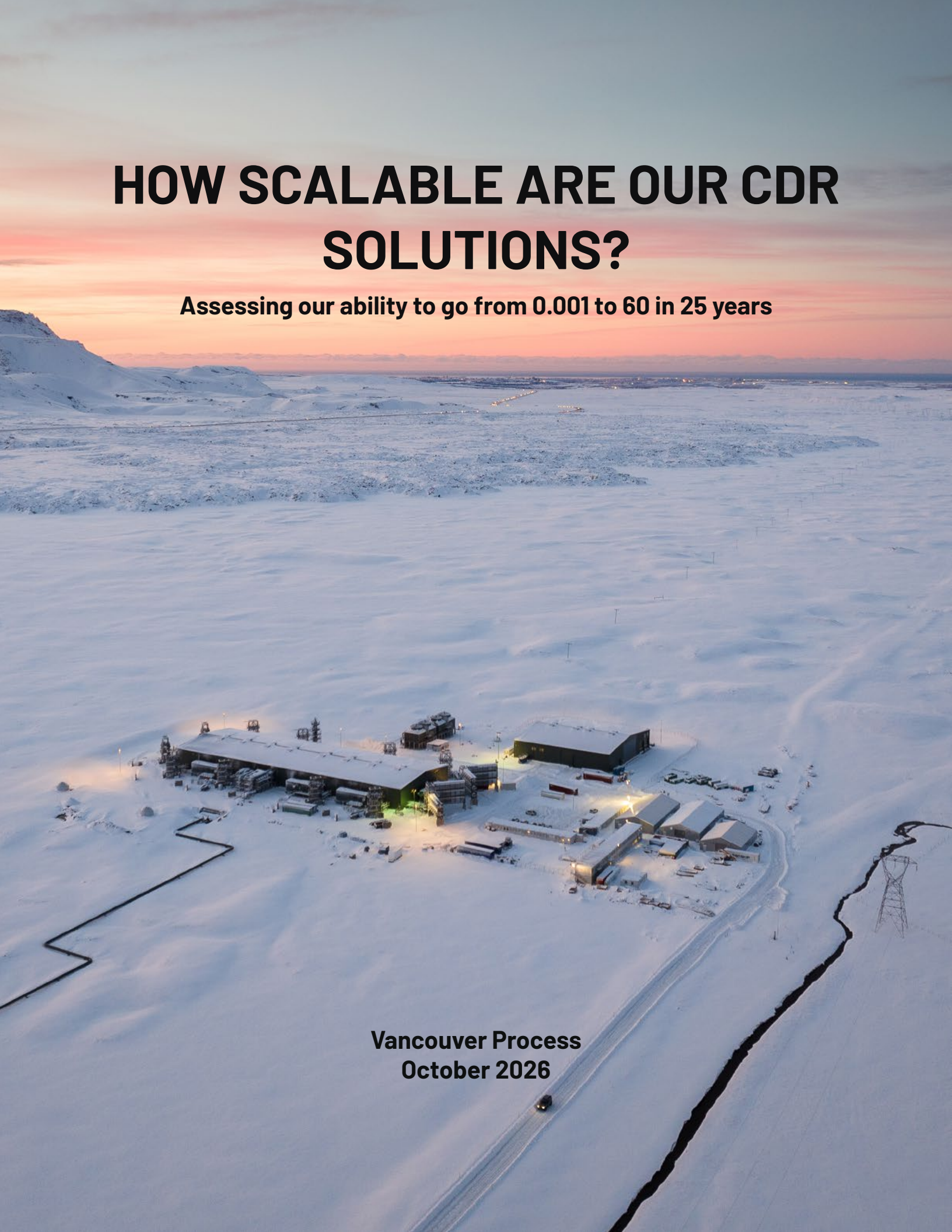
HOW SCALABLE ARE OUR CDR SOLUTIONS?

Assessing our ability to go from 0.001 to 60 in 25 years



Vancouver Process
October 2026

© 2026 Science Communication Institute (SCI)

This work, How Scalable are Our CDR Solutions? (1st ed., published October 28, 2026), was written by Glenn Hampson, SCI's executive director. Except for some figures reproduced here which may be protected under copyright, this report is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License (CC BY-NC 4.0). To view a copy of this license, visit creativecommons.org/licenses/by-nc/4.0.

You are free to share and adapt the text — copy, redistribute, remix, transform, and build upon it — under the following terms:

- Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made.
- NonCommercial — You may not use the material for commercial purposes.
- No additional restrictions — You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.

This document was developed for the Vancouver Process, a global initiative developed via the Carbon Dioxide Removal Action Network (CDRANet) and coordinated by the Science Communication Institute (SCI).

For inquiries, permissions, or attribution details, please contact:

Science Communication Institute
sci.institute
info@sci.institute

Front cover: Climeworks Mammoth site in Iceland. Photo courtesy of Climeworks.

Back cover: Reforestation project in Montana. Photo by Dave Gardner Creative, National Forest Foundation.

Executive Summary

The world's carbon dioxide removal (CDR) policies are organized around the premise that a portfolio of solutions like direct air capture, enhanced rock weathering, ocean alkalinity enhancement and biochar can combine to reach 10 gigatons of annual CO2 removal capacity by around mid-century. Some studies have suggested this goal might be within reach given sufficient investment, technological progress and favorable conditions; other studies have cast doubt. For the most part, however, policymakers have been slowly developing and critiquing CDR strategies with this removal goal and timeline in mind; this has been the CDR community's common truth.

