, which accelerates its natural ability to absorb atmospheric CO_2, and then spreading the pulverized rock on land.

OAE (ocean alkalinity enhancement) expands the ocean carbon sink and reduces ocean acidification by altering the chemistry of seawater, in either of two ways. The first is like EW, through addition of silicate rock material, but with dispersal in the ocean. The second uses onshore facilities to process seawater electrochemically and then return it to the ocean.

CDR does not include naturally occurring biotic, mineral, or marine CO_2 uptake because those processes are not deliberately induced or enhanced by human action. Natural processes provide a baseline amount of atmospheric removal, but the definition of CDR restricts it to deliberate additions to that baseline.

CDR also does not include carbon capture, use, and storage (CCUS) of industrial or power sector CO_2 emissions, except in the context of BECCS, because CCUS captures exhaust gases rather than removing atmospheric CO_2 and is therefore considered an emissions reduction strategy.[7] Finally, CDR does not include avoided deforestation because deforestation is a source of emissions. Avoided deforestation is accordingly considered an emissions reduction strategy, not CDR.

Because BEC and DAC technologies figure prominently in the discussions that follow, additional information on them is provided in Box 1.

7 However, technological improvement in BECCS is to a considerable extent improvement in CCS technology (leaving aside improvements in the efficiency of the facilities using biomass-based fuels). Since the need for CDR depends on the scale and pace of increase in GHG mitigation, the need also will be affected by the extent to which CCS plays a role in GHG mitigation. As noted subsequently, major controversies surround that question.

Box 1: Summary of BECCS and DACCS Technologies

Bioenergy carbon capture and storage applies the point-source carbon capture technologies used for CCUS to the emissions from burning biomass energy inputs. Together with the sequestration of CO_2 in biomass fuels, this is what qualifies the technology as a potential CDR approach. The most common capture technologies involve various chemical reactions (with liquid solvents or solid sorbents) to remove the CO_2 from flue gas. The captured CO_2 then is moved into long-term underground storage (in the United States, that transport will be mainly by pipeline). The capture efficiency of the point-source carbon technologies generally exceeds 90 percent of the CO_2 in flue gas from power and industrial plants, though non-bioenergy CCUS demonstration projects have regularly underperformed (Hong 2022; Osman et al. 2021; National Energy Technology Laboratory n.d.; Robertson and Mousavian 2022).

That level of capture efficiency also does not account for emissions attributable to the electricity used to operate the facility (Scope 2 emissions), emissions generated in securing the feedstock or sourcing materials (Scope 3 emissions), or CO_2 leakage in transportation and storage (Chiquier et al. 2022). A related concern is the life-cycle energy production from BECCS. Fajardy and Mac Dowell 2018) show that the gross energy produced by the biomass combustion, minus the energy consumed by the carbon capture technology and the feedstock cultivation, preparation, and transport, can be less than half of the gross energy produced.

Wood pellets, agricultural waste, and lignocellulosic biomass (straw and grasses) are among the popular fuel types for BEC (Buchheit et al. 2021; Muratori et al. 2016). Municipal and animal waste, algae, and repurposed cooking oil have also received attention as potential feedstocks (Pour et al. 2018). Biomass inputs may be combusted (e.g., in power plants or industrial boilers) or fermented, followed by production of bioethanol that then can be combusted or sold. The most active commercial applications of BEC, wood pellet burning for power generation and bioethanol production, are the most land and water intensive.

BEC also requires land, water, and nutrient inputs to produce feedstock as well as water for the carbon capture process. Rosa et al. (2021) estimate that BEC has the highest water footprint of all carbon capture technologies.

Direct air capture and storage removes low-concentration CO_2 from the ambient air using chemical reactions similar to those for BECCS, followed by transport (as needed) and storage. Because the CO_2 concentration is low (compared with flue gas), more energy is required per unit of CO_2 removed for DAC than for BEC—one reason DAC is currently more expensive (Ozkan et al. 2022). The power requirements also raise a concern about potential Scope 2 emissions and reduced local air quality. Negative emissions via DAC or BEC require clean energy to reduce or eliminate the Scope 2 emissions. Ammonia can be a byproduct emission from both BEC and DAC plants, depending on the choice of sorbent used for CO_2 separation.

3.2. Conventional versus Novel Technologies

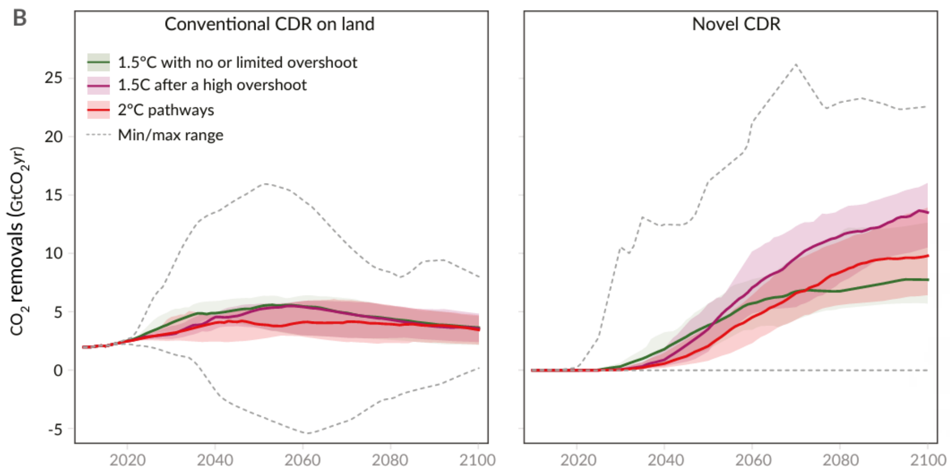
ARI is often termed the "conventional" approach: it already occurs at a large (though insufficient) scale, and its broader deployment faces no significant technological barriers. Of the "novel" approaches, DACCS, BECCS, BC, and BiCRS have all been demonstrated and in some cases deployed, but at limited scale and relatively high cost. Continued basic and applied research and development will be needed to lower costs and expand use. EW and OAE are at an even earlier stage of development. Although considered physically and chemically practical, they have not yet been deployed in any significant way.[8]

Figure 3 conveys the need for both expanded ARI and more significant expansion in novel CDR approaches. In their analysis of integrated assessment scenarios, Smith et al. (2023, Chapter 7) distinguish between "conventional CDR on land" (which corresponds to ARI) and "novel CDR" (all other approaches). They find that a doubling of conventional land-based CDR by 2060 and major increases in novel CDR (up to 1,300 times the current levels) are needed to achieve net zero by midcentury, with even more expansion needed by 2100.

Currently, a doubling of CDR via ARI appears to be physically and technologically possible (Griscom et al. 2017; Roe et al. 2019; Austin et al. 2020), but it would require significant policy intervention. Increases beyond a doubling of ARI would create increasingly difficult land-use trade-offs and other concerns. In comparison, although DACCS and BECCS are technologically feasible, their limited development and deployment constrain dramatic acceleration at an acceptable cost. Lowering the cost of the novel CDR approaches is therefore paramount for achieving the CDR growth necessary to meet the Paris Agreement temperature goals.

8 See Fuhrman et al. (2023) for further discussion of novel CDR approaches.

Figure 3. Scenarios for Expanding Conventional and Novel CDR



Source: Smith et al. (2023, 74). Removal pathways needed to meet 2100 Paris Agreement temperature goals are based on a portfolio of integrated assessment scenarios, with the share of conventional land-based and novel approaches depicted separately. Conventional CDR = ARI; Novel CDR = DACCS, BC, BECCS, BiCRS, EW, OAE.

3.3. CDR Cost Estimates

CDR costs per unit of CO_2 removed vary significantly across these approaches, and future costs are highly uncertain. For novel approaches, costs are expected to decline over time with further innovation and investment, but the magnitude and timing of cost reductions are unpredictable.

ARI cost estimates are \$10–\$100/tCO_2.[9] Although already deployed at scale, there is no central cost estimate: forest-based CDR costs vary greatly because of differences in forest features and forest sequestration strategies (e.g., afforestation vs. changed harvest practices). The opportunity costs of land-use conversion to forests (e.g., its value in alternative uses, such as agriculture or range) and changes in forest management (e.g., the commercial opportunity costs of delayed harvests) also vary significantly.

DAC costs for the two most common removal strategies are \$90–\$220/tCO_2 (for solid sorbent methods) and \$150–\$600/tCO_2 (for liquid solvent methods) (Hong 2022; McQueen et al. 2021; Ozkan et al. 2022; Sinha and Realff 2019). The cost difference between the two methods is driven by the higher thermal energy requirements of

9 Interpreting forest sequestration cost estimates requires distinguishing between the (relatively lower) costs of avoided deforestation (which is an emissions reduction strategy, not CDR) and the costs of forest-based CDR (e.g., from afforestation). For cost analyses, see Mendelsohn et al. (2012); Nielsen et al. (2014); Busch and Engelmann (2017); Griscom et al. (2017); and Austin et al. (2020).

the latter approach, excluding transport and storage costs.[10] A DAC plant operated by Climeworks currently sells removals for \$1,200/tCO_2 (Climeworks 2023).

(Fuss et al. 2018) estimate that **BEC** via combustion costs \$80–\$200/tCO_2, without specifying feedstock. Anticipating higher costs in biomass feedstocks as BEC is scaled up, the Intergovernmental Panel on Climate Change (IPCC) projects that the first 0.3 Gt of emissions captured from BEC will cost \$50–\$100/tCO_2, with additional CDR costing \$100–\$200/tCO_2 (IPCC 2022b). Different feedstocks have different compositions and energy potentials. Bioenergy company Drax reported the joint cost of generating 1 MWh of energy using wood pellet feedstock and capturing 1 ton of CO_2 at \$186 (Gratton 2022). BEC with bioethanol fermentation reportedly costs \$30/tCO_2 (Sanchez et al. 2018). The cost of capture at pulp and paper plants with BEC integrated into the operation is estimated to be \$31–\$73/tCO_2 in the United States (Sagues et al. 2020). Again, these costs exclude transport and storage.

The transport costs of CO_2 for DACCS and BECCS depend on the mode of transportation. In the United States, liquid CO_2 can go by truck at a cost of \$0.175/tCO_2/mile; train transport costs \$0.071/tCO_2/mile (Sandalow et al. 2021). Combined pipeline transport and storage costs per unit of CO_2 have been estimated at \$4–\$45/tCO_2; unit costs decrease as the flow rate rises and increase less than proportionately with distance traveled (E. Smith et al. 2021, Table 5).

BC for CDR costs have received relatively little attention. A survey of estimates suggests \$30–\$120/tCO_2 (Fuss et al. 2018).

BiCRS costs are also not well documented. Costs of transport from biomass sources to storage sites in the United States are \$20–\$40/tCO_2 (Stolaroff et al. 2021). A recent study estimates the cost of "wood vault" storage, where the decomposition of woody biomass is prevented via anaerobic containment options, to be \$10–\$50/tCO_2 (Zeng and Hausmann 2022).

As **OEA** and **EW** rely on similar inputs, their estimated costs are similar. A review of OEA costs reports \$72–\$159/tCO_2 sequestered (Renforth and Henderson 2017). EW costs of \$60–\$200/tCO_2 have been reported, depending on the type of rock used (Beerling et al. 2020; Strefler et al. 2018). A supply chain for rock or silicate powder, which exists in bulk from mining operations but is disparately located and not well catalogued, must be developed before the deployment of EW and OEA can be accelerated (Beerling et al. 2020).

10 Here, levelized cost refers to the combined operating and capital costs per tCO_2 captured. Not all reported costs are levelized; review papers may report operating costs only.

4. Criteria for CDR Policy Analysis

Our analysis of policies to accelerate implementation of CDR emphasizes the following themes.

CDR policies should be designed to minimize costs in achieving their goals.

Cost-effectiveness is self-evidently desirable—both to reduce the overall social burden of a net-zero economy and to minimize political opposition. Cost-effectiveness refers to the minimization of *all* costs associated with a particular CDR approach, not just direct technological expenditure. This includes monitoring and verification costs, community dis-amenities, and negative (or positive) spillovers to other sectors. Moreover, the goal is to minimize costs of the transition to net zero—not just in the short term but also over the coming decades, when innovation could reduce costs significantly.

Policies focused only on accelerating CDR and reducing emissions may not address all the technologies' social costs, especially community and sectoral spillovers. Complementary measures are needed to address these effects, which is why it is important to be attentive to their presence. In addition, ethical and equity concerns, such as those advanced by the environmental justice movement, are not captured in this perspective on costs. Such concerns (as discussed below) must be addressed by any policies that seek the right balance between mitigation and removal.

Policy should be technology neutral.

CDR technologies are diverse, many have not yet been deployed in practice or at a significant scale, and some have yet to be discovered. Accordingly, we advocate policies that reward performance rather than favor one technology over another. Because technology performance will change as CDR costs fall and capacity expands, remaining neutral over time, with consideration of the different characteristics and relative maturities of the technology options, is critical for achieving CDR cost-effectiveness.

Financing sufficient CDR is a core policy challenge.

