CHAPTER 1

Introduction to ROADS TO REMOVAL

Removing CO_2 from the atmosphere is critical to ensuring climate security and resilience. The destructive and profound climate disturbances caused by the past century's excess greenhouse gas (GHG) emissions are unsustainable and already costing the United States trillions of dollars. To address this planetary emergency, human societies must immediately work to "decarbonize" and dramatically reduce GHG emissions, aiming to reach as close as possible to zero. But being pragmatic, we must recognize it will be impossible to decarbonize quickly enough or completely enough to avoid warming beyond 1.5°C. Thus, to sustain the goal of reducing global carbon emissions to net-zero by 2050, we will also need to directly remove CO_2 from the air and subsequently store the carbon for as long as possible. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment (AR6) report states that globally we must remove 100–1000 billion tonnes of CO_2 by 2100 to limit warming to 1.5°C [1, 2] (**Figure 1-1**). Indeed, all climate-model scenarios that hold warming to 1.5–2.0°C depend on global-scale negative emissions techniques that remove 5–15 billion tonnes of CO_2 equivalents (CO_2e) per year by 2050 [1]. In the United States, the Biden Administration has established a goal of removing 1 billion tonnes of CO_2e per year and achieving net-zero GHG emissions by 2050 [4]. While other analyses generated via integrated assessment models and market-equilibrium modeling suggest a range of targets for the United States (as much as 1.4–2.3 billion tonnes of CO_2 per year by 2050 to achieve net-zero [1, 5, 6]), we chose to scale our report's summary presentations to 1 gigatonne (1 billion tonnes) to be consistent with the 2021 Department of Energy (DOE) gigatonne-per-year Carbon Negative Earthshot goal [4, 7, 8].

Goals of Our Assessment

Beneath our feet, the capacity for carbon storage is vast. Achieving net-zero CO_2 emissions and limiting the impacts of global climate change will require active scaling of atmospheric CO_2 removal and, in the near term, a better understanding of technical, biophysical, economic, and sociopolitical hurdles. With a team of leading academic and DOE national laboratory experts, we have conducted the first economy-wide high-resolution technical evaluation of the existing options for achieving this CO_2-removal goal. The United States' net-zero goal includes targets of 100% clean electricity by 2035 with 40% GHG-emissions reductions by 2030 [9, 10]; this helped set the primary boundaries for our report's CO_2-removal supply curve—the cumulative costs and volumes available by 2050 (**Executive Summary, Figure ES-4**). In our analyses, we evaluated feasibility, performance, and costs of

CHAPTER SCOPE

CO_2 can be captured from the atmosphere via photosynthesis or engineered chemical processes and then stored in soils, long-lived products, or deep geologic reservoirs. This report presents an unbiased, bottom-up quantitative analysis of county-level CO_2-removal capacity and costs (a supply curve) in the terrestrial United States, with the goal of delineating the resources required for achieving net-zero emissions by 2050.

In this chapter, we describe:

- Goals of this report
- Guardrails: what we left out and why
- Our analysis approach
- Types of CO_2 storage: ecological versus geologic
- Methodologies and limits
- Resources we deconflicted: biomass, storage, energy, and land
- Durability
- Roads not (yet) traveled: CO_2-removal approaches not included in this report

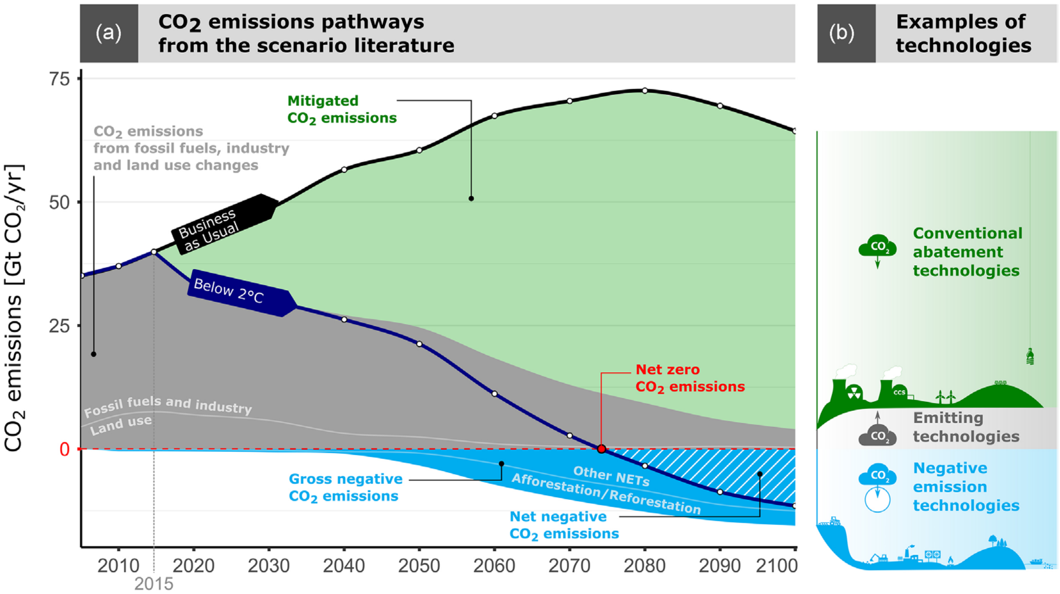


Figure 1-1. *Figure representing the projected global need for CO_2 removal and CO_2 removal (negative emission technologies). Reprinted with permission from Fuss, et al. (2018) [1].*

CO_2 removal on a county-level for the entire United States (including Alaska and Hawai'i), including all removal methods we deemed significant (i.e., capable of removing on the order of 10 million tonnes per year on a national scale, or 1% of national target) and well-developed enough for us to estimate the likely costs in 2050. We conclude that more than one billion tonnes of CO_2e removal per year will be available to the Nation by 2050 at an average cost of less than ~$200/ tonne.

