Roads to Removal – Part 2

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1. Introduction

As happens occasionally, this paper has grown beyond the length that I'm comfortable with, and thus I broke it into two posts.

I'm repeating some introductory text from reference 1 below, followed by the last four removal methods from this source.

There is an urgent need to remove carbon dioxide (CO_2) from the atmosphere to ensure climate security and resilience. In 2022, the United States set a goal of developing carbon dioxide removal (CDR) pathways that will remove CO_2 from the atmosphere and store it at the gigaton scale (at least a billion tonnes per year). [1] [2]

Alongside the larger national goal of rapidly reducing current greenhouse gas emissions (GHG), CDR provides a vital option for achieving net-zero emissions by 2050.

The Roads to Removal report assesses key factors and pathways for physically removing CO_2 from the air at the scale of gigatonnes (billion-tonne) per year and then storing it away from the atmosphere through either ecological or geological means. This gigatonne CO_2-removal target is the climate clean-up needed in addition to dramatic reductions of emissions of greenhouse gases (GHGs) if the United States is to reach net-zero carbon emissions by or before 2050. In this report, sixty-eight authors examine (1) forestry, (2) cropland soils, (3) biomass (such as agricultural waste or municipal trash), (4) direct air capture (machines that remove CO_2 from the air), (5) transportation, (6) available zero-carbon energy, (7) geologic storage, and (8) environmental and socio-economic impacts. What you will read here integrates published data with original research on the major elements of negative emissions. Our granular analysis, with county-level resolution, shows that it is feasible for the United States to accomplish the carbon drawdown needed for net-zero emissions by the year 2050.

The focus and scope of this report is unique. We chose to only address practices and technologies that remove CO_2 from the air. We cover a breadth of strategies where we could make reliable estimates of what their application will require, ranging from land management to the latest technological options. We evaluate the costs for every step of the solution, from collection to transport to CO_2 storage. Our methods are intended to be transparent—we included details of our calculations in the body of this report and the appendices, and the underlying data are available at the report website. [1]

We purposefully chose to avoid discussing policies or current incentives. Rather, Roads to Removal provides a range of options, tradeoffs, and costs, aiming to enable informed decision-making in every community, region, and state in our country. Specifically, our goal is to give decision-makers the lens to see options clearly and make choices that will keep us all safer in the places we call home.

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[1] A large number of authors / institutions created this large document, Click on "Team" in the main document for details, "Roads to Removal," Dec 2023, https://roads2removal.org/

[2] The tonne or metric ton is a unit of mass equal to 1000 kilograms. It is equivalent to approximately 2204.6 pounds, 1.102 U.S. tons. From https://en.wikipedia.org/wiki/Tonne

Author's comment: Note that I have repeated the primary graphic for this series below.