Policymakers must consider many things: creating incentives for innovation, accounting for and dealing with social and environmental co-effects, and ensuring that removal occurs as intended and promised. However, perhaps the biggest questions for CDR policy are how it will be financed and by whom. The cost of transforming economies to meet net-zero and temperature goals will be large, and costs are unavoidable if those goals are to be met. A core policy goal is therefore to create incentives to finance sufficient CDR to meet climate change limitation goals while also trying to achieve the goals cost-effectively and to distribute the cost across society in a way that is equitable and politically acceptable.

Public sector support for CDR research, development, and demonstration is needed, but as technologies mature, it should be scaled back in favor of policies relying on private sector incentives.

Market failures associated with early-stage innovation—in this case, the novel CDR stage—argue for government support for RD&D. One such failure is the non-appropriability of innovation's benefits (arising from the public-good nature of new information), which depresses the incentive to undertake early-stage innovation. Moreover, between small pilots and commercialization—the stage called the "valley of death" in the life cycle of innovation—obtaining sufficient private finance is difficult because financial risks are high and hard to diversify. Given the amount of technological transformation needed and the time required to accomplish it, aggressive and well-funded RD&D programs to improve CDR technologies and lower their costs are urgently needed. However, in the longer run, as technologies mature, the rationale for public sector support declines and a shift to private technology development incentives is more appropriate. Accordingly, we emphasize policies that feature early government RD&D investment but are designed with long-run private sector innovation and investment incentives in mind.

Significant policy transitions are required, and interactions among policies need to be considered.

Existing policy frameworks can be improved to stimulate innovation and increase CDR investment in the near term. However, existing policy approaches, even if they are strengthened, will be inadequate to achieve net zero by midcentury. Policy incentives should evolve from encouraging incremental improvements in the status quo for CDR to a midcentury policy architecture capable of achieving net-zero or even net-negative emissions. In that architecture, policies for CDR and mitigation (emissions reduction) need to evolve in tandem.[11] For example, policies affecting the shift to renewable electricity generation (which mitigates emissions) have a significant bearing on the efficacy and relative cost of CDR technologies like DACCS. Another example is the relationship between voluntary CDR credit markets and compliance-based credit markets if emissions reduction requirements are strengthened and expanded to new sources in the future.

More fundamentally, the linkage between CDR and mitigation is important because adequate CDR cannot be cost-effectively or fairly delivered using only government policies to directly stimulate CDR investment, like subsidies. Policies that create incentives for emitters to undertake or finance CDR are also needed. We develop below the argument that a cost-effective approach to net zero is to strengthen emissions reduction requirements and allow GHG emitters to offset their emissions by financing CDR. The longer that economy-wide emissions mitigation policies are delayed, the greater the need and the difficulty in scaling up CDR.

11 The idea that CDR policy incentives should be integrated into broader climate policy incentives is also emphasized by Zetterberg et al. (2021) in their analysis of BECCS policy.

Negative CDR effects must be identified and addressed.

As noted, CDR technologies can have negative effects and raise equity issues. For example, industrial-scale facilities to capture and transport CO_2 can themselves create local health and safety risks; those capture facilities and the electricity generation needed to operate them can increase local pollution; and siting industrial facilities, pipelines, and large afforestation areas may require extensive changes in land use.[12] Such effects will matter to the politics and fairness of CDR deployment, and they need to be addressed. Complementary policies that address the ancillary effects of CDR also can enhance its practical feasibility by reducing or redistributing costs.

5. Current US CDR Policies

The policies considered in this section fall into several general classes. The largest class is policies that stimulate research, development, and demonstration—that is, policies that encourage innovation in CDR technologies and early investment to test those technologies in the field. Another class is policies to directly stimulate increased use of CDR (in contrast to innovation policies that increase use via cost reductions). An example of this is California legislation—passed by the state senate but not yet enacted—that would require CDR by entities reporting 25,000 or more metric tons of GHG emissions per year.[13]

Other policies address enabling conditions—measures affecting the transport and storage of captured CO_2, as well as policies addressing monitoring, reporting, and verification (MRV). The last class comprises policies for ancillary impacts (e.g., effects on local air quality or land and water use) and for social equity. We retain the label "novel" for all options that are not conventional land-based CDR (like ARI). Currently, no specific policies target advanced or novel nature-based solutions (BC, BiCRS, EW, and OAE), though some government R&D funds could be available soon for these options (see discussion of the CREST program, Section 6.2). Current policies primarily relate to ARI, DACCS, and BECCS.

12 Increasing land devoted to forest cover can have positive environmental effects (e.g., enhancement of species habitat and water resources), but it will also reduce the availability of land for agriculture and human settlement, potentially leading to higher food and living costs and effects on rural communities.

13 California Senate, SB-308 Carbon Dioxide Removal Market Development Act, May 18, 2023 (**https://legiscan.com/CA/text/SB308/id/2814029**). The bill would require some emitters to purchase negative emissions credits beginning in 2028.

5.1. Policies for Stimulating Forest Carbon Removal

Federal programs administered by the US Department of Agriculture (USDA) provide subsidy payments (usually cost-shares) for afforestation, reforestation, and forest carbon management.[14] Notable infusions of new cost-share money were included in the Infrastructure Investment and Jobs Act (IIJA) in 2021 and the Inflation Reduction Act (IRA) in 2022.[15] The text of the IRA establishes a priority to reduce and sequester CO2 and includes payments to small and underserved forest owners for increasing carbon sequestration and storage, as well as to states, Native American communities, and local governments for tree planting.[16] These funds are available to agricultural landowners as well. The IRA also provides $1 billion in technical assistance funds to induce participation in these cost-share programs.

Several other programs are designed to stimulate increased use of wood products, including long-lived forest products that contribute to carbon sequestration. The IIJA provides financial assistance to facilities that purchase and process byproducts from ecosystem restoration projects. The funds can be used to offset the costs of establishing, reopening, retrofitting, expanding, or improving sawmills or other wood-processing facilities. These measures can reduce the cost of switching to long-lived wood products that sequester carbon. Grants and loans to encourage use of woody biomass in energy production are also available under the Rural Energy for America Program.

Some emissions reduction regulations also create demand for increased forest carbon sequestration by allowing forest carbon credits to offset emissions. California's cap-and-trade program allows covered sources to meet a small percentage of their emissions reduction obligations through forest carbon credits and other types of emissions credits (California Air Resources Board 2021).[17]

14 These include the Forest Land Enhancement Program, Conservation Reserve Program (CRP), Environmental Quality Incentives Program (EQIP), Healthy Forests Reserve Program, and Emergency Forest Restoration Program.

15 Infrastructure Investment and Jobs Act, Pub. L. No. 117-58, H.R. 3684; Inflation Reduction Act of 2022, Pub. L. No. 117-19, H.R. 5376.

16 The federal tax code provides tax credits, deductions, treatment of capital gains, and amortization rules that reduce the forest sector's tax burden, thereby increasing forest carbon sequestration incidentally by inducing increased forestland area (Sedjo and Sohngen 2015).

17 The allowed percentages are 4 percent through 2025 and 6 percent over 2026–2030. In the Regional Greenhouse Gas Initiative (RGGI, implemented by Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia to cap and reduce their GHG emissions associated with electricity production), forest-based and other credits can be no more than 3.3 percent of total emissions reductions, and several states do not allow credits for offsetting plants' emissions (RGGI 2023).

Voluntary climate commitments also can create demand for forest carbon credits and thus stimulate forest CDR. Customer, shareholder, and employee concerns drive corporate commitments (such as to net-zero operations) even without regulatory requirements. These commitments have stimulated the market for CDR credits, with forest credits dominating the marketplace. Voluntary markets take various forms, from bilateral agreements between a specific company and forest landowner to marketplace-like exchanges where an intermediary connects offset demanders and suppliers. Currently, hundreds of companies participate in voluntary offset markets, with offsets provided by dozens of forest providers supported by verifiers who validate the claimed increases in carbon storage. In 2021 the size of the global voluntary credit market was estimated to be $700 million, but McKinsey has stated that corporate net-zero commitments could trigger a substantial increase—up to $50 billion by 2030 (Blaufelder et al. 2021).

Finally, a variety of US programs are designed to stimulate innovation in wood product utilization and thus expand demand for forest products that could substitute for carbon-intensive products, such as cement and steel. The Forest Service's Forest and Rangeland Research ($323.6 million in FY 2022) supports technology development, including research by the Forest Products Laboratory. The agency's Wood Innovations Program provides grants to support R&D in wood products, including innovative building materials and biomass-to-energy production. The IRA includes $100 million in additional funds for the Wood Innovation Grant program for the construction of new facilities "that advance the purposes of the program and for the hauling of material removed to reduce hazardous fuels to locations where that material can be utilized" (Subtitle D Sec. 23001(a)(5)). The 2018 Farm Bill directs USDA to support R&D on the use of mass timber for "tall wood buildings" (the Timber Innovation Act authorized under HR 2, the Agriculture Improvement Act of 2018).

5.2. Policies for Stimulating Use of DAC and BEC

The 45Q tax credit, initiated in 2008, was expanded by the IRA in 2022.[18] DAC investments can receive a tax credit of $180/ton of CO2 removed when the CO_2 is geologically stored, or $130/ton credit for facilities that remove at least 1,000tCO_2 per year if the CO_2 is channeled to enhanced oil recovery (EOR). CCUS also receives a 45Q tax credit, which benefits BECCS directly (since it uses CCS) and may benefit both DAC and BEC indirectly through the creation of pipelines and augmented storage opportunities. The credit for CCUS is $85/ton for geologic storage and $60/ton for utilization, including EOR. To receive the tax credit, capture from power generation must exceed 18,750 tons per year and achieve a capture rate of greater than 75

18 Because of high costs, DAC technology has played a limited role to date in compliance-based or voluntary markets for emissions credits. DAC is an option for voluntary action by pioneer investors in the Frontier Climate fund, an advanced market commitment aiming to buy $1 billion of permanent (over 1,000 years) carbon removal by 2030 (**https://frontierclimate.com/**).

percent.[19] Both tax credits are based on gross CO_2 removal by a facility, without considering the emissions associated with the electricity required to operate the facility (Scope 2 emissions).[20]

5.3. RD&D Policies and Investment Initiatives for DAC and BEC

RD&D policies can lower the cost of DAC and BEC. "Supply-push" policies can help fund the initial steps of basic research and lab-scale technology development and have been used at all levels of technology readiness. Most recently, significant funds have been made available for demonstration projects. "Demand-pull" policies create demand for the fruits of RD&D by increasing the economic rewards for technological advances and demonstrations, thus creating an economic incentive to scale up production and commercialization.

Government innovation policies are justified by market failures specifically related to RD&D. One is the difficulty innovators face in gaining market returns commensurate with the full value to society of their technological advances. Patent protections have limited durations, for instance, and sometimes minor changes to patented ideas and technologies can skirt such protections.

Carbon Negative Shot, one of the Department of Energy's (DOE) Earthshot innovation efforts, was established in 2021 to promote R&D for engineered CDR. Its goals are to achieve the $100 per metric ton cost for CDR by 2030, establish rigorous life-cycle analysis accounting, develop cost estimates for MRV with long-term storage, and increase CDR use to the gigaton removal scale. It is most applicable to DAC, but processed pellet or ethanol BEC configurations could also fall within the scope of the innovation target. DOE's 2023 Request for Information on stimulating place-based innovation policies could apply to DAC or BEC. For the early and middle stages of new technology development, supply-push measures also can be used to co-finance pilot tests. Even with recent legislation giving the DOE billions of dollars for demonstration

19 CCUS also benefits from the 48C tax credit, which subsidizes the production of equipment for carbon capture, transportation, and storage alongside other clean energy products. Another IRA tax credit provision, the 45V program, subsidizes production of hydrogen (H_2) with CC. The use of H_2 made in the United States with natural gas through a process called steam methane reforming is widespread in refining, fertilizer production, and other types of chemical production. Adding precombustion carbon capture units to the steam methane reforming process can reduce its direct emissions footprint to the level necessary to receive the credit. The 45Q and 45V credits cannot be stacked. Analysis has found that 45Q is the better option for H_2 producers in most cases (Krupnick and Bergman 2022).

20 Projects receiving 45Q tax credits under the IRA also must comply with several labor-related requirements, including paying prevailing wage rates and conditions governing apprenticeships. Should an operation aiming for the tax credit fail to meet the IRA employment requirements, all credit values are divided by 5.

projects, more is likely to be needed to invest in pilot facilities to improve technology design and operation and demonstrate commercial-scale feasibility.

Another market failure is that private capital markets may either overestimate the risk associated with newly developed technologies or demand a high rate of return on private investment because it is hard to reduce portfolio risk through diversification. A new technology then must pass through this "valley of death" to advance toward market-level application. Demand-pull policies are especially useful for addressing the potential for commercially scaling up a technology once pilot tests demonstrate its promise. They also are useful for fostering the scaling up of technology use to obtain further cost reductions from economies of scale and learning-by-doing.