Our Guardrails

While multiple previous studies have estimated the CO_2 removal *needed* to achieve a given climate target, we set out to calculate what is *available*. Our analysis was inspired by a previous study, *Getting to Neutral* [11], conducted for the state of California in 2020, where the authors used a similar "bottom-up" analysis approach, constrained by where data already exist. In our assessments for *Roads to Removal*, we did not limit our calculations by a specific target (in tonnes of CO_2 per year) other than by rational guardrails of energy, water, land use, and system analysis of air and water pollution and job and justice effects. Our study is also unique in its place-based approach; of the existing assessments of CO_2 removal options, relatively few have been conducted at the regional level [6, 12-14].

A core tenant for our study is that efforts for CO_2 removal must not compete with nationwide decarbonization. Decarbonizing—abatement of GHG emissions produced by the US economy, whether it be in the energy, transportation, agriculture or industrial sectors—is critically needed to reduce the majority of emissions that have raised atmospheric GHG concentrations and caused global warming. Emissions reductions from decarbonization will also result in health benefits valued at ~$200 billion/year [15], with outsized reductions for communities that currently bear disproportionate exposure (e.g., [16-18]). As such, any diversion of efforts away from decarbonization goals would be contrary to a key principle of the federal government's environmental-justice priorities ([19] and references therein). However, even with deep decarbonization, the United States will need CO_2 removal to counteract residual emissions from hard-to-abate sectors (e.g., agriculture, some industries) and environmental feedbacks (e.g., permafrost thawing). Furthermore, when these sectors are decarbonized, residual air and water pollution issues will persist, alongside job losses in "traditional energy communities," that will need mitigation. Without purposefully counteracting the economic-transition challenges associated with decarbonization, fossil energy communities are put at risk of economic and public-health crises [20-22]. Thus, we performed a cross-cutting analysis of energy and environmental resource availability and equity considerations alongside all our quantitative analyses of CO_2-removal capacity and costs. In all analyses:

- We required that CO_2 removal must be additive and a 'true' removal;
- We included land assessments;
- Prioritized protecting US environmental resources (e.g., wetlands);
- Avoided competition with renewable energy sources necessary for decarbonizing the electrical grid [10];
- Highlighted ecological CO_2-removal methods with high restorative-justice opportunities in the country's most vulnerable counties;

- Highlighted counties that may have skilled, underemployed workforces ready to become early leaders in innovative CO_2-removal methods.

These guardrails are embedded in every chapter of this report and are designed to establish what a roadmap to an equity-centered CO_2-removal scale-up could look like in the United States.

Approach

CO_2 can be captured from the atmosphere via photosynthesis (native grasses and shrubs, trees, agricultural crops, macroalgae), biogeochemistry (rock weathering and mineralization), and engineered chemical processes (direct air capture (DAC)), and then stored in biomass, soil/sediment organic matter, long-lived products (wood, plastic, char), minerals, or deep geologic reservoirs (**Figure 1-2**). For the analyses in this report, we considered only CO_2-removal strategies where we judged the science sound and settled, where we could gather sufficient information—with county-level resolution (in 2022)—to estimate costs and the capacity for removal by 2050, and with sufficiently large scalability. We recognize that this means many promising approaches had to be left out and refer the reader to "Roads Not Taken" sidebar discussions that highlight more developmental CO_2-removal approaches. We established a threshold for inclusion of approximately 1%, meaning a CO_2-removal approach needed to be capable of a minimum of 10 million tonnes of CO_2 removal per year to be considered in our analysis. Finally, we limited our analysis to the terrestrial landmass of the 50 states, which had more available and reliable data (this includes Hawai`i and Alaska but not US territories).

We evaluated a palette of well-understood CO_2-removal strategies with quantitative analyses of capacity and costs by 2050 for five sectors—forestry, cropland soils, biomass carbon removal and storage (BiCRS), DAC with storage (DACS), and geologic storage—with county-level geographic resolution wherever possible. Linkages and interdependencies were assessed in a suite of cross-cutting analyses, where we analyzed each CO_2-removal approach in light of realities imposed by the other approaches (**Figure 1-3**) (e.g., transportation infrastructure for biomass and CO_2, freshwater resources, air quality, and energy equity and environmental justice (EEEJ) concerns). Throughout, we prioritized the use of carbon-free energy from renewable sources. We ensured that