But what if this truth is wrong and we end up needing more than 10 gigatons per year (Gt/y) of CDR, maybe even much more? If our net fossil fuel emissions remain high — which is a reasonable assumption (arguably more reasonable than assuming they will drop precipitously in coming years) — then stabilizing temperatures will require more CDR than we're planning to deploy, and more than our current CDR portfolio can provide. A portfolio capable of reaching 10 Gt/y is not necessarily capable of reaching 60 or 100 Gt/y. Most of our solutions have limited physical removal potential, and several compete for the same finite resources, meaning their individual potentials cannot simply be added together. Indeed, evidence suggests that our current portfolio cannot grow significantly beyond 10 Gt/y without starting to rely primarily on direct air capture and ocean alkalinity enhancement, and these solutions will likely not be able to make a climate-relevant contribution to our CDR efforts for decades to come.

Also concerning is whether our current CDR solutions portfolio will be affordable, both at the 10 Gt/y scale and beyond if needed. Lawrence Livermore's 2023 Roads to Removal report estimated the United States could remove one gigaton of CO2 annually for approximately $130 billion. Extrapolating this estimate — not as a forecast, but for perspective — 10 gigatons of annual removals might cost the world $1.3 trillion per year. Although technological progress may lower costs, many solutions will still require enormous investments in energy, infrastructure, and ongoing operations, and substantial economies of scale are far from assured. Sustaining expenditures of this magnitude would be difficult for most governments, and increasingly unrealistic if much higher levels of CDR are required.

Beyond physical capacity and cost, our current solutions also face substantial feasibility challenges involving permanence, verification, environmental impacts, regulation, and public acceptance. These obstacles may become more difficult as deployment expands, especially if removals must be sustained for generations. As well, we must move beyond the goal of merely stabilizing our temperatures and plan for how we will eventually restore them. Since even current levels of warming are causing ongoing damage to human civilization, restoring temperatures to safer levels within a reasonable period of time must become the new normal for CDR policy.

In order to ensure our CDR solutions keep pace with our carbon removal needs, we therefore need to reexamine both our portfolio and our approach to supporting it. This might involve accelerating improvements to existing CDR solutions; it might also mean developing approaches to deploy lower-yield solutions more broadly to make a larger contribution to our CDR efforts, or even searching for fundamentally new CDR approaches that are more scalable, effective and affordable. Scalability and the ability to sustain high removal rates for generations must become design priorities.

None of this is an argument for abandoning today's CDR solutions. We need them, and continued investment and experimentation will hopefully substantially improve their performance. But trusting the ability of our present solutions portfolio to scale to 10 Gt/y is already a leap of faith; getting very far beyond this level will quite possibly be physically and financially impossible. We need to shift our focus from simply building a larger CDR industry to developing a solutions portfolio legitimately capable of meeting whatever CDR requirements the future may have in store.

Glossary of CDR solutions

Afforestation, reforestation, and forest management. Planting new forests, restoring lost forests, or improving forest management to increase the amount of atmospheric CO2 absorbed and stored in trees, vegetation, and soils.

Biochar. Heating biomass in a low-oxygen environment to produce a relatively stable, carbon-rich solid that can be stored in soils or used in construction materials.

Bioenergy with carbon capture and storage (BECCS). Producing energy from biomass, capturing the resulting CO2 emissions, and storing this CO2 underground or in other durable reservoirs.

Biomass burial (direct biomass storage). Collecting plant material that has absorbed atmospheric CO2 and placing it in engineered storage environments designed to prevent decomposition and carbon release.

Biomass Carbon Removal and Storage (BiCRS). Umbrella term for any process that uses plants or algae to absorb CO2 from the air as they grow, and then permanently sequesters that biomass (or the carbon extracted from it) away from the atmosphere.

Cultivated seaweed sinking. Growing seaweed that absorbs dissolved carbon during photosynthesis, then sinking the harvested biomass into deep ocean waters to potentially store its carbon for extended periods.

Direct air capture (DAC). Using engineered equipment and chemical processes to extract CO2 directly from ambient air.

Direct air capture with carbon storage (DACCS). Using engineered equipment and chemical processes to extract CO2 directly from ambient air, then transporting and storing the captured CO2 in geological formations or other permanent reservoirs.

Direct-air mineralization and mineral products. Capturing CO2 directly from the atmosphere and chemically combining it with minerals to produce stable carbonates, sometimes for use in construction materials.

Direct ocean capture and storage (DOCCS). Extracting dissolved CO2 from seawater and storing it permanently, allowing the treated seawater to absorb additional CO2 from the atmosphere.

Enhanced rock weathering (ERW). Accelerating the natural process by which certain minerals react with CO2, typically by spreading finely crushed rock over agricultural land or other suitable surfaces.

Ocean alkalinity enhancement (OAE). Increasing the alkalinity of seawater to enhance the ocean's ability to absorb and retain atmospheric CO2, typically by adding alkaline materials or using electrochemical processes.

Ocean iron fertilization (OIF). Adding small quantities of iron to nutrient-rich ocean waters to stimulate phytoplankton growth, potentially increasing the transfer of atmospheric carbon into deeper ocean waters.

Soil carbon sequestration. Using agricultural and land-management practices to increase the amount of atmospheric carbon stored in soils, such as cover cropping, reduced tillage, and improved grazing.