Turning to specific CDR innovation programs, new prizes have been created to serve as demand-pull mechanisms. The IIJA appropriates new funding for DAC Technology Prize Competitions. DOE has established three prize programs for DAC: the DAC Pre-Commercial Energy Program for Innovation Clusters Prize, DAC Pre-Commercial Technology Prize, and DAC Commercial Prize (National Energy Technology Laboratory 2023). These prizes collectively will provide up to $115 million in funding, with prizes increasing over successive phases. Each prize program is phased and targets a different aspect of bringing this technology to market. Also worth noting are the nongovernmental innovation prizes, such as the XPRIZE awarding $100 million for viable CDR pathways scalable to gigaton removal needs (XPRIZE Team 2021).

The Storing CO_2 and Lowering Emissions (SCALE) Act, which passed as part of the 2021 IIJA, provides billions of dollars for CDR administered through DOE. Included in the IIJA is $3.5 billion in grant funding for regional DAC hubs; two have already been funded, in Texas and Louisiana.[21] DAC facilities located close to one another that capture and either sequester or utilize at least 1 MMT CO_2/year are eligible. The IIJA also provides grants for states and municipalities to procure building materials made using captured CO_2, like concrete and aggregates.[22] The premise of the DAC hubs program is that locating DAC facilities close to storage sites or CO_2 demanders and funding multiple hubs will stimulate positive spillovers through information sharing and learning-by-doing that can accelerate and improve individual companies' RD&D efforts. The SCALE funding also includes money for the Carbon Capture Demonstration Projects Program, which finances projects targeting above 95 percent CO_2 removal for geologic storage. Another $2.5 billion funds carbon storage, validation, and testing

21 SCALE Act. H.R. 8995. 116th Cong. (2020).

22 Steel is hard to decarbonize, so carbon capture technology is considered essential to the production of low-carbon steel. US Steel is planning on incorporating CC technology to meet its midcentury net-zero goal, making production eligible for future procurement under the SCALE Act.

through the National Energy Technology Laboratory's CarbonSAFE initiative, and $2.1 billion in loans is available for the Carbon Dioxide Transportation Infrastructure Finance and Innovation Program.[23]

Finally, demand-pull policies include public sector procurement of goods and services. For example, the IRA and the Biden administration's Buy Clean executive order have emphasized that inputs to infrastructure projects, such as steel and cement, should have low embedded carbon.

5.4. Policies and Regulatory Frameworks for CO_2 Transport and Storage

Long-distance transmission of captured CO_2 is an integral part of CCS and thus of BECCS, as well as for some DAC facilities. At present, the United States has about 5,400 miles of CO_2 pipelines; other pipelines cannot be easily repurposed for CO2 transport. The high-pressure, super-dense state in which the gas is transported has the potential to exacerbate pipeline weaknesses and lead to fracturing. In 2022 the Pipeline and Hazardous Materials Safety Administration released specific safety measures for pipelines transporting CO_2.[24] How these rules might reduce the perceived risk of CO_2 pipelines is uncertain.

A major issue for establishing storage sites is environmental approval of underground CO_2 injection. The US Environmental Protection Agency (EPA) governs the approval of so-called Class VI injection wells, used for carbon dioxide storage, through the Safe Drinking Water Act. Regulatory review of these wells seeks to prevent groundwater contamination through its interaction with injected CO_2. To speed up the approval process, some states are seeking delegation from EPA to regulate Class VI wells, but

23 In addition, $310 million is targeted to the Carbon Utilization Program, including for development of standards and certifications to support commercialization of carbon oxide products. Along with the standardization of carbon oxide products, this demand-pull program awards grants to local authorities to use or procure products derived from the capture of carbon oxides. SCALE also expands the Carbon Capture Technology Program to include pipeline infrastructure, with an additional $100 million over the next five years to be administered by the National Energy Technology Laboratory.

24 These rules include instituting emergency preparedness plans for existing pipelines, providing advisory bulletins on pipeline safety, and funding further research on pipeline safety through a competitive academic grant (PHMSA 2022).

the application process for delegation is lengthy.[25] Requirements for the geologic sequestration of CO_2 are detailed in federal regulation.[26]

Decisions on liability for the integrity of long-term storage vary across states. In states where above- and below-ground property rights differ (so-called split estate ownership), responsibility for verifying the integrity of the storage site is complicated.[27] Some states have set up mechanisms to eventually transfer monitoring responsibility for geologic storage sites to the state government after CO_2 injection has been completed, funded by fees collected from the party doing the injection on a per ton basis. This reduces the long-term risk for carbon storage project developers, who then are responsible only for monitoring and fixing leaks for the duration of injection activity (and a certain interval thereafter, usually five to 20 years). This transfer of the long-term risk to the public increases the importance of prior validation of site integrity.

5.5. Mechanisms for Addressing Equity in Benefits of CDR Expansion

Biden administration initiatives make establishment of community benefits agreements a requirement for grant funding. Plans for sharing benefits with communities must address equity issues associated with CDR projects. The Justice40 Initiative sets a goal that 40 percent of the overall benefits of an applicable government program should reach disadvantaged communities. The provisions for CCUS and novel CDR in the IIJA and IRA are included under Justice40, as are ongoing carbon capture and storage programs at the Office of Fossil Energy and Carbon Management.

Community benefits plans (CBPs) encompass Justice40 considerations specifically for regional DAC hubs (Office of Clean Energy Demonstrations 2022). Funding opportunity announcements for IIJA funds require applicants to submit an initial CBP covering four main goals: community and labor engagement; investing in the American workforce; advancing diversity, equity, inclusion, and accessibility; and contributing to the Justice40 Initiative. CBPs are weighted at 20 percent of the overall technical merit in review of proposals—a significant percentage, illustrating the importance and value of these plans for project evaluation.

25 The Bureau of Land Management (BLM) also has established a protocol for processing applications by parties seeking geologic sequestration on BLM-managed lands. Class II wells, which are used for oil and gas injection, generally can be used for CO_2 storage via EOR and do not require the siting and approval process for Class VI wells. However, California SB 1314, passed in late 2022, bans the injection of CO_2 into Class II wells, thereby effectively banning EOR with CO_2 in the state.

26 75 FR 75079, Dec. 1, 2010., Subpart RR, Geologic Sequestration of Carbon Dioxide.

27 Montana, Indiana, Louisiana, Wyoming, Nebraska, and North Dakota have all acted to establish subsurface pore space rights, often as a piece of comprehensive legislation to enable CCUS (Nixon Peabody 2022). Because BLM-managed lands are not split estate, the process of granting geologic storage rights on these lands is easier.

5.6. Environmental Considerations

BEC requires land, water, and nutrients to produce feedstocks, plus water for the carbon capture process. Effects on environmental quality and natural resources are governed by existing federal statutes regulating water quality, hazardous waste disposal, and endangered species protection, and by agreements for allocating water rights.[28] DAC plants have smaller land footprints and use less water than BEC plants.

The relationship between CCS (with BEC and otherwise) and air pollution can be complex. In the power sector, CCS will modify the profile of local pollutants (fine particulates, sulfur dioxide, and nitrogen oxides) when applied to a specific combustion process, whether that plant uses coal, natural gas, or a form of biomass. There also can be system-wide effects on local pollutants because of changes in the utilization of different types of generating plants.

In addition, gaseous ammonia is a byproduct of the amine-based carbon capture technologies used for BEC. The amount of ammonia emissions from amine-based capture systems can be significant, though it can be limited by introducing water into the system (Heo et al. 2015). The aim is to capture the ammonia in liquid form as a valuable byproduct, but fugitive gaseous ammonia is a precursor for fine particulates ($PM_{2.5}$). Gaseous ammonia also can be a byproduct of DAC if it uses amine-based technology. EPA has produced guidance on $PM_{2.5}$ precursors, including ammonia, to assist the development of state implementation plans. In addition, there are emissions limits for ammonia produced from fossil fuel combustion, which would include instances of BECCS cofiring (Mathias and Wayland 2019; Phillips 1995). Concerns over ancillary emissions from amine-based systems may attenuate as the technology underlying other types of capture systems improves and is more frequently adopted.

Irrespective of emissions, DAC or BEC facilities could be subject to various rules under the Clean Air Act. If located independently of other industrial facilities, they would be considered new sources; if co-located, they would place those existing facilities into the “modified” category. Either way, they would trigger New Source Review rules, which require more stringent limits on pollutant emissions. That in turn typically requires expensive modifications of any facilities (such as cement plants) using captured CO_2 emissions. New Source Review rules thus could be a barrier to adoption of DAC or BEC.

28 Concerns also have been raised over the potential competition between bioenergy crops and food crops for land and the implications for yield, supply, and prices (Hasegawa et al. 2020). However, modeling evidence on food prices from this land-use competition is mixed (compare Fajardy et al. 2021 and Muratori et al. 2016).

That the local pollutants mentioned above are regulated under the Clean Air Act does not automatically preclude worsened air quality. Scope 2 emissions also are a major consideration for DAC and BEC (Fajardy and Mac Dowell 2018). Standards for power plants specify maximum allowed emissions per kWh produced. Air quality could worsen near power plants that increase their electricity generation to supply a DAC or BEC facility if those plants are significant sources of pollution.[29]

5.7. Monitoring, Reporting, and Verification Challenges

An implementation challenge for all CDR policy approaches is measuring and verifying the effectiveness of projects and accounting for risks to and uncertainties in CDR performance. Performance assessment and MRV are related to issues of permanence, life-cycle emissions, additionality, and leakage.

Permanence. In varying degrees, the permanence of CO_2 storage is uncertain for any CDR project. The duration of forest carbon sequestration is inherently impermanent because of trees' natural or harvested life cycle, the life cycle of wood products (which varies by how wood is used), and the potential for fire, disease, and other risks. BC and BiCRS approaches, because they rely on storing biotic material and slowing its decomposition, are also inherently impermanent. Engineered CDR approaches that involve underground storage, including BEC and DAC, involve the risk of CO_2 leakage back into the atmosphere. Although the magnitude of this risk remains uncertain, available evidence (e.g., from CO_2 injection into oil and gas wells) suggests that the risk is low, with underground storage duration anticipated to be tens of thousands of years (Kampman et al. 2016).

Life-Cycle Emissions. Engineered CDR approaches, such as DAC and (to a somewhat lesser extent) CCS used with BEC, require significant amounts of power. BEC also has emissions from the cultivation, harvest, and transport of biomass inputs. ARI projects have emissions from energy use to increase the forest sink. Accordingly, determining the net performance of such projects requires assessment of energy input–related emissions. On the other hand, BEC projects reduce demand for fossil fuel–derived

29 Areas in attainment with the National Ambient Air Quality Standards with and without DAC would not face increased regulatory and compliance pressure. Areas moved by DAC-related emissions from attainment to nonattainment status would be under pressure to reduce emissions to return to compliance. Areas in nonattainment with and without DACs are already under compliance pressure, which could plausibly increase if the severity of their violations increases. Policy in place matters, too. For instance, cap-and-trade systems limit overall emissions.

energy and thus lower (net) emissions. Similarly, the use of forest products in building construction would reduce emissions associated with steel and concrete.[30]

Additionality. To measure the performance of policies designed to increase CDR investment, quantification of the investment and resulting emissions removal must be compared with an alternative, business-as-usual outcome without the policy. Such additionality requires demonstrating that the CDR activity and resulting emissions removal would not have occurred in the absence of the policy. Assessing additionality also is relevant to financial incentives for CDR investment provided in voluntary carbon markets.[31] In practice, verifying additionality can be difficult because the baseline for comparison is a counterfactual situation. For example, suppose a forest owner claims to have produced CDR credits by delaying a harvest by 10 years. The problem is that the owner may—for entirely commercial reasons—have chosen to delay harvest anyway, in which case reduced emissions from the delay should not be attributed to a credit payment or other CDR policy reward. The opposite situation applies to engineered CDR, including DAC and BEC: in the absence of CDR policies, there is no incentive to undertake these projects, but the current high cost of these approaches limits investment.

Leakage. Leakage refers to the possibility that a CDR action taken in one location will trigger reduced storage in another location. ARI and BEC approaches are particularly subject to leakage because they are land-based activities. For example, if managers of some forests delay harvests as a CDR strategy, that can create incentives for managers of other forests to accelerate their harvests. If agricultural land is afforested or switched to bioenergy cropping, other lands may be converted to agriculture. Reduced storage from leakage should be subtracted from project-specific sequestration in calculating the project's net storage effectiveness. Unfortunately, quantifying leakage is difficult because it is determined by complex and often global market forces.[32]

30 To illustrate, we used a figure of 0.37kgCO_2e/kWh for the current average carbon intensity of the US power grid, 5 percent for transmission and distribution losses, and 1400kWh to 2100kWh electricity input per ton of CO_2 removal for DAC (Lux et al. 2023). These figures imply averages of 544–816kgCO_2e released from the electricity powering DAC per ton of CO_2 removed. They do not include energy requirements for preparing, transporting, or storing the captured CO_2.

31 Any sequestration project already required by law or regulation or contractual obligation, financially motivated in the absence of a sequestration incentives, or representing common practice does not pass the test of additionality.