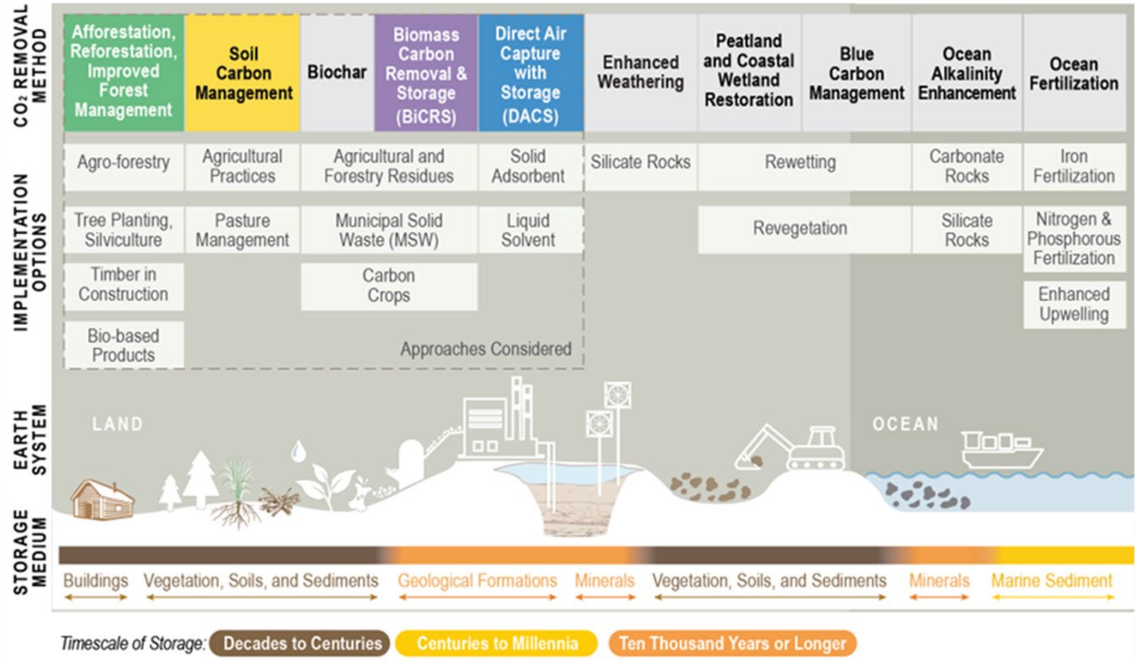

Figure ES-2. Conceptual illustration of options available for CO2 removal, redrawn from Figure 2 in Minx et al. 2018 . CO_2 removal methods analyzed in this report are highlighted in color. We considered only CO_2-removal strategies with sufficient county-level resolution information (circa 2022) to estimate costs and 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.

2. Project-Based Geologic CO_2 Storage

Geologic storage is an integral component of many major types of carbon removal, providing durable storage for CO_2 removed from the atmosphere through processes such as direct air capture with storage (DACS) and biomass carbon removal and storage (BiCRS). Building on extensive previous work, we conducted a new analysis of the distribution and estimated cost of geologic storage resources, introducing two novel elements. First, we explicitly mapped the "storage window"—the subsurface volume where CO_2 storage is possible within sedimentary rocks that are deep enough to be below any fresh water in the area and keep CO_2 as a dense fluid but not so deep as to become logistically difficult to inject CO_2. We only considered onshore resources in this study; however, we note that a large capacity for geologic storage exists in sedimentary rocks beneath state and federal offshore waters. Second, 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 a "storage project" is defined as 1 million metric tonnes of CO_2 injected per year for 20 years. Our analysis should allow developers to better match removal projects with available storage, based on estimated removal volumes and storage costs.

Key Findings:

More than half the land area in the United States is geologically suitable for CO_2 storage in microscopic pore spaces found within vast underground sedimentary rock formations.

Well-studied sequences of sedimentary rock that can accept sustained injection of large volumes of CO_2 (>1 million tonnes annually per project for 20 years) are found in the Gulf Coast region and in dozens of inland basin areas, as well as smaller areas on both coasts. These areas make up 22% of US land area, including Alaska and Hawaii, with average storage costs of less than $20/tonne CO_2

An additional ~28% of the United States has rock formations within the storage window that have not been previously assessed. These basins have a roughly estimated mean cost of >$53/ tonne CO_2. This higher cost is driven by our expectation—albeit based on limited data—that injecting in sites where rock formations are thinner or less permeable will be slower and more costly; these situations may require more wells to sustain 1-million-tonne-per-year projects. Also, it will likely become evident that some locations have no storage resources available; thus, thus the cost of unsuccessful exploration must be factored into the overall cost of development.

If we consider CO_2 storage via mineral trapping in basalts and other igneous rocks, the total prospective storage area could equal as much as 60% of the United States. However, estimating the costs for this type of storage is not possible due to scarce data.

About half of the United States lacks geologic storage resources. These areas are associated with mountainous regions and where basement igneous or metamorphic rocks are found at the surface or at shallow depths and no sedimentary rocks are available for storage. This includes Appalachia, most of the east coast, New England, the greater Rocky Mountain region, much of Alaska, and parts of the mid-continent from Minnesota to the Ozark and Ouachita Mountains.