Additional terms & notations

CDR. Carbon dioxide removal

CO2. Carbon dioxide

Gt. Gigatons (billion tons)

Gt/y. Gigatons per year

MRV. Measurement, reporting and verification

SOCDR. State of CDR report

HOW SCALABLE ARE OUR CDR SOLUTIONS?

Assessing our ability to go from 0.001 to 60 in 25 years

INTRODUCTION

UN climate reports have predicted for decades that once we reach net zero by around 2050, our planet's temperature should begin to stabilize.[1] At this point, according to a wide range of models, we'll need to begin removing somewhere around 10 billion tons of carbon dioxide (CO2) from our atmosphere every year in order to begin slowly drawing down the legacy accumulation of CO2 in our atmosphere.[2]

Can we do this? The answer is mixed. If our goal is to "only" remove 10 billion tons (gigatons) of carbon dioxide per year, then it's possible we will be able to cobble together an effective response. If, however, we need more carbon dioxide removal (CDR) — and it's possible our CDR needs could range as high as 60 gigatons per year (Gt/y) or even 100 Gt/y — then the math becomes much more problematic.[3] In this case, we'll need to drastically improve the efficiency and effectiveness of our CDR solutions, develop strategies for scaling some solutions much higher than currently envisioned, or develop new solutions that work better than now, or some combination of all these approaches.

In any event — whether we aim for 10 Gt/y of CDR or more, using old solutions or new — we'll need to fully commit to the CDR challenges ahead as soon as possible, and lean heavily into these four realities as we do:

1. **We need CDR.** There are no longer any scientifically credible pathways for reaching net zero that don't also involve massive amounts of CDR (UNEP 2025). While it's true we still need to reduce emissions (because without these reductions, the cleanup task ahead may be completely unaffordable — more on this later), reductions alone will not keep temperatures from rising.[4]
2. **We are behind the curve.** The still emerging CDR industry has delivered only 1.7 million tons of durable carbon dioxide removal to date.[5] By the time we develop and deploy solutions capable of removing carbon dioxide at climate-relevant levels — 6,000 times more every year than all the carbon dioxide we've removed so far — global temperatures may already be more than 2°C above preindustrial levels. This is a challenge that can't be postponed for a few more decades.

---

1. Which is to say, once humans no longer contribute to our planet's net increase in carbon dioxide (CO2), either by curbing our fossil fuel emissions or by removing CO2 from our atmosphere or some combination of both.

2. The exact amounts vary widely by model. As well, most models stipulate that we'll need to remove a few gigatons of CDR annually before 2050 to help us reach net zero, and possibly gradually increasing amount of CDR over the course of the century (varying by model) to keep temperatures level.

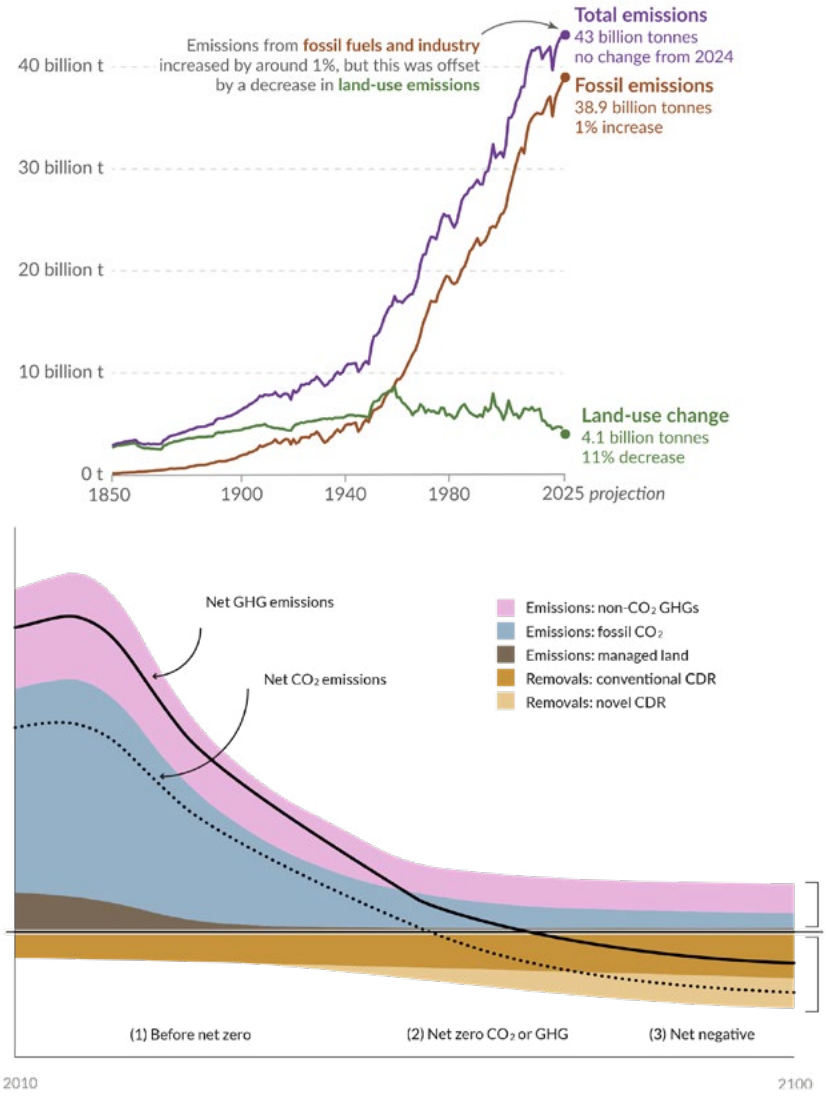
3. See Hampson (2026a). The premise is that if our net CO2 emissions continue on pace at 42 Gt/y, then we will need 60 Gt/y of CDR to stabilize temperatures at 2°C, and 100 Gt/y of CDR to restore temperatures to preindustrial levels by the year 2150. The reason for choosing 2150 as a target date for restoration is to avoid having CDR become a permanent feature of human existence. All of this assumes emissions stay elevated, of course, and that other solutions like solar radiation modification aren't deployed before then.