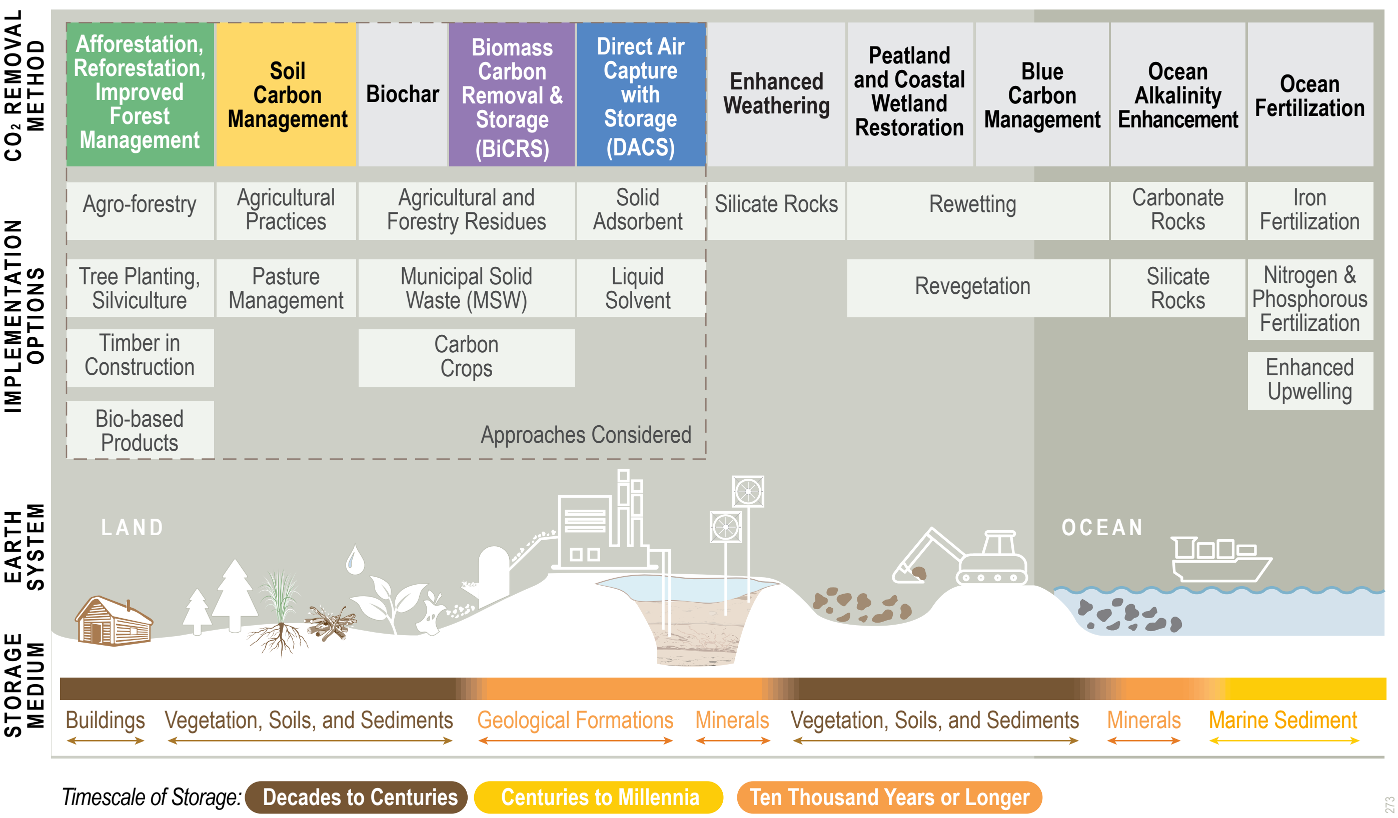


Figure 1-2. *Conceptual illustration of the spectrum of options available for CO_2 removal and storage (redrawn from Figure 2 in Minx, et al. (2018) [3]), ranging from those with **ecological storage** (decades to centuries) to those with more durable **geologic storage** (>thousands of years). CO_2-removal methods analyzed in this report are highlighted in color. We considered only CO_2-removal strategies that had sufficient county-level resolution information (circa 2022) to allow us to estimate costs, and we established an inclusion threshold of at least 10 million tonnes of CO_2 removal per year for a CO_2-removal strategy to be considered.*

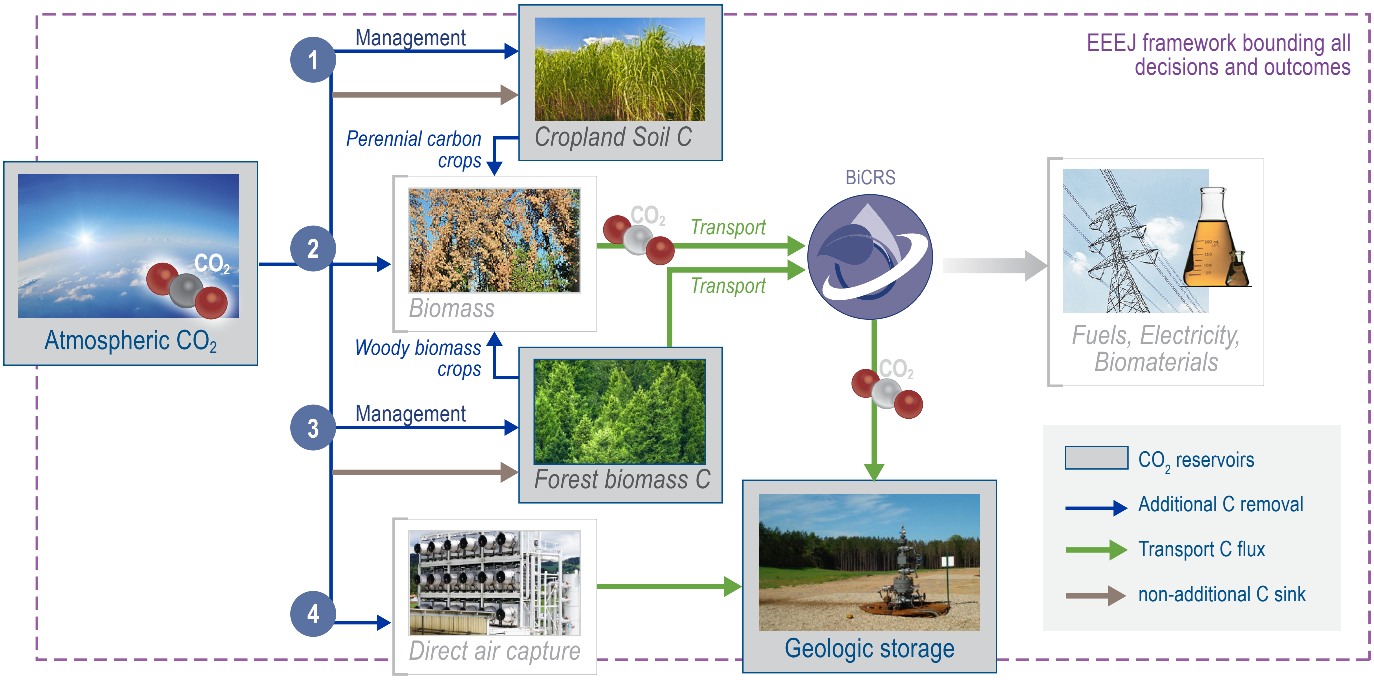


Figure 1-3. *Pathways for atmospheric CO_2 removal and storage in the US are inter-related. CO_2 reservoirs considered in this report (atmosphere, cropland soils, forest biomass, and deep geologic subsurfaces) are highlighted in grey boxes. Fluxes of additional atmosphere-derived CO_2 (via photosynthesis or direct air capture) are indicated with dark blue arrows. A portion of CO_2 captured via photosynthesis through cropland and forest management may be harvested as biomass for BiCRS. We note with grey arrows where CO_2 fluxes are already occurring, without novel management. Transportation of CO_2 between biomass sources, BiCRS thermochemical conversion facilities, or DAC facilities and geologic storage sites are indicated with green arrows. An EEEJ lens bounds all decisions surrounding managed CO_2 fluxes.*

any land surface area used was relied upon only once and considered land-use change for all CO_2-removal strategies. We also integrated region-specific constraints driven by climate (fire risk) or geology (geothermal, depth to basement) and relevant EJ metrics, such as census-track-level social dimensions (from EJScreen's demographic index [23]) and air/water pollution data.