3. CO_2 and Biomass Transportation

Some CO_2-removal pathways, such as direct air capture with storage (DACS) or biomass with carbon removal and storage (BiCRS), involve several steps that may not all occur at the same location. This necessitates transportation of CO_2 and/or biomass between different sites. In the future, CO_2 transportation infrastructure will be most efficient if pipelines are available. To enhance flexibility in capacity and routing, alternative transportation modes like trucking, rail, and barges are also viable options. Developing these transportation options can contribute to job creation and retention. However, routing necessitates careful consideration and strategic actions to avoid perpetuating historical inequities. Equitable distribution of CO_2 and biomass transportation routes is essential to avoid further burdening disadvantaged communities

Key Findings:

Pipelines are efficient but are not essential for CO_2 transportation; other modes, such as rail, trucking, and barges, are viable alternatives with a minimal cost increase.

If available nearby, large trunk pipelines and barges are the most cost-effective options for transporting CO_2, with costs of $0.07 and $0.012/tonne-km, respectively. However, pipeline construction requires multi-billion-dollar investments, and barges have upfront loading costs of $14–$18/tonne before leaving the port.

Trunk pipelines, rail, and barges often require secondary transportation networks with higher transportation costs to gather CO_2 and/or biomass from multiple sources.

For distances under 250 miles (400 km), trucking is more economical than rail for a "roundtrip, no back-hauling" option, at $0.11 and $0.10/tonne-km for CO_2 and biomass respectively, and a flat rate of $9/tonne CO_2 for the process of compressing CO_2.

Multimodal configurations will require transloading facilities (where cargo is shifted between two different transport modes) with adequate infrastructure to properly handle CO_2 and biomass shipments, including temporary storage and reconditioning capabilities for CO_2 when modal shipping conditions differ.

Achieving long-term, sustainable CO_2 transportation involves decarbonizing the rail and trucking sectors, prioritizing public health, and fostering job creation through local hiring commitments.

The infrastructure capacity required to transport biomass and CO_2 (for BiCRS) is of a similar magnitude to what the United States currently uses for transport of corn-ethanol plus pulp and paper industry products, or hazardous class II liquids.

4. Biomass Carbon Removal and Storage

Biomass carbon removal and storage (BiCRS) is a major carbon removal pathway that relies on living plants to capture CO_2 from the air. Carbon removal is achieved when the carbon in plant biomass—which would otherwise be re-released to the air through natural decomposition processes—is captured and stored in materials or through geologic storage of CO_2.

All integrated assessment-model projections with a reasonable chance of limiting warming to 1.5 °C by 2100 rely on BiCRS as a primary carbon-removal approach. The outsized potential impact of BiCRS (the amount of long-term carbon removal at an intermediate cost (<$100/tonne CO_2)) lies in the ability to generate a wide range of materials and energy products from plant biomass, thus generating revenue streams while also providing alternatives to fossil-based products in addition to carbon-removal services. Our BiCRS analysis includes biomass drawn from carbon crops, or wastes and residues from forestry, agriculture, and municipal sources. We recognize that BiCRS is not risk free; crops dedicated for CO_2 removal can have negative effects on ecosystem biodiversity, carbon storage in trees and soils, and can put pressure on land needed for food production. Displacing food production creates a risk of indirect land-use change and unforeseen adverse climate impacts. Other major BiCRS risks are associated with its complexity. BiCRS requires collaboration between biomass producers; biorefinery investors, constructors, and operators; and operators of bioproduct and CO_2 distribution and storage systems. Due to the broad scope of BiCRS, this chapter is necessarily wide ranging and addresses land use, biomass availability, biomass conversion pathways, and opportunities for biorefinery siting in the US.

Key Findings

In the United States, BiCRS has the potential to exceed 800 million tonnes of CO_2 removed from the atmosphere per year at a net cost less than $100/tonne CO_2, with no impact on food production.

Every region has a role to play in BiCRS carbon removal in the United States; interaction between regions is required for the full value chain.

We found a wide range of potential biomass availability for BiCRS in a mature market—from 0.5 to over 1 billion dry tonnes of biomass per year depending on the land use.