4. Assuming we don't take other measures as well, like trying to dim the sun through solar radiation modification measures.

5. See CDR.fyi (2026a). The 1.7 million-ton figure represents cumulative delivered durable removals tracked by CDR.fyi as of October 2026, not removals contracted for future delivery.

3. **We aren't being realistic about our future CDR needs.** The climate scenarios we're relying on generally assume global emissions will fall rapidly over the next few decades, reaching net zero CO2 by around mid-century. This doesn't mean fossil fuel emissions will disappear entirely, but that our remaining emissions will be balanced by carbon removals. Even so, the reductions in these scenarios are far steeper and more sustained than anything we've achieved so far. If our global emissions remain stubbornly high or CDR progress too slow, our future CDR requirements could be vastly greater than the 10 Gt/y around which much of our current planning revolves. By designing removal strategies around overly optimistic scenarios, we may be developing solutions that won't be fit for task. And,

Figure 1. Emissions reality versus the levels idealized in climate models

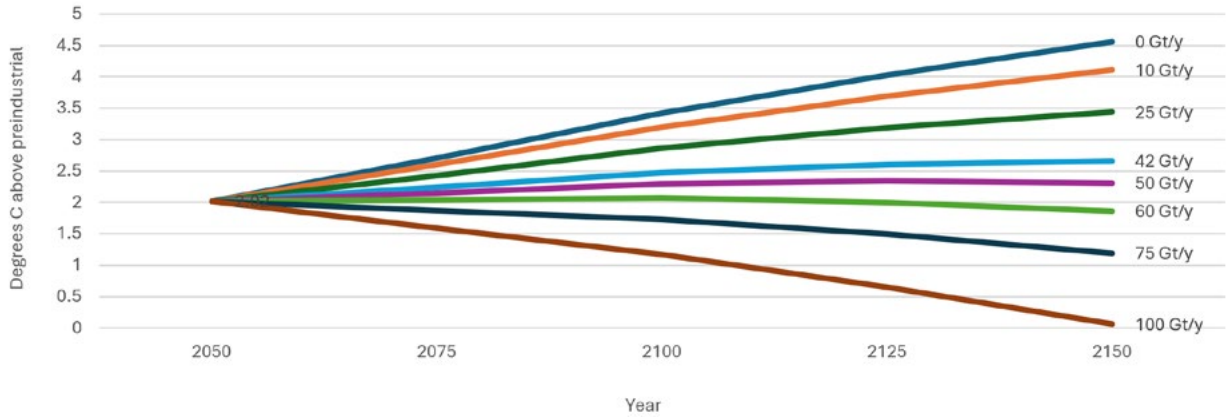


Sources: Top figure from Ritchie (2025), bottom from Edwards et al. (2026).

4. **We need a restoration mindset.** Most climate-policy scenarios are designed to examine how we might limit warming to 1.5°C or 2°C, or return to these thresholds after temporarily exceeding them. Our policies don't ask what it will take to restore global temperatures to preindustrial levels (assuming such restoration will still be possible in the future). These high temperature thresholds are our goals. And yet, our world is already very near 1.5°C, and experiencing significant climate impacts as a result; why should we endeavor to stay at this plateau, or worse still, at the 2°C plateau we will reach in a few decades, both of which are substantially warmer than the environments human civilizations have known throughout history? We should be developing CDR strategies capable not simply of stabilizing temperatures, but restoring them to more livable levels.

With these four realities in mind, how likely is it that on our current trajectory — at our current pace, with our current goals in mind, and at current levels of funding, technology readiness, and policy attention — we will be able to scale CDR to the levels we need?

Figure 2. Potential CDR needs if net human-caused CO2 emissions plateau at 42 Gt/y



Source: Hampson (2026a).

REMOVAL POTENTIALS

POTENTIALS VS. LIKELIHOOD

Table 1 on the following page provides estimates from the 2026 State of CDR Report (hereafter referred to as SOCDR) for how much CO2 various CDR solutions might be able to remove by 2050, and how much CO2 these solutions might be able to remove in the future. As mentioned in the introduction, all our durable CDR solutions together have removed around 1.7 megatons of carbon dioxide from our atmosphere.[6]

We need to increase this — scale this — to around 10 gigatons per year within the next few decades according to most expert analyses. Trying to understand whether we can do this and how — and what this will mean for our environment, societies and economies — hinges on our best estimates of whether:

1. The specific CDR solutions we're developing are capable of expanding to the levels we require
2. The portfolio of CDR solutions we're relying on is capable of expanding to the levels we require
3. Our CDR solutions and/or portfolio are realistic at scale after considering their costs and other feasibility factors, and
4. Our CDR solutions and/or portfolio can expand to climate relevant scales in a climate relevant period of time. Solutions that can scale to needed capacity by the year 2200 — at which point global temperatures might be 5°C above preindustrial levels — should be less appealing than solutions that can scale by 2050.