Our report draws upon and leverages existing data syntheses (e.g., US Forest Service Forest Inventory and Analysis (FIA), Billion Ton Report [24], National Energy Technology Laboratory (NETL) products, National Renewable Energy Laboratory (NREL) renewable energy models, peer-reviewed publications) but is not meant to duplicate any of those existing analyses; our goal is to provide an integrated and interdisciplinary analysis that is wholly novel and unique. Where data currently exist, we analyzed EEEJ issues (air/water pollution, nutrient loading, socioeconomic factors, density, etc.) quantitatively –these results are interwoven with our other CO_2-removal analyses. However, we did not collect new EEEJ data or conduct social surveys.

For each CO_2-removal approach, we have included discussions of additionality, leakage, and durability and were conservative in the assumptions we made to address these concerns. For example, we did not allow purpose grown biomass crop ('carbon crop') expansion to increase commodity prices in our economic models; this ensures that the modeled biomass supply will not create incentives for land-use change elsewhere. Uncertainty in important parameters (e.g., available land, energy, and water; learning and implemental curves; new technology options; and soil carbon measurement, reporting, and verification) could create extremely large ranges in future costs and capacity. These are key areas where new research and development can effectively advance understanding. Where possible, we addressed these issues by examining how existing uncertainties affect the supply curves and how preferred options might change with reduced uncertainty.

As noted above, our analyses are best described as a bottom-up calculation of CO_2-removal availability and costs; specifically, we generated a high-resolution supply and cost curve that considers associated uncertainty and human impacts (EEEJ) across the United States to 2050. We did not seek to indicate a "best path" nor make policy recommendations, but rather, we provide the critical data that can enable decision-making at all levels. That said, wide-scale implementation of any type of CO_2-removal will likely require new financial incentives, streamlined permitting, job training and other new policy approaches. We hope that our results will inspire further analysis by states, counties, and city governments, and additional policy support from Congress to bring about the CO_2-removal infrastructure that is needed. All data used and calculated in this report are publicly available—either through citations we have noted or at the Roads to Removal report website, https://roads2removal.org/.

Ecological CO_2 Storage Solutions

To sequester carbon in our Nation's forests and soils, durability is a major challenge (**Box 1-1**). We argue that even short-term storage has value, particularly because CO_2 storage in ecological reservoirs can be implemented in the near term. Costs are likely to be low on an annual basis but may become significant over long periods of time. A larger question is whether forest and soil management incentives maintain practices to keep carbon out of the atmosphere for the next century? Ultimately, durable ecological carbon storage, as a function of both social factors that determine land-management decisions and future climate effects, requires a sustained commitment to ecosystem stewardship. Investments in measurement, reporting and verification (MRV) will be critical, along with systems-level assessments of additionality. Solutions may require management on a portfolio basis, with explicit discounting of benefits for some expected number of project failures or changes.

The United States has vast amounts of forested lands with high potential for increased carbon-sequestration rates in forest tree growth and long-lived wood products. Improved forest-management practices, such as reducing stocking densities in high fire-risk areas and routing timber to long-lived forest products, have the potential to increase forest-carbon stocks and decrease forest-carbon emissions by promoting tree growth while still supplying critical wood products for market. In our forests analysis (**Chapter 2–**

BOX 1-1

Using Both Ecosystem and Geologic Storage to Meet Mid-Century Climate Targets

Achieving net-zero CO_2 emissions necessarily requires CO_2 storage. But net zero is not a one-time target and needs to be sustained over many decades. Thus, it is important to consider how different CO_2 sinks have inherently different durability timescales (**Figure 1-2**), and plot out a strategy (ideally within this century) where we transition to a "like-for-like" balance of emissions and removals (i.e., where any ongoing fossil CO_2 emissions are balanced by permanent disposal (such as geologic storage) [25]).

CO_2 in geologic storage is highly durable and likely permanent. By contrast, CO_2 stored in ecosystems (forests, soils) has variable durability, ranging from years to centuries at the landscape scale [26], but overall, it is likely not permanent. These differences present a challenge when comparing the climate-change-mitigation potential of CO_2 removal and storage based on the amount of CO_2 removed. However, these challenges do not preclude temporary storage from contributing to achieving climate targets alongside rapid decarbonization [27-29].

Storage of removed CO_2 in deep geologic subsurface is a primary target due to its high durability. However, permitting, scaling, and widespread deployment of technologies to remove and store CO_2 in geologic storage has been slow and must expand rapidly in the next two decades to meet 2050 climate targets [30].

The durability of CO_2 stored in forests and soils depends on management decisions around implementing and continuing practices that remove CO_2 and maintain stored carbon. Carbon stored in ecosystems is vulnerable to wildfires and may be influenced by future climate change. Taken together, CO_2 stored in ecosystems is not likely to be as durable as geologic CO_2 storage and cannot be substituted for permanent CO_2 storage. However, along with the many environmental co-benefits of managing cropland soils and forests to increase CO_2 storage, the immediate deployability and scalability of ecological CO_2 storage allow forest and cropland management to function as near-term storage options (e.g., within a century) for meeting more immediate (2050) climate goals. Eventually, these options could largely be replaced with permanent geologic storage once technology has scaled sufficiently.