BiCRS pathways that produce hydrogen (H_2) are favorable for maximizing CO_2 removal at low net cost per tonne CO_2 due to high CO_2 removal per tonne of biomass and revenue streams from the sale of H_2.

The most influential factors determining cost per tonne of CO_2 are the capital and operating costs of biorefineries and the selling price of co-products, followed by biomass feedstock costs and biomass transportation costs.

While not the dominant pathways in terms of quantity, production of long-lived carbon products (bio-oil for asphalt, polyethylene, wood products) can play a major role in carbon removal due to low costs per tonne CO_2 and less reliance on geologic storage.

A wide range of technologically mature BiCRS pathways can serve social, political, regional, and national goals (e.g., production of hydrogen and aviation fuels, reducing the burden of pollution on communities) while providing high-capacity carbon removal; in any approach, hundreds of mid- to large-scale facilities must be built across the United States that link reliable biomass supply, biorefineries, geologic storage, and bioproduct distribution. The complexity and scale of implementation, coupled with the potential for significant climate and regional benefit, requires urgent action.

With purposeful scale-up that assesses the baseline pollution burdens of each biomass feedstock and the people who are inequitably exposed to them, BiCRS can be used as a tool for restorative environmental justice for a number of environmental pollutants (e.g., PFAS, PM2.5, odorific gases, and excess nutrients.)

5. Direct Air Capture with Storage

Direct air capture with storage (DACS) has the potential for billion-tonne atmospheric CO_2 removal but will require concurrent buildout of energy resources. For renewable-electricity-powered DACS, the land required for deploying wind or solar-photovoltaic electricity generation limits the maximum potential capacity. However, several regions of the United States have significant potential to generate renewable electricity beyond what is needed for decarbonizing the electrical grid; these regions intersect with the geologic formations required to safely store the CO_2 removed from the atmosphere. Additionally, domestic natural-gas reserves in the United States could enable additional regions to participate in large-scale DACS projects if we decide as a society to tap into these resources.

While the potential for DACS deployment is massive, DACS will likely remain the most expensive form of the CO_2-removal options considered in this report. As such, the ability to reduce the cost of the technology, regulatory mechanisms or incentives, and maturation of a carbon-removal marketplace will likely determine the extent of deployment. However, DACS may bring co-benefits, including allowing communities to evolve from dependence on fossil-fuel-based jobs to carbon management jobs. In the near term, scientifically guided and rigorous standards for DACS monitoring, reporting, and verification (MRV) are needed across existing and emerging DACS technologies and energy sources, including consideration of all emissions associated with DACS energy sources and the additionality of renewable energy projects.

Key Findings:

For low-temperature adsorbent DACS powered by renewable electricity, the United States has a technical potential capacity of over 9 billion tonnes of CO_2 per year. For high-temperature solvent DACS powered by natural-gas reserve, the United States' technical potential capacity is over 4 billion tonnes of CO_2 per year (Table 7-1). The costs predominantly range from $200 to $250/tonne CO_2. This estimate is a theoretical maximum constrained by energy and land availability and does not reflect the expected or required level of deployment. However, understanding where and at what scale the opportunity exists is important. Social, ecological, regulatory, and market factors not evaluated in this report will further limit this potential.

The West Texas and Upper and Lower Rocky Mountains regions have the largest potential for million-to-billion-tonne adsorbent DACS deployment with renewable energy, while the Appalachia, West Texas, South Central, and Alaska regions have large potential for solvent DACS deployment with natural gas.

In the near-term, DACS deployment will identify critical areas for technology improvement and help more rapidly improve the cost of DACS carbon removal; however, scientifically guided and rigorous standards for DACS MRV are needed across existing and emerging DACS technologies and energy sources.

Regions of high opportunity for DACS overlap with areas of the country that are experiencing persistent job loss in fossil-fuel sectors; prioritizing DACS development in these regions may help maximize socioeconomic co-benefits, such as economic solvency and infrastructure improvements.