How we weigh these four considerations can and has led to very different conclusions about which CDR strategies are best. Researchers have constructed a wide variety of models over the years,

6. Durable CDR refers to solutions capable of permanently sequestering CO2 for centuries to millennia. While global forests and land use currently absorb approximately 2.2 gigatons of CO2 annually, this baseline sequestration is generally excluded from modern CDR capacity targets. To qualify, removals must meet the standard of additionality—occurring explicitly due to deliberate human interventions that would not have otherwise happened—and permanence. Because biological carbon storage in soils and forests operates on vulnerable, short-term timescales (often ~100 years or less), it lacks the permanent isolation required to safely offset long-cycle fossil emissions.

Table 1. How much can existing CDR technologies scale?

CDR APPROACH	2050 MODELED DEPLOYMENT (GT/Y) (1)	UPPER LIMITS DEPLOYMENT (GT/Y) (2)
Afforestation, reforestation, and forest management (3)	3.3–8.4	<0.1–8.9; one more restrictive sustainable estimate is up to 2.2
Soil carbon sequestration in croplands and grasslands	<0.1–0.8	0.5–3.4 under more constrained assumptions
Biochar from sustainably sourced biomass	<0.1–1.1	Up to 2.7 in a recent sustainable removal assessment
Bioenergy with carbon capture and storage (BECCS)	0.7–4.2	0.5–5 under more constrained assumptions; 0.1–0.9 for some dedicated-crop sustainability assessments
Biomass burial, including additional removal from diverted residues	Not separately reported	Some estimates exceed 10; no well-established sustainable range
Enhanced rock weathering	<0.1–1.5	0.2–2 in common technical assessments; approximately 0.7 in one sustainability-constrained study
Ocean alkalinity enhancement (OAE)	<0.1–1.4	<1–100; exceptionally uncertain
Ocean iron fertilization (OIF)	Not separately reported	Generally 0.1–1. Higher yields are theoretically possible but have not been substantiated yet (4)
Direct ocean capture and storage (DOCCS)	Not separately reported	0.1–1 under resource constraints
Cultivated seaweed sinking	Not separately reported	0.1–1; subject to substantial ecological and durability uncertainties
Direct air capture with geological storage (DACCS)	<0.1–1.8	0.5–40 across differently constrained assessments, assuming adequate storage space
Total	6.5–13.3 across all methods	Not reliably additive (5)

Sources: Gidden et al. (2026); Fuss et al. (2026). Additional assessments can be found in reports such as RMI's Applied Innovation Roadmap (2023), which evaluated 32 approaches, and Kahsar et al. (2026), which examined 14 approaches.

Table notes:

1. Deployment estimates in the SOCDR's Highest Ambition scenarios, which have a median value of 8.8 Gt/y in 2050. Not all technologies are represented; a missing estimate does not mean zero potential.
2. Potential annual removal capacities, incorporating varying assumptions about resources, technological development, sustainability, and economic constraints. Some estimates are substantially more speculative than others. Also, these are the removal potentials for individual technologies, not technologies working together in a solution set.
3. These modeled deployment totals include some continuation of existing land-based removals and therefore are not directly comparable to the additional removal capacity discussed in this report.
4. Estimates of OIF's removal potential vary widely. The National Academies (2022) reviewed models suggesting initial removal rates as high as approximately 18 Gt/y, but these rates decline substantially with continued deployment. Such estimates have not been experimentally demonstrated, and their implications for durable net atmospheric removal remain uncertain. Sources**:** National Academies (2022); Fuss et al. (2026).
5. Individual estimates cannot be added together since several technologies compete for the same biomass, land, mineral resources, energy, or geological storage capacity. Moreover, published upper limits frequently assume favorable conditions that cannot necessarily be achieved simultaneously.

but their reference point has generally been tethered to UN policy assumptions that we'll need to remove around 10 Gt/y of CO2 starting by mid-century.[7]

The general perspective throughout all these analyses is that the longer we wait to get started, and the less fossil fuel emissions we remove today, the more CO2 we'll need to remove in the future. In the 2026 SOCDR report, for example — which assumes we'll reach net zero emissions mid-century — in order to stay on the "Highest Ambition" track, the world needs to reach 2.9 Gt/y of total CDR by

7. See Neumann (2026) for a discussion of how this number came to be accepted as gospel.

2030, and inch toward removing 7-9 Gt/y of CO2 by the year 2050. If we miss our 2030 target and stay below it for too long, we will end up on a "Delayed Ambition" track which will require scaling our CDR requirements from 7-9 Gt/y in 2050 to 23.6 Gt/y in 2100.

There is no shortage of opinions about whether we can reach these targets, whether they're too high or too low, if we should do this at all (e.g., whether CDR will only distract us from emissions reductions or adaptation work), which solutions we should use (opinions are particularly divided along natural versus engineered solutions), how long it will take, and more. It would be inaccurate to say "most experts think," or even to say that academic researchers, CDR policy analysts and industry experts all view the future of CDR with equal objectivity; researchers tend to be more conservative in their assessments, policy analysts more judgmental, and industry experts sometimes come across as overly optimistic. In accord with Miles' Law, where you stand depends on where you sit.