Forests), we assessed the potential for US forested lands to store and sequester carbon in forest biomass and long-lived wood products. Specifically, to evaluate forest-management practices at the regional level, we used quantitative and statistical models to produce regional estimates of forest-CO_2 sequestration under shifting practices. The practices we assessed included implementing fire-resilience treatments for wildfire-prone western forests, promoting regeneration-focused forest management, planting new forests, and using novel wood-product markets. At the regional level, we combined estimates of practice costs to determine the price of management changes. We considered forestry optimized for carbon management, but not offsets for keeping forest in place. We also considered short-rotation forests as a biomass source. As not all of the United States has forest cover, we focused our detailed, county-level estimates on three important forested areas: southeastern pinelands, dry western forests that are at high fire risk and near human settlements, and hardwood forest in southern New England and southeastern New York. Due to a lack of data availability, we did not include forest carbon leakage through volatile organic compounds (i.e., conifers emitting isoprene, volatile monoterpenes), and only considered changes in forest soil carbon stocks in our southeastern pinelands study. Thus, while the full breadth of forest-based CO_2 removal has not been prescribed for every acre in the US, our case studies and regional synopses provide examples that we hope will jump-start future dialogues.

On croplands and managed agricultural landscapes, soil-carbon storage can be increased most effectively with management strategies that increase the amount of year-round plant cover and root inputs on the landscape. These strategies either integrate with existing annual crops (e.g., cover cropping and perennial field borders) or replace annual crops with perennial crops (e.g., perennial carbon crops). However, new research is urgently needed. All efforts to increase soil-carbon storage can benefit from investing in cost-effective monitoring technology to quantify soil carbon and emissions of GHGs from soil, particularly nitrous oxide (N_2O), and improve MRV protocols. In addition, more distributed, well-replicated field trials are essential for establishing emerging soil-based carbon-removal approaches and for fully exploring already established practices that target grazing lands.

For our Cropland Soil analysis (**Chapter 3 – Soils**), we assessed three land-management practices with the potential to increase soil-carbon storage: cover cropping, perennial field borders, and perennial carbon crops, and constrained our analysis to the 114 million hectares of United States cropland not under tree-crop or perennial specialty crops. We chose these practices because of their proved effectiveness based on published field-scale measurements in climates and soil-types thought the USA. On data from 37,283 sites across the country, we used biogeochemical models driven by county-specific crop and soil conditions, along with future climate projections, to estimate the effects of these management practices on soil-carbon storage and emissions of GHGs. We avoided double-counting of soil carbon accrual (in the order of perennial carbon crops, cover crops, and field borders). We integrated these results with an economic model to simulate the area of land in each county where land managers could profitably implement each practice to constrain potential for soil-based CO_2-removal at the national scale. Our analysis accounts for the costs of maintaining sequestered carbon at the national scale until 2050 and explicitly distinguishes the full climate benefit (e.g., avoided GHG emissions) from soil-based CO_2 removal alone.

Even though the potential amount and duration of carbon storage in soils is uncertain (Box 1-1), the potential for short-term carbon removal from the atmosphere, numerous environmental co-benefits and potential for rapid implementation make carbon storage in cropland soils an attractive option. Accounting for both carbon and EEEJ outcomes of on-field strategies such as cover cropping, perennial field borders and perennial carbon cropping is more straightforward than other management practices such as no-till and composting, and so these were the practices considered.

Geologic CO_2 Storage Solutions

For CO_2-removal approaches that lead to deep geologic CO_2 storage—including DACS and BiCRS—the availability of large quantities of CO_2-removal capacity is more assured than for ecological CO_2-storage solutions, but the associated costs are likely higher and need to be established with confidence. As such, the timeframe over which BiCRS and DACS can be implemented will depend on factors such as capital investment, permitting requirements, and community acceptance, but by 2050 we expect their annual rates will be large (see **Executive Summary, Figure ES-3**).

BiCRS pathway can deliver significant and durable carbon removal while also providing sustainable (aviation) fuels for decarbonization. To meet the Biden Administration 1 billion tonnes per year by 2050 goal [3], biomass CO_2 removal represents the largest-volume component of future US CO_2 removals. The challenge with BiCRS is not capacity but implementation. BiCRS requires the engagement of multiple stakeholders who must produce, collect, and transport biomass; construct and operate biomass conversion facilities; and transport CO_2 for geologic storage. While several biomass-conversion technologies for BiCRS are mature, most have yet to be implemented at scale. For these reasons, we focused on identifying lowest-cost regional BiCRS solutions (including profit from generation of needed sustainable fuels) and co-benefits to communities to propel the “leap” over this implementation gap. Using waste biomass (agricultural, forest, trash/municipal solid waste (MSW), and food waste) is vital to achieving this goal.

In **Chapter 6 – BiCRS**, we analyzed 27 BiCRS carbon-removal pathways. These pathways process biomass (residues, wastes, carbon crops) so that its carbon (which originated from CO_2 in the air) can be captured and sequestered, either geologically or through the production of durable carbon products. These pathways can also produce other valuable products (electricity, fuels, and chemicals). Our BiCRS analysis is divided into three major assessments of biomass availability/potential that could be processed while still protecting current carbon stocks and avoiding leakage. We focused on residues and wastes as the primary biomass resource, but also calculated how marginal land or land currently used for ethanol could be converted to a profitable biomass resource, possibly via carbon crops or perennial grasses. We then linked these assessments to a comprehensive analysis of biorefinery-biomass suitability criteria and techno-economic and life-cycle assessment (LCA), also including logistics for biomass and CO_2 transportation (**Chapter 5 - Transport**). Through this analysis, we were able to develop regional CO_2 supply and cost curves, identifying unique regional opportunities for BiCRS-based carbon-removal impact and co-benefits.

DACS is the most expensive of the CO_2-removal approaches, requiring land, a source of low-carbon energy, and a place to permanently store the collected CO_2. Based on our analysis, these facilities are likely to be sited in the southwestern and western United States to access geologic storage and zero-GHG-emission power. In **Chapter 7 – DACS**, we focused on DACS technologies that have sufficient published information (solvent and adsorbent) for us to perform our analyses. Further, we identified locations around the Nation that are likely to provide the best conditions for deploying DACS along with the additional renewable-electricity resources it requires (but that do not compete with renewable-electricity resources needed for electrical-grid decarbonization). We identified key US regions where we could deploy large amounts of DACS, and we quantified the costs to do so. For these analyses, we considered a completely electrified adsorbent-based DACS process, using renewable electricity, and a solvent-based DACS process powered by natural gas and capturing the associated emissions.