32 Empirical studies reveal very wide ranges (10 to 90 percent) in estimated leakage (Murray et al. 2004).

5.8. Policy Responses to Implementation Challenges

Cross-Cutting Issues. CDR by ARI generally has more significant permanence, additionality, and leakage issues. If the associated reductions in ARI performance are underestimated and not reflected in policy incentives, ARI's "CDR return on investment" will appear artificially high, and investment will be inappropriately skewed toward it. A greater capacity to address these issues would build trust in the land sector, allowing it to sell credits at higher prices. For BECCS and DACCS, in contrast, the challenges arise in not underestimating life-cycle emissions.

Policy adjustments can be made to counteract such distortions. For example, CDR credit programs can actuarially account for permanence risks, if those risks can be reasonably well quantified given available information. Calculations of CDR credits can require adjustments based on estimated leakage losses and estimated life-cycle emissions that reduce net removal, either by reducing the amount of GHG removal in a CDR credit or by discounting its price. Currently, nature-based credits are typically "discounted" (or margins of error are built into the amount of CDR that can be claimed) because they have performance risks and thus are harder to verify. However, these adjustments are empirically challenging.[33]

We stressed in Section 4 the importance of policies that deploy CDR cost-effectively and that are technology neutral. Performance measurement and MRV issues relate to both. Cost-effectiveness assessments and the application of appropriate incentives will be undermined if uncertainty about permanence, life-cycle emissions, additionality, and leakage for different CDR technologies are not (or cannot be) properly addressed. Similarly, policy will not be technology neutral if a failure to account for these differences skews incentives.

Therefore, *improved quantification of MRV uncertainties, performance risks, and offsetting life-cycle effects (including leakage) is an essential cross-cutting challenge for CDR policy*. The challenge should be treated as a priority for research and development. The importance of R&D investment to advance novel CDR technologies also applies to improving performance assessment and MRV.

Institutional innovations would also help address the MRV challenge: in particular, a greater governmental role in evaluating and reconciling the numerous overlapping or conflicting credit protocols being used in carbon credit markets. Ideally, the issue would be addressed collaboratively by agencies with technical expertise in CDR (e.g., DOE, USDA) and environmental monitoring (e.g., EPA, National Oceanic and Atmospheric Administration), as well as agencies with expertise and authority in monitoring other commodity markets (e.g., Securities and Exchange Commission, Commodity Futures Trading Commission).

33 The California emissions program allows purchase of forest offsets and requires purchase of a buffer pool of credits to account for fire and other performance risks. Analysis of the buffer pool has indicated that its size is insufficient to cover expected forest damages over the next 100 years (Badgley et al. 2022).

Challenges with ARI. Incentives for ARI in the United States generate some CDR, but not nearly enough for ARI to contribute its share in meeting the midcentury net-zero goal. For context, the Biden administration's US Long Term Strategy anticipates a 30-year need for US CDR ranging from 1 to 1.8 Gt/year, or 1.2 to 3.2 times current levels, mainly from conventional land sources (US Department of State and Executive Office of the President 2021). However, the US forest sink has been declining for several decades and will continue to do so, absent new policy incentives (Wear and Wibbenmeyer 2023). More aggressive policies are needed to promote afforestation, reforestation, and carbon-storing commercial forestry practices.

As already noted, ARI approaches are currently inhibited by the challenge of quantifying and verifying CDR performance. Forest carbon science, modeling, and data collection are fairly advanced, with tools available to account for vegetation growth and harvest rates; wildfire, disease, and drought risks; and other factors affecting carbon removal dynamics. Nevertheless, place-based MRV is informationally demanding, and thus it is institutionally difficult to assess the amount and timing of incremental CO_2 removed.

Forest CDR removal claims are often met with skepticism (Greenfield 2023; Elgin 2021). Even in a governmentally regulated (as opposed to voluntary) forest carbon credit program with relatively formal and stringent eligibility criteria, concerns are regularly raised about the accuracy of claimed removals. For example, critiques of the claimed additionality and permanence of forest offset credits figure prominently in recent analyses of the California emissions market (IEMAC 2022).

Similar quantification and verification challenges also apply to government subsidy programs. Much of the current policy support for increased forest sequestration on private lands under the IRA involves government cost-shares. Improved quantification and verification of CDR will be important to the success and public support of such programs.

Challenges with DAC and BEC. As noted, incentives for market penetration by DAC and BEC focus on stimulating initial investments and are not large enough for scaling up these approaches to meet the midcentury net-zero goal. In addition, as with ARI, BEC approaches need to be subjected to life-cycle analysis to assess emissions from growing, transporting, and processing the biomass feedstock, as well as the emissions involved in operating a BEC facility. For example, large-scale farming operations apply nitrogen-based fertilizers to bioenergy crops, leading to N_2O emissions, and they may release soil carbon through tillage practices. These emissions reduce the net GHG removal provided by BEC. Estimates of overall removal efficiency with combustion BEC range from 50 to 80 percent of the CO_2 stored in the feedstock biomass (Chiquier et al. 2022; Rosa et al. 2021). In contrast, it is relatively easy to quantify the CO_2 captured by a DAC plant, though the Scope 2 emissions from the electricity used by the DAC plant also need to be assessed.

The 45Q tax credits present specific issues for DAC and BEC because of its their reliance on CCS. The magnitudes of the 45Q tax credits are fixed in the IRA until their expiration almost a decade hence; there is no provision for reducing them as publicly funded RD&D brings down the costs of the technologies over time. Moreover, the IRA tax credits are based on gross removals; they do not account for differences in the overall carbon intensity of various DAC and BEC projects or life-cycle emissions. Thus, it is timely to consider how to transition to other policies that can be more effective (and cost-effective) in scaling up the technologies.

Programs to provide government financing for DAC and BEC face administrative challenges: deciding whether projects are eligible, picking the projects most likely to meet program goals, and where cost-shares apply, raising the necessary private funds (usually 100 percent matching). A good object lesson on the tax credit program is that almost 50 percent of the credits for CCUS projects allowed by the Internal Revenue Service (which administers the program) under the pre-IRA rules had to be clawed back because of defects in MRV systems (George 2020).

The current focus on tax breaks and RD&D grants for improving DAC and BEC and encouraging initial investments in their use leans toward supply-push measures to promote technology development up to pilot testing. This is useful for technologies at early stages of development. However, DAC and BEC have advanced past the earliest stages. In this situation, innovative demand-pull measures (discussed in Section 5.3) to support advanced development and commercialization of those technologies would be more useful.

Safety and Legal Issues. Construction of pipeline infrastructure almost invariably involves lands held by individuals or local communities, including Native nations. These situations can be legally and politically challenging. Similar land use–related challenges can arise in locating underground storage facilities and the carbon capture facilities themselves, not to mention electricity transmission lines to serve the facilities. Permitting and other legal requirements, as well as political opposition, will delay and increase the costs of infrastructure development.[34]

Aside from siting, public health and safety are major concerns for CO_2 pipelines. Because CO_2 moves through pipelines at extremely low temperature and high pressure, a pipeline rupture or even a significant leak could have catastrophic consequences—blasts from depressurization of the escaping gas, freezing from exposure to its low temperature, displacement of breathable oxygen. A 2020 rupture of a CO_2 pipeline in Yazoo County, Mississippi, lasted about four hours and affected approximately 200 people, with 45 hospitalized for oxygen deprivation. Though the accident was not linked to any fatalities, it prompted the Pipeline and Hazardous Materials Safety Administration to release safety rules for CO_2 pipelines, and it remains a commonly cited story in popular press amid expectations of CO_2 pipeline expansion (Simon 2023). Thus, an important step for CDR policy is to bolster public confidence by validating (or strengthening, if necessary) the pipeline safety rules.

34 To the extent that direct air capture facilities and energy supply facilities in BECCS projects can be located near underground reservoirs for CO_2 storage, the burden of pipeline siting and construction is reduced. DOE has mapped available reservoir space in its Carbon Storage Atlas (National Energy Technology Laboratory 2015).

Another important but less commonly noted policy gap concerns economic regulation of long-distance CO_2 pipelines and owners or operators of CO_2 storage facilities to limit the exercise of market power while also addressing risks inherent in large investments in a new industry. CO_2 pipelines are like natural gas pipelines (and unlike oil pipelines) in lacking other competitive means for transmitting the CO_2 and having increasing returns to scale (so duplicating pipelines would be wasteful). Investments in BEC or DAC facilities connected to CO_2 pipelines will be deterred if pipeline operators use their market power to raise tariffs above the cost of service. On the other hand, large investments in CO_2 pipelines also will be deterred without some assurance of sufficient throughput and an adequate price to recover investment costs.

Concerns about market power and investment start-up risk are likely to arise with storage facilities, too. Although CO_2 can be sequestered underground in many locations, cost advantages from proximity to a facility (from lower CO_2 transportation costs) can give its manager a degree of market power. Yet, large investments in storage capacity will be held back if the pricing of storage services or the volume of storage demanded is uncertain.

A final concern is who owns the CO_2 at different points along the chain of collection, transmission, and storage. Ownership must be established to clarify legal responsibilities if policies are breached, to enter into contracts for the services provided along the supply chain, and to implement incentive-based policies like emissions credits or allowances based on removal.

Equity in Benefits Sharing. Making CDR projects (including their siting) more equitable through Justice40 and community benefits plan requirements raises several issues (Krupnick 2023). To generalize, environmental justice advocates do not want additional industrial-scale activities in disadvantaged neighborhoods, both because existing industrial activities and distribution networks are located disproportionally in communities of color and because capture and distribution networks can pose hazards from air pollution (see below for ancillary impacts) and CO2 leaks from infrastructure.

Krupnick (2023) finds several issues with CBP requirements for grants. One is determining who represents the community in negotiating the plan and reporting and addressing concerns about an on-going project—particularly if some groups adamantly oppose the development. CBPs should describe prior community engagement efforts and the benefits flowing to disadvantaged communities further down the supply chain or farther away. A second issue is the culture of private sector actors entering into CBPs, since the required two-way engagement may be difficult for some companies. A third is the weak enforcement mechanisms in community benefits agreements (part of the CBP requirements), which often keep CBPs from meeting their goals (Belongie and Silverman 2018). A fourth issue is the lack of attention paid to economic efficiency—that is, the goal of maximizing net benefits to disadvantaged communities (although CBP guidance recognizes there will be both positive and negative effects). Even under the best of circumstances, it may be difficult to identify, let alone quantify and monetize, all the benefits and costs of CDR projects.

Ancillary Environmental Impacts and Environmental Justice. An important part of siting and operating DAC and BEC facilities will be addressing the environmental and natural resource concerns summarized above. Although DAC facilities could provide increased property and income tax revenue for local governments, and siting requirements could include providing local jobs and amenities, those benefits do not ameliorate environmental justice issues.

Any land and water degradation likely will be a local responsibility unless the Endangered Species Act or Clean Water Act is triggered. As for air quality, we noted that the Clean Air Act does not preclude worsened air quality due to local pollutants emitted from BEC biomass combustion or Scope 2 emissions from increased electricity generation (across the grid) to supply DAC and BEC facilities (Fajardy and Mac Dowell 2018).[35]

Environmental justice advocates are understandably concerned about adverse air pollution impacts of DACCS and BECCS (see Section 4.6). The two technologies are electricity intensive and their demand could increase emissions from fossil fuel power plants, at least until the electricity grid is decarbonized. The resulting pollution would not necessarily be adjacent to the DACCS or BECCS facilities, however, because of the interconnected nature of the grid. The facilities themselves could also emit pollutants: BEC plants combust biomass-based fuels, and DACCS and BECCS processes that rely on amine-based systems emit ammonia.

Even if air pollution does not worsen from DACCS or BECCS, policies for implementing CDR could cause unacceptably high levels of current air pollution harming disadvantaged downwind communities to persist. If existing combustion plants with high levels of local air pollution can extend their operational lives by using CDR credits to offset GHG reduction obligations, longstanding harm to downwind communities will continue. If CDR credits are not available for offsets, the prospective use of CDR still could cause some GHG emissions reduction obligations to be softened or postponed (McLaren 2020).

35 An additional regulatory issue is that a DACCS or BECCS project installed on or adjacent to a facility covered by Clean Air Act rules for local pollutants raises the issue of whether that installation is a "major modification" of the facility that triggers New Source Review (NSR). NSR rules require more stringent limits on pollutant emissions, and that in turn typically requires expensive modifications of the facilities in question. NSR rules thus could be a barrier to adoption of DACC or BECCS. On the other hand, more stringent GHG mitigation rules may trigger the same rule.

6. Policy Recommendations for Initiating the CDR Transition

Given the urgency of substantially increasing CDR deployment over the next two to three decades, policies to facilitate that expansion are needed. Scaling up CDR presents several interrelated challenges. One is the current high cost of CDR approaches, especially (but not exclusively) DAC and BEC. Policies are needed not just to stimulate innovation and reduce costs for these technologies but also to provide the enabling conditions for scaling them up.

This section discusses on-ramp policies for expanding CDR deployment over the near term. Another challenge is devising strong, cost-effective, and properly sequenced policies that remove barriers and create economic incentives for increased adoption of CDR as the transition proceeds. We discuss this challenge in Section 7.