However, it is possible to at least quantify the concerns researchers have (which are widely shared across all groups) about our current prospects for success. These are described in Figure 3 on the following page, reproduced from a 2024 survey of nearly 700 researchers who recently published in the field. Survey respondents mostly cited high costs as impediments to scaling, along with weak demand, regulatory gaps, technological constraints, and insufficient R&D funding.

As well, the majority viewpoint of this group was that we won't reach 10 Gt/y of CDR capacity until around 2100; instead, our capacity might reach 2.3 Gt/y by 2050, and 5 Gt/y by 2075. Recalling the SOCDR modeling, not being able to reach 7-9 Gt/y by 2050 would push us onto a "Delayed Ambition" track where we would need to remove much more CO2 in the latter part of this century than in 2050.

DIVERSIFICATION

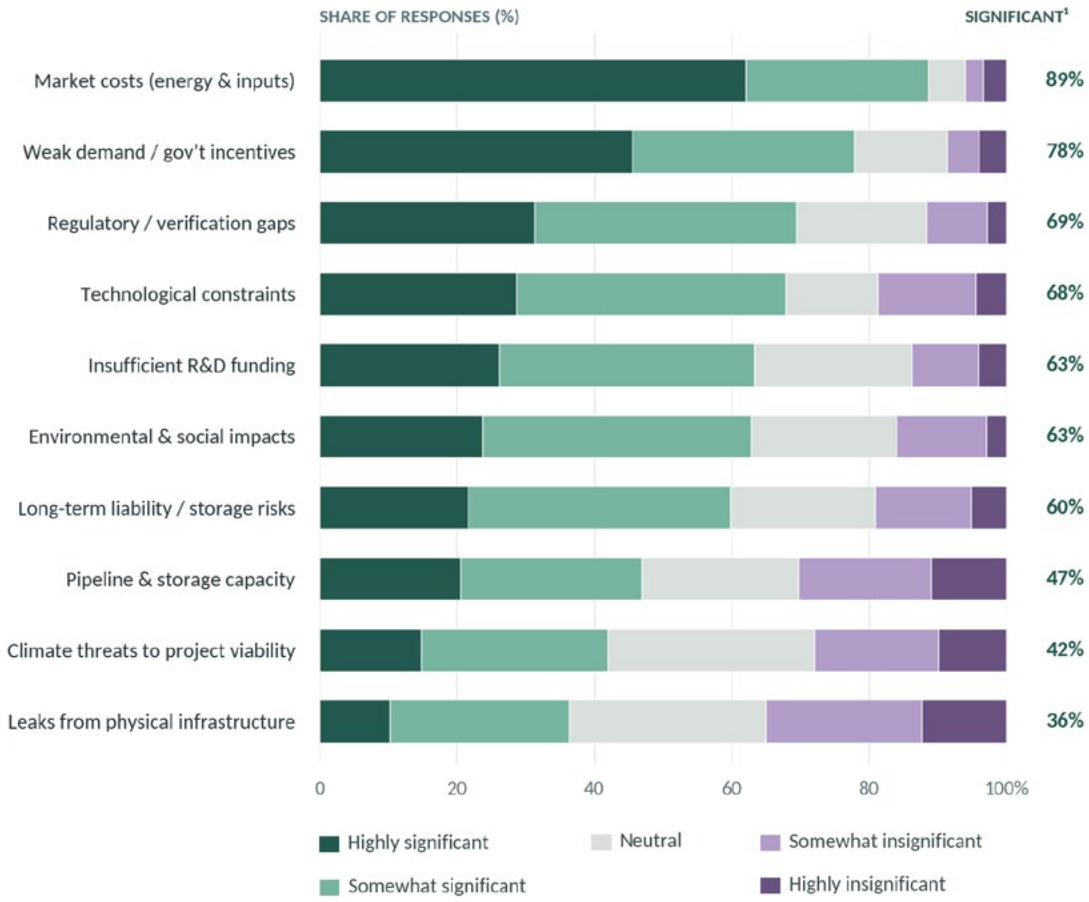
Because there are so many unknowns at the moment regarding which of our CDR solutions will succeed — particularly which solutions might scale the fastest and most realistically — most policymakers prefer a portfolio approach. The three main advantages of this approach are that it reduces risk, accelerates innovation, and accelerates adoption:

1. **Reduces risk.** No single technology needs to succeed everywhere, or even at all. If one approach disappoints, others can compensate. A diversified portfolio also allows different technologies to capitalize on local advantages, such as suitable geology, mineral resources, renewable energy, or agricultural conditions.
2. **Accelerates innovation.** Engaging more researchers, investors, and institutions across more locations creates more opportunities to experiment with different approaches, improve technologies, reduce costs, and learn from experience. Thousands of independent projects may generate advances that would be harder to achieve through a handful of massive installations.
3. **Accelerates adoption.** Rather than relying on a few enormous investments, a diversified portfolio allows CDR capacity to grow incrementally, through projects of different sizes and costs. This creates more opportunities for countries, communities, and investors to participate, including those unable to finance industrial-scale operations. It can also distribute economic benefits more widely, build political support, and encourage international cooperation.

THE PHYSICAL LIMITS OF SCALABILITY

Setting aside questions of cost, technology readiness, public acceptance, and related considerations, which we'll explore later, what are the physical limits of our current CDR portfolio? At first glance, the scalability estimates in Table 1 suggest that our existing CDR portfolio has more than enough capacity to meet even our most ambitious removal goals. Several technologies appear ca-

Figure 3. Expert opinions on most significant barriers to scaling CDR



Source: Adapted from Howard and Sylvan (2024).