As previous studies have shown, suitable geologic storage is available in many parts of the country [31]. Our study confirms the findings of previous work that well-studied geologic basins and formations are more than adequate to meet estimated storage needs. However, we were keen to know at a higher spatial resolution whether storage exists in proximity to ideal BiCRS and DACS locations. We added to previous work by mapping all onshore sedimentary rocks in which storage may be possible and included prospective storage in basalts and other mafic rocks. We included new factors that impact the cost of geologic CO_2 storage, including how land-leasing costs are affected by CO_2 plume size and pressure, storage fees paid to landowners, the costs of characterization and monitoring, and monetary benefits to communities that host storage projects. We also estimated costs on a project basis, where an individual “storage project” is defined as 1 million metric tonnes of CO_2 injected per year for 20 years. In **Chapter 4 – Geologic Storage**, we display a new map that shows all the counties in the United States where storage is possible—and where it is not possible—and at what cost. Our approach should allow CO_2-removal project developers to better match removal projects with storage options based on volume and cost and, for projects not near low-cost storage, helps guide decision-making on whether resources are better spent exploring for prospective storage near a project or on transporting CO_2 to well-characterized storage resources. We note that while a large capacity for geologic storage exists in sedimentary rocks beneath state and federal offshore waters, we only considered onshore resources in this study.

Cross-cutting Analyses

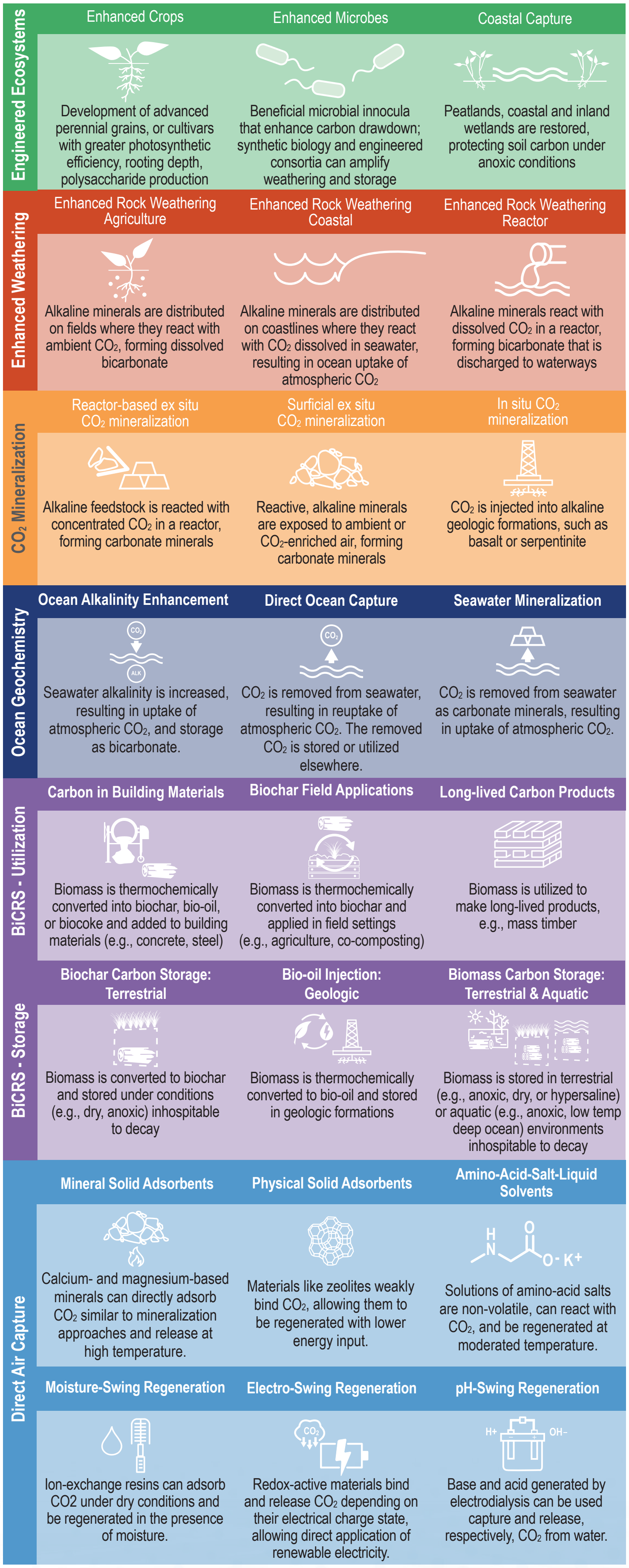
We applied a series of objectives and constraints to our forest management, agricultural soils management, BiCRS, and DACS analyses to determine interactive effects on the potential scale and costs of large-scale CO_2 removal. Each strategy yields some co-benefits, such as reduced wildfire risk and new employment opportunities, while also placing new demands on constrained natural resources, such as land and water. In **Chapter 8 – Cross-Cutting**, we discuss the timing of CO_2-removal scale-up in the United States and the implications of CO_2-removal strategies for natural resources, including land, water, and air. We de-conflicted the forest management, BiCRS, DACS, and agricultural soil management strategies to ensure that we did not double-count key natural resources in our estimates of potential CO_2-removal scale. The dramatic expansion in wind and solar energy necessary to decarbonize the electrical-grid means that we needed to set aside substantial land area for that purpose in our analysis. By prioritizing grid decarbonization, we ensured that DACS co-located with renewable-energy generation would not compete with renewable energy needed for the grid.