6.1. Policies to Increase Conventional Land-Based CDR

As noted in Section 4.8, the country's conventional CDR sink (mostly from forests) is currently declining, and without policy intervention, it will continue to decline over the coming decades. To expand conventional land-based CDR, an aggressive ramp-up in ARI incentives is needed. In the absence of stronger compliance-based mechanisms for reducing GHG emissions that also reward forest sequestration, and with voluntary credit markets currently providing only limited incentives, the government could increase land-based CDR through public investment in afforestation. For example, land management agencies could establish a national forest carbon reserve program[36] to provide direct incentives to convert land to forest from other uses (and reduce conversion away from forests). The government also could increase the IRA's $4.9 billion for supporting restoration and protection of national forests (Section 23001) and state and private forest improvement and conservation (Sections 23002 and 23003). Another important government strategy is to incentivize demand for longer-lived forest products so that more carbon is stored in wood products and landowners have an incentive to expand planting and forested area.

The design of the IRA does not ensure that the funding will be directed toward the most effective land-based CDR investment: afforestation. Except for the examples mentioned above, IRA funds for addressing GHG emissions mostly target reducing emissions and increasing soil carbon sequestration on working farms and ranches, rather than encouraging land-use conversion from agriculture into forestry. Moreover, although the

36 Such a reserve is likely needed in any event to provide a larger backstop to compensate for forest carbon sequestration credits that fail to perform because of wildfire, disease, or other forest losses.

IRA committed $20 billion to GHG reduction and removal, that is not enough to drive significant increases in the US land sink.

To underscore the scale of what is needed, consider the following scenarios based on recent research on the US forest carbon sink (Wear and Wibbenmeyer 2023). Under a business-as-usual scenario, the sink between now and 2060 will remove 0.73 Gt per year, on average. This reflects a decline in the sink from a 2021 yearly removal of 0.84 Gt. If 3 million forested acres are added to the landscape each year for 30 years, the amount removed increases to 0.95 Gt per year, on average.[37] In other words, expanding US forest cover by 90 million acres (an area roughly equal to Montana) increases annual CDR relative to 2021 rises by only 0.11 Gt. Accelerating the rate of afforestation and increasing the acreage would improve the numbers. Nevertheless, the example indicates the scale of land-use change needed to meaningfully expand the US land sink.

Another land-based CDR strategy is carbon storage in agricultural lands. Such lands hold only a fraction of the carbon stored in forests, however, and the carbon is hard to measure and maintain. Improved forest management strategies—altering forest composition, lengthening harvest rotations—can also be expanded and applied across existing managed forestland, but they inherently yield less net carbon removal per acre than afforestation.

Afforestation provides net CDR that is easier to quantify and verify than improved forest management. For one thing, the baseline from which CDR gains are measured is clearer: the land use prior to afforestation. The performance of afforestation projects can be measured by satellite relatively cheaply by observation of the plantings and forest features. Net CDR gains for improved forest management, in contrast, require more complex and hard-to-measure baselines. How would the forest have been managed without policy intervention? This involves assessment of commercial and economic information. Claimed CDR from improved management practices (the actions yielding additional net CDR) are also harder to monitor. It is relatively easy to confirm when unforested land is converted to forest, but harder to verify that management and harvest practices have changed as promised.[38]

37 This would cost $5 billion to $7 billion per year (roughly $17 to $24 per ton of CDR).

38 The CEO of Lyme Timber, a firm that has extensively participated in both compliance and voluntary offset markets, recently noted that an "honest assessment" of many forest carbon projects, "including some that Lyme has developed, is that while legal and fully compliant with the protocols, they may not have required the forestland manager to reduce near-term harvest levels relative to historical harvests or change management practices to increase carbon sequestration" (Hourdequin 2022).

6.2. Policies for Catalyzing Increased Investment in DAC and BEC Technologies

As noted previously, the focus of policies for engineered CDR has been mainly on R&D and near-term initial investments. Creating the on-ramp for scaling up those approaches requires a shift to technological development through commercial-scale investments and, to support those investments, increased financing for CDR. Improving a technology's energy efficiency through the acceleration of alternative capture methods is also crucial for wide-scale deployment.

Table 1, from Bergman et al. (2023), shows how the choice of effective policy type for RD&D can be linked to the technology readiness level (TRL) of engineered CDR technology.[39] The TRL is an indicator from 1 to 9, with the lowest numbers (1 to 3) associated with novel or otherwise nascent technologies for which basic and applied R&D is still crucial; the higher numbers (7 to 9) correspond more advanced stages of technology development.

At present, 19 DAC plants are operational (Hong 2022; McQueen et al. 2021; Ozkan et al. 2022), most at a pilot scale. The most common chemical approaches for DAC report TRLs between 5 and 8, with less-advanced approaches at TRL 5 or below (Smith et al. 2023; Hong 2022; Mission Innovation 2022). TRLs for BEC are reported to lie between 5 and 7 (Smith et al. 2023; Hong 2022).[40]

In general terms, early-stage technologies needing basic and applied R&D are good candidates for supply-push policies, such as R&D grants and innovation prizes. Use of these policies is illustrated by the Advanced Research Projects Agency-Energy (ARPA-E), created in 2009. ARPA-E supports high-risk, high-reward projects, based on the idea that returns to innovation are considerably skew-distributed (Scherer and Harhoff 2000). Projects often are selected for funding even when they fall below the peer-review cut-off line. The outstanding success of certain projects can help support other projects that would not receive funding. Unfortunately, relatively few ARPA-E projects have succeeded (Azoulay et al. 2019).

39 TRLs represent a systematic approach to assess technological maturity, from basic research to system testing and utilization, that can be applied across a broad range of technologies. TRL levels range from 1 to 9, with higher numbers indicating greater maturity (Frank 2015).

40 TRLs for afforestation and reforestation are 8–9, indicating the maturity of this longstanding approach to carbon removal. For novel CDR solutions, the TRLs are as follows: ocean fertilization, 1–2; ocean alkalinization, 1–2; enhanced rock weathering, 3–4; and burial of biochar in soil, 6–7 (Smith et al. 2023).

Table 1. Technology Readiness Levels and Applicable Policies for Technology Advancement

Policy	Policy type	TRLs
Traditional grants and cooperative agreements	Supply-push	1–9
Public loans and loan guarantees	Supply-push	9
Targeted research funding (ARPA model)	Supply-push	1–6
Inducement prizes	Demand-pull with push elements	3–6
Public procurement	Demand-pull	8–9
Advance market commitments	Demand-pull	7–9
Milestone payments	Supply-push with pull elements	2–9
Technology standards	Demand-pull	6–9
Carbon contracts for difference*	Demand-pull	7–9

Source: Adapted from Bergman et al. (2023).

Note: A "contract for differences" is an offer to ensure that specified quantities of output are purchased at a guaranteed price, with the provider of the contract agreeing to make up the difference between the prevailing market price and the guaranteed price. Contracts for differences can ensure a revenue stream for the provider of carbon removal when a removal technology is first being adopted but demand remains limited. This includes the possibility that removal quantities are sold to private buyers, with the government topping up the payment to ensure that the provider receives a minimum price for specified quantities of removal over a specified period. The contract for difference is like a put option, which gives the contract holder the assured opportunity to sell a specified number of stock shares at a predetermined strike price.

DAC and BEC technologies with TRLs between 5 and 8 are targets for increased scale-up and commercialization, but these stages still have technology cost risks that require larger-scale investments to overcome. Demand-pull policies should play a larger role in advancing these technologies because they can promote greater scaling-up and because they shift the focus from support of inputs (investments) to outputs (removed CO_2). Beyond technology prizes and other examples of demand-pull policies described in Section 5.3, advance market commitments (AMCs) can be used by the government (and subsequently, private buyers) to purchase specified quantities of removal using an emerging technology over a specified period at an agreed price. Procurement can be undertaken using contracts for differences (defined above) or a reverse auction mechanism.[41] AMCs are better than grants for later-stage TRL technologies because they give developers incentive and time to build at scale to meet the commitments. They are especially relevant for the highest TRLs because removals can occur in the near future rather than waiting for a technology to further mature. Both AMCs and public procurement have advantages over a tax credit for removal that is not directed at stimulating development of more efficient, lower-cost options. A rapid policy shift in this direction is essential for ramping up these technologies.

The CREST Act, introduced in June 2022 but not yet passed,[42] could create a pilot purchasing program, implemented by the DOE secretary, with $110 million over three years to fund both DAC and BEC.[43] This approach could be particularly useful for DAC technologies that can achieve technological maturity at somewhat smaller scale, since a small program still can help lower unit costs as investments scale up, as well as reduce technological uncertainty. Under CREST, the pilot purchasing funding would be allocated using a reverse auction. The bill requires that eligible projects must have at least a 99 percent likelihood of retaining stored emissions for 100 years or longer. Under the bill, 30 percent of funds each year would be allocated to projects aiming for storage between 100 and 1,000 years, and 70 percent of funds to projects targeting 1,000 years or more. The CREST Act also contains stipulations for how additionality, timing, MRV planning, and permanence should be addressed in bids.

Although demand-pull measures are useful for helping promising technologies cross the valley of death into commercial application, some technology advances do not survive. Public sector cofinancing can make it more challenging to determine which technologies are failing and when to cut off support. This is especially the case for policies providing direct or indirect subsidies for capital investment, since such policies benefit stronger and weaker companies, and the government cannot measure the strength of an innovator in the precommercial stages of the RD&D cycle.

Along with strong policies to encourage innovation and a takeoff of investment in engineered CDR, there is a potential opportunity to improve on the current IRA 45Q tax breaks for DAC (discussed in Section 5). One possibility is to transition from tax breaks toward publicly financed AMCs. However, the 45Q tax breaks have relatively low transaction costs, and the risk of unproductive use of the tax credit is low because the recipients must prove they made the required reductions in emissions. AMCs have higher transaction costs, at least initially, and auditing their performance is more complicated than audits associated with the tax code.

41 In a reverse auction, participating entities offering CO2 removal would submit bids with information on their desired price per ton of removal, estimated removal capacity, assessment of removal permanence, and any pertinent details associated with transport and storage. DOE would fund proposed removal projects starting with the lowest bid price and moving through projects with higher bid prices until the appropriation for the year is fully committed.

42 CREST Act of 2022, S.4420, 117th Cong **https://www.congress.gov/117/bills/s4420/BILLS-117s4420is.pdf**

43 It also would support some novel nature-based approaches.

Policymakers should understand that an aggressive program of ramping up BEC and DAC will have significant costs. In the IIJA, more than $3.5 billion was allocated for DAC hubs and $4.6 billion was allocated for development of pipeline infrastructure and geologic storage for DACCS and BECCS. These figures do not include the tax expenditures in the IRA. Although the total cost of ramping up is uncertain (and unknowable at this juncture), the figures mentioned above are only an initial down payment on the demand-pull and supply-push outlays likely needed for bringing these CDR technologies to commercialization.

6.3. Policies Governing CO_2 Transportation and Storage

To enable expanded investment in DACCS and BECCS, new legislation should establish federal jurisdiction over all aspects of CO_2 pipelines.[44] At the top of the list for federal action is establishing uniform, strong health and safety standards.[45] Federal policy also is needed to create fair, effective, and expeditious permitting for new CO_2 pipelines so that the country can scale up carbon capture with underground storage. The standards need to address social justice concerns and provide fair compensation for pipeline rights-of-way.

Siting challenges may arise for locating industrial-scale DAC facilities near natural CO_2 reservoirs. Compensated land takings for co-locating DAC facilities could reduce the need for pipeline construction. Fair and effective federal standards to compensate for DAC sites are needed here as well. These issues are part of a larger debate on siting and permitting energy-related facilities. The debate is illustrated by the Lower Energy Costs Act,[46] which passed in the House of Representatives in 2023, and a press release by the White House in the same year (Biden-Harris Administration 2023).

In addition, a regulatory mechanism is needed to curb market power in setting tariffs or limiting access to CO_2 pipelines. Effective control over market power in storage will require both limits on prices and a public utility "obligation to serve" that prevents storage facilities from exercising price discrimination in access. The rationale for this regulatory structure is the same as for natural gas pipeline regulation: large economies of scale and the inefficiency of constructing multiple competitive lines. An unanswered question here is what degree of vertical integration among collection, transport, and storage in CDR may be desirable.

Although control over market power by CO_2 pipelines will reduce the operating revenue risks for DAC facilities and reservoirs, developers of new pipelines and storage facilities

44 This can build on the process for designating federal energy corridors in the 2005 Energy Policy Act.

45 As noted in Section 3, PHMSA has specified safety measures for pipelines transporting CO_2 (PHMSA 2022).

46 Lower Energy Costs Act, H.R.1, 118th Congress **https://www.congress.gov/bill/118th-congress/house-bill/1/all-info**.

may need to lower their revenue risks from underutilization. Natural gas pipelines are treated as public utilities, with prices set to recover costs subject to regulatory review. How to do this for CO_2 pipelines without dulling operators' incentives to compete for business remains an open question.

As noted in Section 5.8, CDR policy needs to clarify who owns the CO_2 captured from the atmosphere. An approach consistent with practices in the natural gas sector would vest ownership of collected CO_2 with the facility that carried out and bore the cost of collection. Long-haul CO_2 pipelines would function as common carriers, providing transmission service without taking title to pipeline contents.