Table footnote 1: Significant column is sum of "highly significant" and "somewhat significant" response percentages.

Description:

A 2024 survey conducted by researchers at New York University solicited responses from 5,326 CDR researchers who had published at least one article related to CDR/ negative emissions in a peer-reviewed journal between 2017 and 2022; 687 answered the question illustrated above.

Respondents identified market costs as the leading obstacle to widespread deployment, with 89% rating these as significant or highly significant. Insufficient market demand and government incentives followed at 78%. Regulatory and verification gaps (69%), technological constraints (68%), inadequate R&D funding (63%), and environmental and social impacts (63%) were also prominent concerns. These findings reflect expert judgments about deployment barriers, rather than measured limits on the physical scalability of CDR technologies.

Elsewhere in the survey, respondents' median projections for actual global CDR deployment increased from 2.3 Gt annually in 2050 to 5 Gt in 2075 and 10 Gt in 2100. Yet when asked about a hypothetical global net-zero scenario in 2075 requiring 123 Gt of emissions mitigation, the median respondent estimated that 20%—roughly 25 Gt—would need to come from carbon removal. More than 85% anticipated a requirement exceeding 12 Gt, with some estimates reaching or surpassing 100 Gt. Comparing anticipated deployment against these requirements, the authors concluded that respondents generally did not expect sufficient CDR deployment to achieve global net-zero emissions by 2075.

Cost projections were similarly consequential. Respondents estimated average removal costs in 2075 of approximately $163/tCO2 for direct air capture, $108 for bioenergy with carbon capture and storage, and $49 for forest-based removals (2023 dollars). They identified carbon pricing, government procurement, R&D funding, and supply-side incentives as important policy interventions.

pable of removing multiple gigatons annually, and a few — notably DAC and OAE — have significant theoretical upper limits. But these potentials can't be added together. They come from different studies, use different assumptions, and often depend on access to the same finite resources. For example, biochar might remove several gigatons annually, while BECCS and biomass burial might remove several more, but in reality, all three approaches might compete for the same biomass.

Similarly, enhanced weathering, mineralization, and various industrial processes might compete for the same mining capacity, energy, transportation infrastructure, and suitable materials, while DAC and BECCS together might compete for geological storage capacity and associated transportation networks. At the gigaton scale, forest restoration might compete with agriculture, renewable-energy development, and the land needed to support growing populations.

Another reason to be cautious about adding theoretical potentials is that over time, maintaining the intensity of these deployments will become increasingly difficult. The first gigaton of removals will exploit the easiest opportunities. The next ten may be harder, and the final fifty could be much harder still. We'll need to keep pushing the limits of this system for decades, and possibly centuries, and there's no guarantee resource-intensive solutions will be able to finish the job.

And finally, perhaps the most revealing conclusion from this scalability assessment is that DAC and OAE may be the only two solutions in our CDR portfolio with truly hyperscale potential. In a future where we'll need to remove more than 10 Gt/y of CO2, these two solutions may be needed, yet neither are close to reaching their scaled potential, nor are we sure — as we'll discuss in the next section — whether deploying these solutions at scale will even be affordable.

CONCLUSION

Reaching 10 Gt/y may indeed be possible with our current portfolio of CDR solutions if key barriers can be overcome, but there is no agreement whether this goal is realistic, particularly with respect to timing. And while diversifying our solutions portfolio can help us reduce risk, and accelerate innovation and adoption, the benefits of diversification may weaken at scale: several of our solutions depend on the same finite resources, meaning that scaling one may reduce the potential of another. Moreover, only DAC and OAE have theoretical potentials extending into the tens of gigatons annually. Scaling our CDR capacity well beyond 10 Gt/y would mean relying heavily on these two solutions, and OAE is still largely experimental.

These weaknesses are important to recognize and address because if our CDR deployment falls short of 10 Gt/y by mid-century, we will need higher annual removals later this century to compensate. Missing our mid-century net-zero emissions targets will increase this burden further. Slow CDR progress plus continued high emissions would push future removal requirements far beyond 10 Gt/y, and far beyond what our current CDR portfolio can reliably deliver.

COSTS

THE ANNUAL BILL

How much will our 10 Gt/y CDR portfolio cost? Estimates vary based on assumptions about the mix of solutions used, the future price of carbon, which regions will be involved, how much electricity we will need, how fast our learning will evolve, and more. Most scenarios suggest that the annual bill for 10 Gt/y of removals will be in the low trillions of dollars annually.

Table 2. How much will gigaton-scale removal cost?