Author's comment: Only a tiny portion of the text from reference 1 is used in this paper. This source is almost 500 pages including front-matter and end-matter. It's also crammed full of enlightening graphics. For someone interested in carbon removal as a powerful mitigation tool for climate change, it's the best report that I have seen.

One other benefit of reference 1: if you go through the link to the home page for Roads to Removal (below), you will see a set of colored tabs on the right side, one for each section of the main document. Each of these except for the last has an associated professionally produced (and reasonably short) video. Click each tab and scroll down until you see the video symbol ▶ or ▶ and click on it. Note that the section 1 (Overview) video symbol will probably be on view when the main R2R site comes up.

https://roads2removal.org/

6. Burial at Sea

As I was struggling to keep the first portion of above paper to a single post, I came across an excellent article in my latest issue of Science, that fit in perfectly, thus I gave up the fight, and added this as my final section in Part 2.

Dror Angel, a marine ecologist at the University of Haifa, had for years heard his archaeologist colleagues talk about ancient shipwrecks on the bottom of the Black Sea that were perfectly preserved by the low-oxygen environment. "You can see ropes," Angel says. "It's something which is quite spectacular."[3]

[3] Saima Sidik, Science, "Plant waste buried at sea to fight climate change," Jan 5, 2024, https://www.science.org/content/article/combat-climate-change-companies-bury-plant-waste-sea

Now, Angel wants to combat climate change by purposefully adding to the wreckage, sinking waste wood to the sea floor, where carbon that the trees stored up while living can remain locked away for centuries.

Angel is a science lead for an Israeli company called Rewind, one of many companies riding a wave of investment in technologies that could help limit global warming by drawing carbon out of the atmosphere and locking it up. Whereas some carbon capture schemes require expensive machines and complex chemistry, burying terrestrial biomass at sea is exceedingly simple: All it takes are tugboats, barges, and woody waste from forestry and agriculture.

The approach has advantages over another popular ocean-based carbon capture strategy: growing, and sinking, massive amounts of seaweed or phytoplankton. Because the plant material is grown on land rather than in the ocean, it is less likely to rob nutrients from the surrounding water and upset the ecology. Industrial agriculture and forestry have an extensive infrastructure for growing, processing, and transporting plants, in contrast to marine farming, which has never been attempted at scale. And because woody plants are tough and unlikely to degrade, they are good at hanging on to their carbon. "Decomposers don't like to eat them—they don't get much out of it," says Ning Zeng, a climate scientist at the University of Maryland.

At the same time, the approach may fall short of what's needed to fight climate change. To keep warming below 2°C, the world needs to capture and store about 10 billion tons of carbon dioxide per year by midcentury, according to the International Energy Agency. But terrestrial biomass can be sunk only where supplies of waste are located near suitable bodies of water. By one recent estimate, the approach could sequester a few tens of billions of tons of carbon dioxide in total—just a fraction of the need.

"The terrestrial biomass thing is not going to solve the full problem," says ocean engineer Kate Moran from Ocean Networks Canada, a group that is assessing the efficacy of carbon capture strategies. "It's going to be a small piece of the pie if it is deemed to be more beneficial than risky." But, she adds, "We need all the tools in the toolbox."

In the Black Sea, Rewind has one of the world's great carbon burial sites. The sea is much saltier at the bottom than at the top, so the two layers don't mix much at all—one reason why very little oxygen makes it to the sea floor. Without oxygen, microbes are limited in their ability to convert the carbon in biomass back into greenhouse gases, such as methane, and even if some methane is produced, chemical reactions in the sulfate-rich waters will break it down. And because the layers don't mix, any trace greenhouse gases that are produced will be locked in the depths for hundreds or thousands of years. "There's all these additional processes that add more layers of security," Angel says.

The advantages are enough to lure investors hoping to sell credits for the carbon removed from the atmosphere. Carbon credit marketplace Supercritical recently became Rewind's first customer, and this summer the company plans to start sinking biomass in burlap sacks—possibly including forestry residue, river driftwood, and agricultural waste. Bulgaria, Romania, Turkey, and Georgia have all shown interest in the project, Angel says.