When the CO_2 is stored, ownership could transfer from the collection facility to the storage facility (as is done today when natural gas is purchased for storage). The storage facility would be liable for costs incurred from leaks arising from negligent operation—for any damages caused and compensation for release of the previously sequestered CO_2.[47] Because of ongoing operational costs plus amortization of investment costs, a long-term storage facility would require a long-term service agreement with the operators of collection facilities to maintain safe and secure storage.

If the storage facility owns the stored CO_2, it could also provide the "merchant function" for selling CO_2 removal services to other entities that have emissions to offset. If CDR regulations are written to require an ownership connection between emissions credits or allowances and the physical quantities of CO_2 removed, then the collection entities may need to retain ownership of the CO_2 and have long-term "rental" agreements to store it.

6.4. Benefits Sharing

Given concerns about locating engineered CDR in communities that already bear a disproportionate share of industrial pollution, community benefits plans (discussed in Sections 5.5 and 5.8) are a way to provide offsetting benefits. CBPs were a requirement of DAC hubs, for instance, and they are a requirement for many DOE demonstration project grants. Below are some ideas for changes to CBP guidance that could improve their performance (see Bergman et al. 2023).

New investment can bring different types of benefits to a community but also many harms (including noise pollution, not yet mentioned). All pros and cons should be considered by agencies issuing CBP guidance, and grant applicants should quantify them using common financial metrics.

47 Realistically, no facility could fully insure against a catastrophic failure: government would be responsible for addressing dire consequences. This is why federal oversight of CO_2 storage facilities for technical soundness and public safety must be strict, much as utilities are held to stringent standards for storage of spent nuclear fuels.

A particularly difficult benefit to quantify is job creation. The jobs created could be part-time or full-time, and they may displace other jobs, implying no net employment gain. Indeed, it is generally not possible to know whether a specific new job is fully additive to the workforce. Moreover, the benefit of a new job to the community is related to the wages earned and therefore the money spent in the community, not just the new job per se. Wage data need to be part of the assessment.

Efforts by agencies and CDR facility investors should be tempered by acknowledgment that the communities themselves need to speak to which benefits (and detriments) are most important and how to weigh them. CDR investment may not be acceptable to some communities, even if it provides additional jobs. Finally, it is useful to develop metrics of success for CBP goals, especially for defining how Justice40 goals are measured and achieved.

6.5. Ancillary Environmental Consequences and Environmental Justice

Policies are needed to address the water and land-use effects associated with BECCS and forest carbon capture and the air quality effects from DACCS and BECCS, including environmental justice issues (see Sections 5.6 and 5.8).[48]

Air Pollution. In 2022, EPA proposed new limits on emissions of methane as well as smog precursors (volatile organic compounds) and air toxics from oil and gas facilities, and in 2023, EPA proposed new CO_2 limits for power plants.[49] Nevertheless, these new policies may take time to implement, however, especially in the current legal climate. The continued operation of polluting facilities, many of which disproportionately harm disadvantaged communities, is a central part of the environmental justice debate and thus the debate over the potential consequences of expanding engineered CDR use. A prohibition on use of CDR credits to extend their operating lives likely is a necessary condition for addressing the environmental justice community's concerns, but it may not be sufficient. A direct response to the air quality issue would entail tightening the stringency and geographic focus of Clean Air Act standards to force effective abatement of local pollutants.

Community engagement in CDR siting will also be a necessity. Project developers need to provide explicit information on their anticipated environmental performance, including possible exceedances of regulatory limits for any environmental concern, and what mitigating measures they will take to address them. This is part of a larger effort to devise new engagement structures that address deep-seated community tensions

48 Some groups have philosophical objections to continued reliance on fossil fuels regardless of CDR use or control of ancillary pollution, seeing fossil fuels as an inherent obstacle to a sustainable future.

49 See **https://www.epa.gov/climate-change/climate-change-regulatory-actions-and-initiatives#:~:text=In%202015%2C%20EPA%20issued%20a,limits%20remain%20in%20place%20today**.

associated with industrial-scale development by facilitating two-way dialogue and engaging all relevant parties. Third-party facilitators and auditors will play an important role.

Land and Water Use. As BEC deployment increases, the sourcing of water and the use of land for feedstock growth will increase pressure on these resources, particularly if feedstock crops compete with food crops. Under current policies, many of these land and water challenges must be addressed by state and local policymakers. That offers opportunities for more fine-tuned balancing of interests in various areas. Except in extreme cases, such as a violation of federal water quality policies, having state and local actors address these issues seems appropriate. Potential BEC operators will then locate in areas where the required land and water resources are available and secure transportation for their captured CO_2 (pipeline or otherwise).[50] Although public support for afforestation may be greater than for BEC, as gauged by Smith et al. (2023), the consequential equity considerations for land and water are comparable.

7. Policy Recommendations for Achieving Net Zero by Midcentury

In what follows, we assume that the United States will develop and expand enforceable emissions reduction incentives applied to a wide range of emitters, along with expanding CDR, to achieve net-zero emissions. This is obviously a significant assumption. We make it, however, because we take seriously the IPCC's midcentury and 2100 warming projections as well as its illustrative pathways to limit warming. As observed in Section 2, those warming limits have virtually no chance of being met without greatly expanded CDR as well as far more robust international emissions reduction measures.

We also make the simplifying assumption that emissions reductions and carbon dioxide removals can be determined through measurement and thus deemed to be real and verifiable. We have reviewed the challenges to verification of emissions reductions and CDR performance in Section 5.7. Any meaningful net-zero policy framework will require strong capacity for verification.[51]

CDR and efforts to link CDR and emissions goals have met opposition, as mentioned in Sections 5 and 6. Opposition arises from concerns that claimed removals are not

50 Biomass can be transported for use elsewhere. There is already a robust market for US biomass in bioenergy production in the United Kingdom and European Union (Brack et al. 2021).

51 As indicated previously, CDR technologies and specific projects will differ in permanence, risk of failure, and verifiability. These differences are important to capture in any scheme that treats CDR alternatives as interchangeable options. In practice, equivalence adjustments (e.g., trading ratios) will be required to adjust for these differences.

real, storage may be impermanent, some technology can have social harms, or the goal should be zero fossil fuel use—and therefore, CDR is a poor substitute for emissions reductions. There is an element of truth in many of these concerns, and some skepticism is understandable. However, because removal is “emissions in reverse,” it should be evaluated on an equal footing with emissions reductions in terms of costs and benefits, including the abovementioned concerns.

In a net-zero economy, all CO_2 emissions not eliminated by responses to mitigation policies are offset by corresponding amounts of CDR. This identity (residual emissions = total CDR required for net-zero) creates a fundamental link between the stringency and breadth of emissions reduction (ER) policy and the amounts of CDR needed and provided. In this section, we first discuss the balance between CDR and ER that minimizes the cost of achieving net zero. Using that outcome as a point of departure, we then look at other midcentury net-zero policy options.

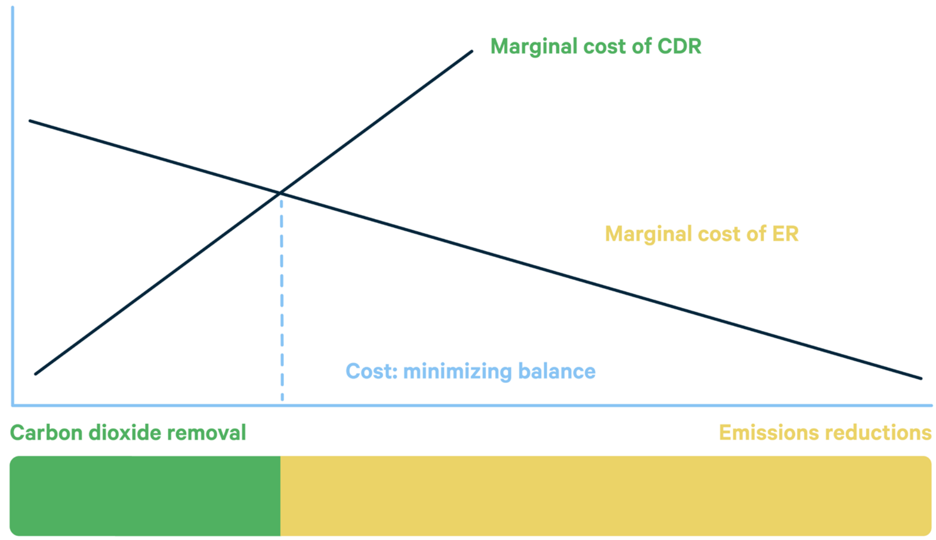
7.1. Cost-Effective CDR and ER

The policy criteria in Section 4 emphasize that the “right” balance of ER and CDR depends on a variety of factors, including mitigation versus CDR policies and costs, speed of potential scale-up, incentives for innovation, and equity considerations. One important characteristic of the right balance is cost-effectiveness: the CDR-ER combination that minimizes the cost of reducing net emissions.

The cost-effective combination of CDR and ER is illustrated in Figure 4, in which CDR and ER technology options are described using marginal cost curves. Marginal cost curves reflect the fact that some options are more costly than others and that more costly options must be used when more CDR and ER are required (marginal costs are increasing). Here we are concerned with the *social* costs of ER and CDR, not just the direct investment and operating costs. The social costs include the costs of environmental and social spillovers from CDR, and the environmental co-benefits (negative costs) of reduced local pollutants from ER. They also include externalities from building and operating CO_2 pipelines and storage facilities.

The cost-minimizing balance between CDR and ER occurs where the marginal costs cross in Figure 4. Any ER or CDR policy that leads to a different allocation of ER and CDR will increase the costs of net-zero compliance, either by underexploiting lower-cost CDR (if the share of ER is too large) or by underexploiting lower-cost ER (if the share of CDR is too large).

Figure 4. Marginal Costs of CDR and ER Determine Cost Minimizing Balance



7.2. Achieving Cost-Effective Policy: Cap-and-Trade or Carbon Pricing with CDR (CAT+ and CP+)

To minimize the total cost of CDR and ER across the economy for achieving net zero, ER and CDR policies need to be integrated so that cost trade-offs across the combined ER-CDR options portfolio can be perceived and used to guide decision making toward equalizing the marginal costs of ER and CDR. Policy frameworks that keep ER and CDR incentives separate are highly unlikely to achieve the cost-minimizing balance between the two portfolios. Getting the balance right would require climate policymakers to know in advance the cost-effective balance so that they can set independent ER and CDR goals. But the cost-effective balance cannot be known with any certainty by policymakers, now or in the future, given prospective technological and commercial innovation.

ER and CDR policies can be linked in either of two ways to minimize costs of achieving net zero, both involving market mechanisms: (1) an economy-wide cap-and-trade program that integrates ER and CDR, or (2) a carbon price to mitigate GHG emissions where emitters can purchase CDR credits to reduce the quantity of unabated emissions. For brevity, we refer to these as CAT+ and CP+.

Under a CAT+ policy, all emitters would reduce emissions to the point where it becomes cheaper either to buy ER credits from other emitters or to buy CDR credits to offset their emissions. The economy-wide emissions cap would be adjusted downward over time until it is set at net-zero emissions (so there is no gap). At that point, all emitters would have either reduced their GHG emissions to zero or purchased CDR credits sufficient to cover their residual emissions.

Under a CP+ policy, all emitters would reduce emissions to the point where it becomes cheaper either to pay the carbon price or to buy CDR credits to offset some of their financial obligation. The CDR credit price will equal the carbon price. The price would be adjusted upward over time to induce net-zero emissions through increased ER and CDR. At that point, no revenue would be generated by the carbon price, as all residual emissions would be offset by CDR credits.

In both cases, economic self-interest leads emitters to undertake ER and CDR actions that minimize their own costs. CAT+ and CP+ policies create incentives for CDR by allowing emitters to use CDR as an alternative to emissions reductions. Moreover, because both policies allow reallocations via credit purchases, self-interested reallocations minimize emitters' aggregate ER+CDR costs. The integration of ER and CDR choices in emitters' profit-driven decisionmaking yields this desirable outcome.

However, CAT+ or CP+ do not necessarily minimize the aggregate *social* cost of cutting GHG emissions—including environmental and other spillover effects. This is why the enabling policies and policies to control externalities in Sections 5 and 6 are so important.

A CAT+ or CP+ approach also creates desirable long-run innovation incentives. Because the schemes are flexible, are technologically neutral, and reward both CDR and ER cost reductions, they create a continuous market incentive for innovation in both CDR and ER.

Under both CAT+ and CP+ approaches, CDR is funded and financed by emitters and ultimately paid for by consumers, as is ER. Public funds would not be expended for CDR. The public would not be subsidizing GHG emitters with general revenues, general tax rates would not be raised to cover government outlays for CDR, and the government would not need to establish and implement CDR financing mechanisms. Emitters and their customers should see and bear the costs to allocate consumption, production, ER, and CDR choices efficiently.