As a large-scale endeavor that will touch so much of our land, population, and economy, deployment of CO_2 removal needs to focus on social and environmental justice considerations and basic public awareness—these are fundamental limits to the scope of implementation [32]. At this point, it is too early to say what changes and limitations must be placed on CO_2-removal approaches to improve the lives of all Americans, including members of Tribal nations. However, with the large number of CO_2-removal options available to the United States, the Nation should be able to find an array of solutions that provide environmental and socioeconomic co-benefits tailored to the needs of counties throughout the United States. In **Chapter 9 – EEEJ,** as well as embedded sections on equity for each CO_2-removal method throughout the report, we review potential trade-offs, both environmental and socioeconomic, for each CO_2 removal method. Based on geospatial data availability for these trade-offs, we constructed an EEEJ Index for each CO_2-removal method, which we compared to the Center for Disease Control's (CDC's) Social Vulnerability Index (SVI) to assess highly vulnerable counties that currently suffer from inequitable pollution problems that CO_2-removal methods (e.g., forest and soil management) could help abate. We also identify numerous counties across the country that are poised, both environmentally and socioeconomically, to serve as early leaders in innovative CO_2-removal methods, such as BiCRS and DACS, that take advantage of geologic carbon storage.

The United States is made up of geographically diverse and distinct regions, each of which contains an array of resources that can contribute toward carbon-removal targets. In **Chapter 10 – Regional Opportunities**, we looked for regional similarities in CO_2 removal and resource availability and assigned each of the United States counties to one of 22 regions.

Roads Not Taken

There are multiple emerging pathways for CO_2 capture and/or storage that we did not considered in our analyses, due to low technology readiness, a lack of high-resolution (county-level) data, or our judgement that the technique was not yet able to deliver 10 million tonnes of CO¬$_2$ removal per year. For example, readers may find it surprising that we did not evaluate the CO_2 removal potential of enhanced rock weathering—the addition of fast-reacting, crushed alkaline minerals (e.g., crushed basalt rock) to agricultural soils [33-35]. This technique is thought to facilitate the drawdown of atmospheric CO_2 that is then captured in the terrestrial or marine system as soluble bicarbonate (alkalinity) or as soil carbonate minerals [36]. However, while enhanced weathering on croplands has high scalability and theoretical capacity for CO_2 removal [33, 37], very few published field studies have verified modeled estimates [38], and it may take several years before region-specific data exist. Thus, we could not include this approach. We deemed many other approaches 'out of scope' for similar reasons. In **Figure 1-4**, we highlight a suite of pathways that show exciting potential to scale, but where fundamental research is ongoing. We refer readers to several recently published reports and articles that provide additional details for these pathways, ranging from engineered crops [39], to microbial and soil treatments [40], to the relative scale and implementation timeline of CO_2 removal approaches that are still in the research and development pipeline [41].



Conclusions

In Roads to Removal, we provide comprehensive high-resolution data and discussion on CO_2-removal availability and costs, along with metrics of associated uncertainty and human impacts (EEEJ) across the United States to 2050. We consider the suite of mature CO_2-removal approaches where country-level information is currently available, including forestry, cropland soils, BiCRS, DACS. Our analyses also consider cross-cutting effects: where geologic storage is available, transportation networks, availability of land, renewable energy, and freshwater, and impacts on society and environmental health. While we purposely avoided identifying the "best path" or making policy recommendations, our intent is to provide the critical data needed for decision-making in response to the climate crisis. Even though many in-development CO_2 removal approaches were not included, our analysis shows the Nation can meet its carbon removal targets fairly affordably. But the highest capacity/lowest cost technologies and land management solutions vary widely on a regional basis. Using the results in this report, policy leaders and communities have the evidence they need to establish the CO_2-removal infrastructure urgently needed to achieve net zero emissions.

Figure 1-4 *CO_2-removal "roads not (yet) taken." There are numerous emerging biologic and geologic pathways for CO_2 capture and/or storage that we did not consider in this report due to low technology readiness or data gaps. Many of these pathways show potential to scale, but research is ongoing. (A) Biological and ecology-based pathways include those targeting tree and crop cultivars, soil microbes, and wetland carbon capture. Geochemistry-based pathways in development include (B) enhanced rock weathering, (C) CO_2 mineralization, and (D) ocean-based approaches. Non-energy BiCRS pathways (purple) involving (E) utilization and (F) storage are in development. Additional DACS (G) materials and (H) processes have also been proposed.*

References

1. **Sabine Fuss, et al.,** *Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters, 2018.* **13(6): p. 063002,** https://dx.doi.org/10.1088/1748-9326/aabf9f.

2. Mustafa Babiker, et al., *Cross-sectoral Perspectives: Supplementary Material, in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, P.R. Shukla, et al., Editors. 2022, Cambridge University Press: Cambridge, UK and New York, NY, USA (DOI: 10.1017/9781009157926.014).*

3. *Jan C. Minx, et al., Negative emissions—Part 1: Research landscape and synthesis. Environmental Research Letters, 2018.* **13(6): p. 063001,** https://dx.doi.org/10.1088/1748-9326/aabf9b.

4. US Department of State and the US Executive Office of the President. *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. 2021. Washington, DC, USA;* https://unfccc.int/documents/308100.

5. Eric Larson, et al. *Net-Zero America: Potential Pathways, Infrastructure, and Impact. 2021. Princeton University, Princeton, NJ;* https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf.

6. Chloé Fauvel, et al., *Regional implications of carbon dioxide removal in meeting net zero targets for the United States. Environmental Research Letters, 2023.* **18(9): p. 094019, 10.1088/1748-9326/aced18.**

7. **U.S. Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM).** *DOE is Addressing Climate Change by Removing Carbon Pollution from the Air. 2023 Published by DOE FECM; Available from* https://www.energy.gov/fecm/articles/doe-addressing-climate-change-removing-carbon-pollution-air.

8. U.S. Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM). *Carbon Negative Shot. Accessed November 2023 Published by DOE FECM; Available from* https://www.energy.gov/fecm/carbon-negative-shot.

9. Paul Donohoo-Vallett, Nicole Ryan, and Ryan Wiser. *On the Path to 100% Clean Electricity. 2023. U.S. Department of Energy's Office of Policy,* https://www.energy.gov/sites/default/files/2023-05/DOE%20-%20100%25%20Clean%20Electricity%20-%20Final%20v3_0.pdf.

10. Paul Denholm, et al. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035. 2022. National Renewable Energy Laboratory. NREL/TP-6A40-81644, Golden, CO;* https://www.nrel.gov/docs/fy22osti/81644.pdf.