Frontier Climate—a group that makes commitments to buy future credits from carbon sequestration startups—recently awarded $250,000 R&D grants to Rewind and another firm, Houston-based Carboniferous, which hopes to sink sugarcane waste in an oxygen-starved region of the Gulf of Mexico known as Orca Basin. The waste is abundant on Gulf Coast farms, says Morgan Raven, a biogeochemist at the University of California, Santa Barbara and the company's chief science officer. "It's already sitting in piles," she says. "The alternative for this material is essentially that it degrades, releases methane, and requires tending so it doesn't light on fire." Carboniferous is now applying for permission to test its strategy from the Environmental Protection Agency.

Portland, Maine–based Running Tide is combining terrestrial and marine biomass in one carbon capture strategy. The company takes waste wood from a forestry operation in Nova Scotia that would otherwise be burned or left to decay and presses it together to create floating "buoys" no bigger than a basketball that are seeded with seaweed spores. The buoys are released off the coast of Iceland, where ocean currents carry them over a deep region with little oxygen. Eventually they become waterlogged and sink, along with any seaweed that has grown en route. Last summer, Running Tide sold its first carbon credits to Shopify, and the company says it has sunk tens of thousands of tons of material into the North Atlantic Ocean.

Marine scientist David Koweek of the nonprofit Ocean Visions, which has previously supported Running Tide's research, lauds the simplicity of sinking terrestrial biomass, because technology exists for almost every step in the process. That's a strong reason why "you might think about doing this," he says.

Beyond that, the benefits are murkier. Even though boats are a climate-friendly form of transportation (trucks emit at least 100 times more carbon per kilometer), Angel says it wouldn't make sense to ship biomass around the world to get it to favorable sites. And although sunk terrestrial biomass doesn't steal nutrients from marine life, removing it from land could deplete soil of nutrients. "Over time we're going to also be losing some of the fertility that crops and forests need," says Charlotte Levy, a biogeochemist at Carbon180, which advocates for scaling up carbon removal projects. Levy also worries that as innovators find new uses for scrap biomass—for example, as sustainable building materials or biochar, a charcoal-like soil additive—sinking the biomass might not be the most environmentally friendly use.

Zeng agrees that sinking terrestrial biomass will be limited to a few areas of the ocean for the foreseeable future. But the urgency of carbon removal demands that every possible scheme be explored thoroughly, he says. "I think every idea deserves $1 billion of support to test it out."

7. The Final Words

Overall, the efficiency of how we use electric power is increasing. However, at the same time, we use electricity for more functions. Mobility is one function that is in the midst of a major migration from fossil fuels to electricity, but there is another that may be below your radar.

Our insatiable appetite for web-based services and streaming platforms has required the construction of ever more powerful data centers, all of which need more and more electricity to operate. Managing that growing demand adds to the challenge of slashing carbon emissions from the grid. Some estimates see energy needs for data centers tripling by 2030, accounting for 7.5% of U.S. energy consumption. The surge in controversial cryptocurrency mining is part of that, as is the fast-emerging AI industry. The U.S. Energy Information Agency took a look at the impact of crypto's energy needs and estimates it may already account for up to 2.3% of U.S. energy consumption.[4]

As for AI, ChatGPT's Sam Altman[5] *acknowledged that its vast computer networks and high-powered chips are going to need ever more electricity to achieve all that he envisions. At the World Economic Forum in Davos last month, he conceded that "we still don't appreciate the energy needs of this technology" and that an energy breakthrough was probably necessary for AI. Until then, the growth of power-hungry AI-enabled tech may already be slowing efforts to shutter dirtier, carbon-spewing power plants.*

[4] Forbes, Current Climate, Feb 5, 2024 issue. This is a subscription newsletter, https://www.forbes.com/newsletter/currentclimate/#fae9a7e6b462

[5] ChatGTP is a generative AI application from OpenAI, Sam Altman is the CEO of OpenAI, https://en.wikipedia.org/wiki/Sam_Altman