Emitters and their customers likely would resist significant, visible cost increases associated with expanded use of costly CDR. Given the current CDR costs (Section 3), expanding CDR as discussed in Section 1 would be costly. At current costs, the balance between CDR and ER would lean toward ER, and the need to undertake very substantial amounts of expensive ER would imply a high cost for achieving net zero. This underscores the importance of the on-ramp policies (Section 6) to spur innovation to reduce CDR costs. The ultimate driver of high cost is the net-zero goal. If that goal is retained but less CDR is deployed for cost or other reasons, then costly ER must take its place.

Would CAT+ and CP+ be "fair" ways to allocate responsibility and pay for CDR? Fairness is subjective and can be assessed in different ways, but one frequently invoked test of fairness is the polluter-pays principle, under which emitters (and ultimately their customers) should pay, rather than the broader public. Although the broader public comprises customers, the correspondence between taxpayers and consumers isn't exact. By increasing the relative cost of high-emissions products, policies that make emitters and their customers bear the costs of ER and CDR lead consumers to reduce the carbon content of their consumption. Policies that spread the costs of ER and CDR to the broader public do not.

Another aspect of distributional fairness is the avoidance of regressivity—cost burdens that fall disproportionately on lower-income households. Under polluter-pays policies, some increases in energy costs may be regressive because energy costs are a bigger share of low-income households' expenditures. Other price increases will not be regressive, if consumption involves higher-income consumers (e.g., airline travel).

7.3. Different Approaches to Midcentury CDR Policy

Alternative ways to engender CDR investment include (1) government CDR mandates, (2) voluntary markets, and (3) government financing of CDR (public procurement). We consider in this subsection the potential of these alternatives to CAT+ and CP+ on cost, effectiveness, financing, and equity.

Mandates. Emitters could be required to purchase specified amounts of CDR relative to emissions (performance mandates). If emitters can choose CDR providers, their motivation to purchase CDR at the least possible cost would create incentives for CDR innovation and favor deployment of lower-cost approaches. CDR providers could be required to invest in specific CDR approaches (technology mandates). Technology mandates may appeal to some stakeholders because they seem to reduce uncertainty about the technologies to be deployed, and as a way of ensuring that CDR is deployed as needed to eliminate residual emissions, including those seen as hard to abate. However, they are undesirable when the costs of technology options (including those not yet developed) change over time and regulators lack information about costs and cost trajectories (conditions that are particularly relevant for the CDR landscape). Prescriptive determination of CDR technology is likely to raise CDR costs and thwart cost-reducing innovation.

One version of a CDR mandate is the proposal for a "carbon takeback obligation" by Jenkins et al. (2023), which emphasizes extended producer responsibility. Those authors suggest that all emitters be required to pay for removal of a certain fraction of their total emissions each year. The percentage would start small to reflect the still-evolving state of CDR technology and grow over time. They do not address what maximum percentage of removal would be required or how removal and emissions reduction policies might be integrated.

The difficulty with CDR mandates is that the quantity of CDR mandated very likely will be either too low or too high relative to a cost-effective outcome. It is not realistic to suppose that the regulator could determine how much CDR to require from different sectors and from different emitters within sectors in a cost-effective way. If too little CDR is required, either there will be a net-zero gap or emitters will be forced to comply with costlier ER requirements (ER levels where the marginal cost of ER is higher than the marginal cost of CDR). If too much CDR is required, again, the cost-minimizing balance between CDR and ER does not occur, and total compliance costs will be higher than they need to be.

The only performance standard that could achieve a cost-minimizing amount of CDR is one that is operationally equivalent to a CAT+ or CP+ policy that links the emitters' ER and CDR decisions (and therefore leads to the cost-minimizing balance between the two). However, CAT+ and CP+ do not require that a regulator identify and mandate specific CDR and ER levels in advance. Unlike the situation in the initial years of ramping up CDR (discussed in Section 6), when government policy seeks to ensure growing investment in CDR as the technology matures, such intervention assurance is costly in the longer term.

Voluntary CDR. Corporate net-zero and sustainability goals, motivated by consumers', shareholders', and employees' climate change concerns, already deliver CDR via voluntary carbon markets. In fact, most existing conventional CDR (mainly forestry related) is attributable to voluntary, not compliance-driven, incentives.[52] Voluntary CDR is a kind of crediting approach, except credit is assessed and validated by third-party, private sector institutions. Government agencies can get involved, however. For example, the Commodity Futures Trading Commission, under its regulatory authority over derivative exchanges, recently issued proposed guidelines for what constitutes permanent, real, verifiable, and additional CO_2 credits registered on these exchanges. Voluntary credit programs are currently delivering CDR (though the amounts are small and contested) and act as test beds for the design and implementation of future compliance programs. They are valuable in the near term but an inadequate substitute for compliance-driven policies: they will not be able to generate the scale of CDR needed by midcentury.

Already, some consumers are willing to voluntarily pay somewhat more to buy some products where some emissions are offset with CDR. But because stemming climate change is a public good, it is unrealistic to think that voluntary global consumer choices will ever be enough to motivate the large amounts of CDR needed to achieve net zero. A fully implemented, market wide CAT+ or CP+ policy at midcentury eliminates the need for voluntary carbon markets. In effect, they disappear because the consumer motivation for them disappears: all residual emissions must be offset by emitter-driven CDR incentives.

Government Procurement of CDR. Government procurement is the public purchase of CDR using tax revenues. Broadly, two forms of procurement are possible: (1) government ownership, construction, and operation of CDR facilities, and (2) government purchase of CDR from the private sector. In the short term, with many CDR technologies still maturing or in their infancy, there is an argument for early-stage, direct government financing of CDR (Section 6). In the longer term, government technology decisions shielded from competition and market incentives are less likely

52 As noted in Sections 5 and 6, voluntary markets currently lack government oversight and face a variety of performance and MRV challenges, particularly related to ARI-generated credits.

to stimulate cost-reducing innovations. Accordingly, competitive sourcing of CDR by government becomes the preferred approach.

To that end, governments would need to set up an institutional mechanism to facilitate innovation and selection of the lowest-cost CDR options. This can be accomplished via reverse-auction mechanisms (see Section 6.2), where the government gets competitive bids from CDR producers and selects the lowest-cost bidders to supply its chosen amount of CDR.

As with CDR mandates, however, the government would not know how much CDR to procure in the midcentury net-zero economy. The government will procure either too much or too little CDR, again increasing the costs of achieving net zero.

Government procurement is a "public pays," not "polluter pays," policy approach. Allocating the cost of CDR to taxpayers, as opposed to emitters and their customers, has political pros and cons. It may in some cases have less regressive cost implications and may obfuscate some of net zero's costs. But as noted earlier, it also prevents the full internalization of climate costs by emitters and consumers and thus mutes price signals that otherwise would incentivize optimal production and consumption decisions.

Another problem with long-term public procurement of CDR is that it would require long-term budgetary commitments by government.[53] Spending decisions are reviewable annually, and long-term commitments are difficult. This is a problem for ensuring the delivery of adequate CDR for net zero. It can also undermine private sector investment in CDR innovation and deployment by introducing uncertainty about the government's long-run demand for CDR services.[54]

7.4. Other Midcentury Policy Scenarios

Other policies for ER and CDR to achieve midcentury net zero are likely to emerge from the political process. Some are hybrid approaches that combine CAT+ and CP+ features with other incentives, such as those described above.

Subsidies for CDR Costs. Subsidies transfer part of the cost of CDR from emitters and their customers to the public via direct outlays or tax breaks. This may be politically attractive, for reasons noted earlier. Moreover, there is a near-term rationale for certain types of subsidies for novel CDR approaches as these technologies develop (Section 5). But in a mature net-zero policy framework, subsidies distort climate change decisions and costs in undesirable ways.

53 As discussed below, this will also be true, and unavoidable, for procurement of CDR to go beyond net zero (i.e., to achieve net-negative emissions).

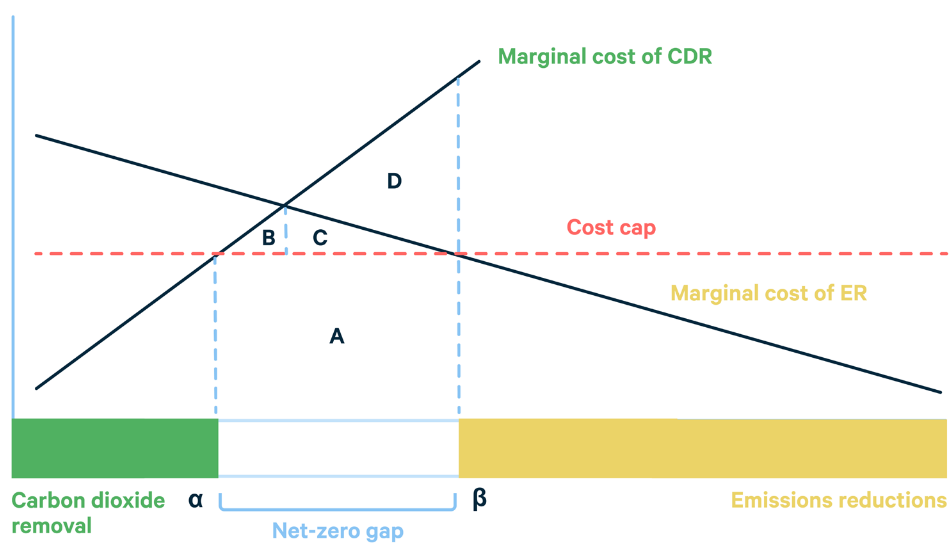
54 The same problem would arise with CP+, in which the government would procure CDR using revenues from emitters.

Consider how CDR subsidies would interact with a CAT+ or CP+ policy. By lowering the net cost of CDR to emitters, subsidies lead to overinvestment in CDR and a corresponding underinvestment in ER. Although they lower emitters' costs of compliance, they make the total cost of CDR and ER (the combined costs borne by emitters and the public) higher than it needs to be. And, as with any shift away from a pure polluter-pays policy, subsidies externalize costs and thus distort production and consumption decisions that generate GHGs. Similar distortions arise if the cost of complying with mandates is subsidized.

A Compliance Cost Cap. One way to reduce political resistance to CAT+ and CP+ schemes is to impose a politically determined cap on emitters' compliance costs. In one version, emitters are not responsible for additional CDR or ER once the incremental cost of further ER or CDR hits the cap. This creates the situation shown in Figure 5: emitters generate a unit of CDR and (g – b) units of ER, where marginal compliance costs are equal to the cap. The CDR cost cap induces insufficient CDR and ER, creating a net-zero gap of (b – a). The gap would have to be filled via government procurement of CDR. This design thus functions as a subsidy to all purchasers of GHG-emitting goods and services (who face lower product prices because of the cap). The subsidy is paid by the public through the government financing and procurement of CDR.

To fill the net-zero gap with additional CDR, the government (and ultimately the public) pays an amount represented by the areas A + B + C + D. Because the cap holds down investment in private ER as well as CDR, the government purchases CDR that is more costly than available emissions reduction options. Relative to the cost-effective amounts of private ER and CDR, society at large incurs an efficiency loss from the price cap, represented by the area D.

Figure 5. A Compliance Cost Cap



In another version of a cost cap, emitters are required to achieve net zero via a combination of CDR and ER, but the government pays the difference between their total compliance costs and the cost cap. This eliminates the net-zero gap. However, once the cap is binding, emitters are indifferent to where and how the net-zero gap is filled by CDR and ER—they pay only the costs represented by area A, regardless of the CDR and ER approach. They may invest in too much ER or too much CDR, knowing that the government will cover any costs associated with getting the balance wrong. Also, with the government paying excess costs over the cap, emitters have less incentive to seek cost-minimizing CDR or ER technologies. Although it is unlikely that private actors would choose to engage only in CDR, leading to the efficiency cost shown by area D, there still would be inefficiency.

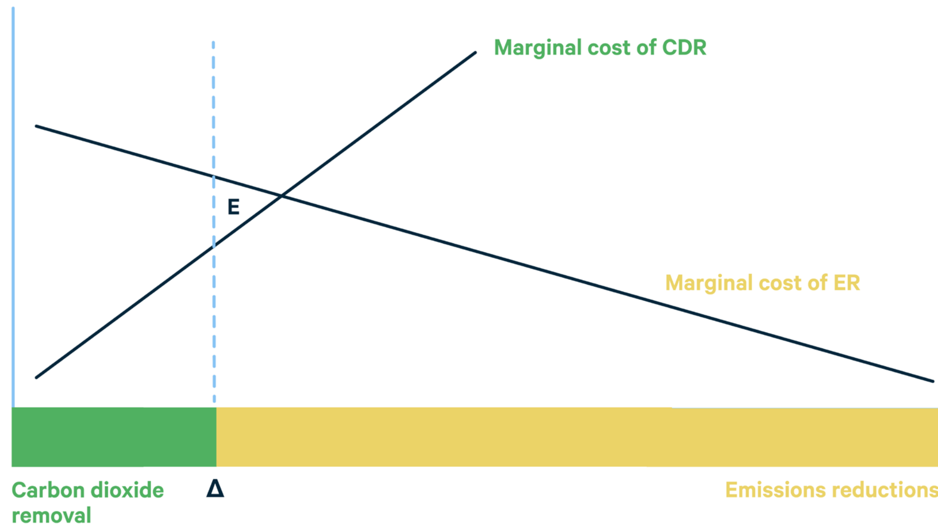
The conclusion to be drawn is that cost caps can reallocate some compliance costs from emitters and their customers to the public in ways that may be politically appealing and not that visible. However, they also increase the total costs of achieving net zero. Similar concerns arise if the cap with CAT+ or the carbon price with CP+ is insufficient to induce enough ER and CDR to achieve net zero, and the government must close the net-zero gap through public financing and procurement of CDR.