11. Sarah E Baker, et al. *Getting to Neutral: Options for Negative Carbon Emissions in California. 2020. Lawrence Livermore National Laboratory (LLNL), Livermore, CA, United States,*

12. *Jay Fuhrman, et al., Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. Nature Climate Change, 2023.* **13(4): p. 341-350,**

13. **Jessica Strefler, et al.,** *Carbon dioxide removal technologies are not born equal. Environmental Research Letters, 2021.* **16(7): p. 074021,**

14. **Johannes Förster, et al.,** *Framework for assessing the feasibility of carbon dioxide removal options within the national context of Germany. Frontiers in Climate, 2022.* **4: p. 758628,**

15. **C. L. Gallagher and T. Holloway,** *Integrating air quality and public health benefits in U.S. decarbonization strategies. Front. Public Health, 2020, 10.3389/fpubh.2020.563358.*

16. *Timothy Q. Donaghy, et al., Fossil fuel racism in the United States: How phasing out coal, oil, and gas can protect communities. Energy Research & Social Science, 2023.* **100: p. 103104,** https://doi.org/10.1016/j.erss.2023.103104.

17. Teagan Goforth and Destenie Nock, *Air pollution disparities and equality assessments of US national decarbonization strategies. Nature Communications, 2022.* **13(1): p. 7488,** https://doi.org/10.1038/s41467-022-35098-4.

18. John E. T. Bistline, et al., *Economy-wide evaluation of CO_2 and air quality impacts of electrification in the United States. Nature Communications, 2022.* **13(1): p. 6693,** https://doi.org/10.1038/s41467-022-33902-9.

19. The White House. *Environmental Justice. Accessed November 2023 Published by The White House; Available from* https://www.whitehouse.gov/environmentaljustice/.

20. Travis Young, et al., *Mining, loss, and despair: Exploring energy transitions and opioid use in an Appalachian coal community. Energy Research & Social Science, 2023.* **99: p. 103046,** https://doi.org/10.1016/j.erss.2023.103046.

21. Brian F. Snyder, *Vulnerability to decarbonization in hydrocarbon-intensive counties in the United States: A just transition to avoid post-industrial decay. Energy Research & Social Science, 2018.* **42: p. 34-43,** https://doi.org/10.1016/j.erss.2018.03.004.

22. Jorge Barro, John W. Diamond, and Richard Evans. *The Effect of Transition to Low-Carbon Energy on Texas Tax Revenues: 2021–2050. 2021. Rice University's Baker Institute for Public Policy,* https://doi.org/10.25613/EMR2-HS57.

23. United States Environmental Protection Agency. *EJScreen: Environmental Justice Screening and Mapping Tool. 2023 Published by US EPA; Available from* https://www.epa.gov/ejscreen/overview-socioeconomic-indicators-ejscreen.

24. Matthew H. Langholtz, B. J. Stokes, and L. M. Eaton. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy. 2016. United States; 10.2172/1271651.* https://www.osti.gov/biblio/1271651.

25. Myles R Allen, et al., *Net zero: science, origins, and implications. Annual Review of Environment and Resources, 2022.* **47: p. 849-887,**

26. Margaret S. Torn, et al., *Mineral control of soil organic carbon storage and turnover. Nature, 1997.* **389(6647): p. 170-173,** https://doi.org/10.1038/38260.

27. H. Damon Matthews, et al., *Accounting for the climate benefit of temporary carbon storage in nature. Nature Communications, 2023.* **14(1): p. 5485,** https://doi.org/10.1038/s41467-023-41242-5.

28. H. Damon Matthews, et al., *Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario. Communications Earth & Environment, 2022.* **3(1): p. 65,** https://doi.org/10.1038/s43247-022-00391-z.

29. Jens Leifeld and Sonja G. Keel, *Quantifying negative radiative forcing of non-permanent and permanent soil carbon sinks. Geoderma, 2022.* **423: p. 115971,** https://doi.org/10.1016/j.geoderma.2022.115971.

30. R. Stuart Haszeldine, et al., *Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2018.* **376(2119): p. 20160447,** https://doi.org/10.1098/rsta.2016.0447.

31. National Energy Technology Laboratory (NETL). *Carbon Storage ATLAS. 2015 (accessed July 2023) Published by NETL; Available from* https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas.

32. Kevin Anderson, et al., *Controversies of carbon dioxide removal. Nature Reviews Earth & Environment, 2023: p. 1-7,*

33. David J. Beerling, et al., Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature, 2020. **583(7815): p. 242-248, 10.1038/s41586-020-2448-9.**

34. Daniel Goll, et al., *Potential CO_2 removal from enhanced weathering by ecosystem responses to powdered rock. Nature Geoscience, 2021.* **14: p. 1-5, 10.1038/s41561-021-00798-x.**

35. Shuang Zhang, et al., *River chemistry constraints on the carbon capture potential of surficial enhanced rock weathering. Limnology and Oceanography, 2022.* **67(S2): p. S148-S157,** https://doi.org/10.1002/lno.12244.

36. Jens Hartmann, et al., *Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. Reviews of Geophysics, 2013.* **51(2): p. 113-149,** https://doi.org/10.1002/rog.20004.

37. Phil Renforth and Gideon Henderson, *Assessing ocean alkalinity for carbon sequestration. Reviews of Geophysics, 2017.* **55(3): p. 636-674,** https://doi.org/10.1002/2016RG000533.

38. Iris O Holzer, Mallika A Nocco, and Benjamin Z Houlton, *Direct evidence for atmospheric carbon dioxide removal via enhanced weathering in cropland soil. Environmental Research Communications, 2023.* **5(10): p. 101004,**

39. Christer Jansson, et al., *Crops for carbon farming. Frontiers in Plant Science, 2021.* **12: p. 636709,**

40. Energy Futures Initiative. *From the Ground Up: Cutting-Edge Approaches for Land-Based carbon Dioxide Removal. 2020.* https://efifoundation.org/reports/from-the-ground-up/.

41. Rocky Mountain Institute CDR Initiative. *The Applied Innovation Roadmap for CDR. 2023.* https://rmi.org/download/37776/?tmstv=1701203044