CDR Capped or Disallowed as a Compliance Mechanism. What happens if CDR is disallowed or its quantity is capped as a compliance mechanism? In the extreme case, where no CDR is allowed, emitters can achieve net zero only by guaranteeing zero emissions. CDR will almost certainly be cheaper than the most expensive ER investments needed to eliminate emissions. The cost of relying only on ER for net zero is likely to be economically onerous.[55] The excessive costs of such a scenario would be politically problematic and have no upside virtue in terms of getting production and consumption price signals right. In fact, such a policy would distort price signals by overpenalizing emitters and their customers.

A less extreme case arises if CDR can be used in a CAT+ or CP+ scheme, but the amount that can be credited is limited (CDR is capped at Δ in Figure 6). One possible motivation is the concern, noted previously, that some types of CDR are less permanent or less reliable than what can be achieved with ER measures. This policy is a special case of the mandates discussed above. Again, compliance costs are increased. In this case, the cap on CDR requires use of costlier ER to achieve net zero, and the additional cost from the efficiency loss is represented by the triangle E in Figure 6.

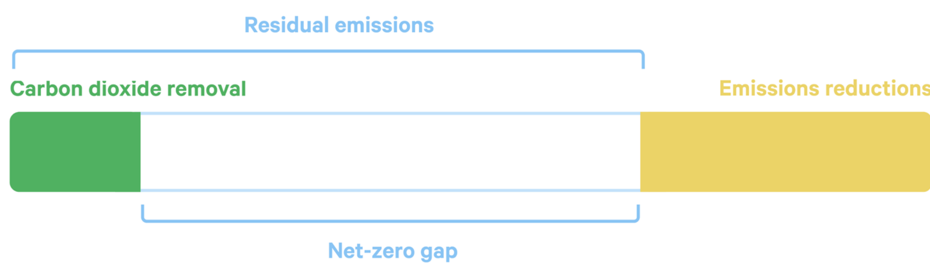
55 It is debatable whether such an approach is technically feasible, given, for example, GHG emissions from agriculture vis-à-vis practical limits on the expansion of forest carbon sequestration. Perhaps still-infant nature-based technologies like rock weathering and ocean sequestration could close the gap, though it is impossible to say what the cost might be.

Figure 6. CAT+ or CP+ with Capped CDR



Excluded Sectors. This scenario arises if the CAT+ or CP+ policy is not extended to all emitting sectors. Either a net-zero gap occurs (Figure 7) or other, less cost-effective policies need to be used in the excluded sectors. In agriculture, for example, the gap could be addressed with subsidies for GHG mitigation like those in the US Farm Bill (Toman et al. 2022).

Figure 7. Net-Zero Gap Created by Excluded Sectors



Another way to fill the gap is government procurement of CDR. The problem with that is the same one we noted in discussion of the cost cap: the government may have to purchase CDR that is more costly than available emissions reduction options (which would occur if ER policy were expanded to require net zero in all sectors).

Excluding sectors from CAT+ or CP+ might lower the cost of compliance faced by producers and consumers in those sectors, depending on what alternative measures are used. This may have particular appeal on distributional or other fairness grounds for, say, agriculture, given the burden of higher food costs on low-income households and the limited options for ER in the sector. However, it increases total costs if net zero is still the goal.[56] It also ignores the possibility that CDR will advance such that the cost burden on producers will fall.

7.5. Overshooting and the Need for Net-Negative Emissions (beyond Midcentury)

Achieving net zero by midcentury may be insufficient to keep the global temperature increase below 1.5°C or 2.0°C in the long term because of the prior accumulation of GHGs in the atmosphere (the overshooting). Accordingly, at midcentury, policy will need to go beyond what is needed to attain net zero and generate additional CDR to achieve net-negative emissions.

Note, though, that having achieved a net-zero economy, the private sector has no residual emissions. There is therefore no compliance-based leverage to incentivize "beyond net zero" CDR. Accordingly, at midcentury and beyond, government procurement of additional CDR will be required to overcome overshoot. The net-zero policies discussed above would remain operative. But a tandem public investment in, and procurement of, overshoot-driven CDR would also be needed. This global procurement problem will be politically challenging, given the need to coordinate investment and assign responsibility for negative emissions across the global community.

7.6. Sequencing of ER and CDR Policies over Time

Essential to the transition to a net-zero policy framework for ER and CDR is attention to "policy sequencing" (Pahle et al. 2018). The general idea is that moving from a weaker regulatory setting to one strict enough to attain net zero requires a sequence of policies that work on two margins. More narrowly targeted policies need to be applied more broadly over time, and policy stringencies within different industries or sectors need to ramp up as institutional, technological, economic, and political barriers (like interest group dynamics) are being relaxed.

Policy sequencing is a dynamic process that occurs from the beginning of the on-ramp for scaling up CDR to achieve a net-zero economy. It involves interactions between ER and CDR policies, as well as interactions between CDR on-ramp policies and policies used for fully scaling up CDR. Some of these interactions are relatively straightforward: for example, the more aggressive the on-ramp policies, the faster CDR costs decline, and the more ambitious CDR and ER can be. The more slowly strong ER policies are implemented, the weaker are the incentives for CDR investment to create offsetting

56 Moreover, commodity costs are a small fraction of retail food costs, so the consequences of decarbonization for food costs may rest more with other segments of the supply chain, like transportation. In addition, higher energy prices may affect low-income households more than higher food commodity prices.

removal credits. The slower the efforts to address enabling conditions for CDR, including ameliorating actual or potential environmental justice problems from CDR activities, the slower CDR will grow.

To illustrate the sequencing of ER and CDR policies over time, suppose that mitigation policy starts with performance standards (carbon intensity per unit output ratios) in certain sectors, and then evolves toward absolute quantity limits in all sectors that tighten over time. In the first phase, once regulators set emissions intensity targets for covered sectors (decline over time to increase stringency), regulated entities whose carbon intensity exceeds their target can buy carbon intensity reduction credits from other entities that reduce their carbon intensity below the target.[57] That can include purchases of GHG reduction credits from suppliers of CO_2 removal services to lower carbon intensity, net of quantities removed.

Performance standards can reduce the effects of GHG mitigation on consumer prices, thereby reducing political resistance while encouraging innovation to reduce GHG intensity in the regulated sectors (Yeh et al. 2021). However, performance standards do less than CAT or CP to stimulate reductions in demand for higher-carbon goods and services. Demand for CDR credits will be limited to the quantities used by emitters covered by the performance standards to reduce their carbon intensity and will not offset the lack of demand-side signals. Meanwhile, if other sectors are weak (e.g., subsidies and voluntary measures), innovation for mitigation in those sectors will slow.

If ER and CDR are brought together in one integrated policy framework, their sequencing will adjust to changes in innovation as well as the tightening of total emissions limits. On the other hand, the longer that policies include mandates, emissions price ceilings, or omission of sectors, all of which limit the benefits of economic incentives on mitigation and removal, the slower and less cost-effective the transition to net zero.

Finally, there is an important potential distinction between CAT+ and CP+ in the adjustment of the economy over time. CP+ is a revenue-raising policy, except in the limit as net zero is approached. CAT+ also could raise allowances are auctioned. Andreoni et al. (2024) use an integrated-assessment simulation model to show that introduction of CDR with a carbon price reduces total revenue and thus reduces the potential to improve distributional equity through progressive redistributions of that revenue. In their analysis, moreover, CDR (specifically, DAC) becomes fairly inexpensive over time, but there is a binding constraint on its total application. This also increases income inequality by increasing economic rents for owners of CDR capital, who will tend to be in higher-income deciles. The authors suggest that the inequality may warrant operating CDR policy separately from carbon pricing or (revenue-raising) cap-and-trade policy for emissions reductions. These findings warrant additional study in order to refine estimates of potential inequality and potential improvements in cost-effectiveness through deployment of CDR.

57 This is broadly similar to the approach in the California Low Carbon Fuel Standard (Yeh et al. 2021).

8. Conclusions

Getting to net zero in the next two to three decades will require significant global emissions reductions and CDR. Beyond midcentury, CDR remains important to both maintain net zero and achieve net-negative emissions. To aggressively ramp up CDR, immediate measures—with commensurately large investments—are needed to overcome gaps and weaknesses in current CDR policies.

To tie together the various elements of our study, we refer to the themes listed in Section 4.

- **CDR policies should be designed to minimize costs in achieving their goals.**
- **Policy should be technology neutral.**
- **Financing sufficient CDR is a core policy challenge.**

A long-term policy framework for achieving and maintaining net zero with an economy-wide cap-and-trade or carbon pricing system (CAT+ or CP+ in our terminology), in which CDR functions as a complement to remove residual emissions, satisfies the first two conditions. In this setup, the relative costs of CDR and mitigation drive innovation and investment choices, as well as determine the balance of mitigation and CDR needed to achieve net zero. A CAT+ or CP+ policy framework also provides incentives for private financing of CDR (assuming the technologies have matured beyond the need for the on-ramp policies discussed in Section 6).

Even if GHG emissions by midcentury are not regulated sufficiently to achieve net zero (e.g., because regulation of certain emitting sectors is limited), incorporating CDR credits with ER policies will have the attributes noted above. The difference would be the need for government financing and procurement of additional mitigation and/or removal to close the net-zero gap. As discussed in Sections 7.3 and 7.4, even if the government obtained additional CDR cost-effectively, the mix of ER and CDR would not be cost-effective. There may be political arguments for public sector involvement, but the accompanying efficiency losses in the path to net zero require careful consideration.

- **Public sector support for CDR research, development, and demonstrations and early-stage adoption is needed, but as technologies mature, it should be scaled back in favor of policies relying on private sector incentives.**
- **Significant policy transitions are required, and policy interactions need to be considered.**

To facilitate the transition to a midcentury net-zero policy framework, we have made recommendations for immediate and near-term actions. These are geared toward (1) acceleration of conventional CDR on land (primarily via afforestation), where land-use conversion and credit verification issues loom large; (2) DACCS and BECCS, where costs, enabling conditions (related to siting, CO_2 transport, and storage management), and environmental and equity concerns (including better assessment of net CO_2 reductions for BECCS) must be addressed; and (3) RD&D incentives and investments to identify and develop other novel CDR technologies and to speed cost reductions and learning-by-doing across the entire portfolio of CDR options. Prompt policy interventions are needed both to achieve a timely scale-up of CDR and to lower political resistance to tougher mitigation standards (since the CDR backstop, by design, lowers the cost of net-zero compliance).

We discussed in Section 7.6 the transition from near-term promotion of CDR technologies to longer-term scaling up of GHG mitigation and removal policy, and the interactions among different elements of the policy matrix. However, significantly more analysis and discussion with stakeholders are needed. The transition involves active government engagement throughout, with major shifts in the role of government and policy incentives employed during successive stages.

- **Negative CDR effects must be identified and addressed.**

We discussed environmental justice concerns with expanding CDR in Sections 5 and 6. The possibility that even introducing CDR could create a policy tradeoff between emissions reduction and removal through future GHG standard-setting is difficult to weigh. Nevertheless, regulatory changes can and should be undertaken to require existing combustion sites with high levels of local air pollutants to reduce those emissions, by directly controlling them or through decarbonization of the facilities, and that CDR credits should not allow such sites to continue polluting. These policy changes should be undertaken now, not after efforts to scale up CDR are well under way. Disadvantaged communities should not be told, yet again, that their concerns will be addressed sometime in the future.

Other concerns reflect the larger challenge of achieving net zero with the use of ER and CDR, not just CDR itself. Regressive effects on low-income households or particular sectors may engender political opposition to any net-zero approach can be addressed with complementary tax and redistribution policy mechanisms that compensate for distributional inequity (Blonz et al. 2012; Morris and Munnings 2013). Concerns about certain sectors and associated communities already have arisen with fossil fuel industries (Raimi et al. 2023; Look et al. 2021), and they will grow. Our primary suggestion is to employ an incentives-based, innovation-positive system like CAT+ or CP+ to cover as much of the total volume of GHG emissions as possible, as well as some phasing in. This will support a greater degree of cost-effectiveness in reducing the carbon footprint. As discussed in Section 6, the government then can undertake public procurement for filling any net-zero gap. In addition to using incentive-based mechanisms for obtaining CDR from private suppliers, the government should examine possibilities for cofinancing the procurement from levies on the sectors that receive more favorable treatment.

The case for greatly expanded CDR has faced headwinds in the United States and internationally. However, if the world is going to achieve net-zero by midcentury, the case for large and rapid scaling up of CDR, as outlined in Sections 2 and 3, is compelling. CDR at scale is necessary to limit dangerous anthropogenic interference in the global climate system, and well-designed CDR and ER policies can lower the social cost and provide financing for achieving a net-zero economy.

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