STUDY / INSTITUTION	SCOPE / CONTEXT	PROJECTED US$/TON	TOTAL ANNUAL COST PER GT	KEY STRATEGIC ASSUMPTION
Lawrence Livermore National Laboratory (Roads to Removal Report)	US only, 1 Gt/y by 2050	~$130	$130 billion	Evaluates optimal county-by-county U.S. land and geological storage. Mixes low-cost soils/forests with scalable BiCRS and DAC.
McKinsey & Company	Global, 6-10 Gt/y by 2050 (favoring nature-based solutions)	$10 to $250	$10 billion to $250 billion	A portfolio heavily dependent on conventional land management (reforestation, agricultural soil management). Lower cost but faces high reversal risks.
McKinsey & Company	Global, 6-10 Gt/y by 2050 (favoring tech-based solutions)	$60 to $1,000+	$60 billion to $1+ trillion	A highly durable, permanent portfolio dominated by DACCS and BECCS. High upfront capital expenditure.
US Department of Energy (Carbon Negative Shot Initiative)	US, 1 Gt/y by 2050	<$100	<$100 billion	Target supported by national laboratory analyses identifying technological improvements capable of substantially reducing CDR costs.
Climeworks / Academic Partners (Global Optimal Portfolio Study)	Global, 1-10 Gt/y by 2050	~$225	$225 billion	Assumes nature-based solutions scale up quickly before 2040, after which engineered pathways take over 70% of the burden to avoid ecological ceilings.
Energy Transitions Commission (Mind the Gap report)	Global, approx 12 Gt/y by mid-century	$91 (calculated; see last column)	$91 billion average	Diversified portfolio. $91/ton assumes $15 trillion in cumulative payments divided by 165 Gt of cumulative removals between 2020 and 2050.
Bezos Earth Fund / RMI (Global Roadmap to 2050)	Global, 10 Gt/y by 2050	$100 to $1,200	$100 billion to $1.2 trillion	Evaluates global scaling across 83 unique milestones to rapidly transition novel capture approaches into cheap, massive commodities.

Sources: Pett-Ridge et al. (2023), McKinsey (2023, 2024), US DOE (2025), Climeworks (2024), Energy Transitions (2022), Kashar et al. (2024)

For example, Lawrence Livermore's 2023 Roads to Removal report (Pett-Ridge et al. 2023) concludes that the US could remove one gigaton of CO2 annually by 2050 — using our current portfolio of existing CDR technologies deployed in different regions depending on suitability — for an estimated annual cost of $130 billion. Assuming these costs scale linearly — which they won't, of course, but just to get a better general sense of the cost burden of this solution portfolio — 10 gigatons of CDR might then require somewhere around $1.3 trillion annually, which is in line with the $900 billion to $2.5 trillion lower range estimates from several other models.

WHO PAYS?

Governments aren't building CDR infrastructure or mandating removals at climate relevant levels just yet.[8] Instead, investors are building pilot scale CDR infrastructure and companies are voluntarily complying with carbon removal incentives designed and run by the marketplace and in rare cases, governments.

In this markets-first world — an approach which is firmly ensconced at the moment — the CDR industry's goal has been to drive costs down to around $100 per ton. At this goldilocks level, removals will still be profitable enough to encourage investment in CDR solutions, but also cheap enough to encourage companies to purchase CDR-based emission credits. So in a world where CDR companies would sell carbon credits for, say, $200 per ton, the hoped-for carbon marketplace — compa-

8. Governments have yet to accept responsibility for CDR in a climate-relevant sense. The overwhelming majority of government work is still centered on developing and improving market mechanisms for CDR.

Table 3. Global annual consumer expenditures by category, 2026 (2026 US$ trillions)

CATEGORY	EXPENDITURES
Housing, utilities, and energy	$14.37
Food and nonalcoholic beverages	$10.70
Transportation	$8.27
Financial services	$6.89
Healthcare	$6.78
Restaurants and hotels	$5.26
Recreation and culture	$4.64
Furnishings and household equipment	$3.19
Clothing and footwear	$2.86
Personal care	$2.30
Communications	$2.00
Education	$1.86
Alcohol and tobacco	$1.80
TOTAL	$70.92

Source: worlddatalab.com

Table 4. Global government expenditures by category, 2025 (2026 US$ trillions)

CATEGORY	EXPENDITURES
Welfare transfers	$19.61
Pension transfers	$7.79
Healthcare	$7.73
Education	$6.30
Infrastructure	$4.45
Government administration	$4.39
Military	$3.07
Research and development	$0.35
TOTAL	$53.70

Source: Moyer (2026).

Table notes: Figures are modeled estimates rather than reported national-account totals. Figures have been converted from 2017 to 2026 dollars for comparison. Consumer and government spending categories overlap and should not be added together.

nies acting voluntarily — would spend $200 billion annually per gigaton of carbon removals, $2 trillion annually for 10 gigatons of removal, and $5 trillion annually for the 25 Gt/y of removals we're already on track for needing by 2100. Our possible carbon removal needs of 60 and 100 Gt/y pencil out at $12 trillion and $20 trillion annually. To help put these figures into perspective, the total global economy in 2025 was $118 trillion — $20 trillion was the entire GDP of China. And it's about twice what households, businesses and governments spend annually on energy (IEA 2024).

The gaudy magnitude of these numbers is one reason why we've argued CDR needs to become a government responsibility rather than a corporate hobby, underwritten by governments and managed as a normal part of government responsibility (Hampson 2026b). Even then, however, government taxing and spending obligations would be massive. Let's assume, for example, that the US agrees to spend the next 100 years removing about one quarter of the world's legacy CO2 pollution (since the US is responsible for about a quarter of it).

If our CDR goal is 10 gigatons annually, this means the US will try to remove 2.5 Gt/y. Extrapolating linearly from Roads to Removal estimates, the annual cost to US taxpayers would be around $325 billion annually ($130 billion/Gt times 2.5 Gt).[9]

This is a lot of money, but here again for perspective, the US spent $900 billion on defense in 2025 and $1.5 trillion on Social Security, so $325 billion is a lot — as a single budget item, it would rank as the seventh largest — but it isn't necessarily unthinkable. However, if our global goal is to remove 25 gigatons annually, then annual US spending on CDR would catapult from $325 billion annually to $812 billion annually. Removing 60 gigatons would require spending almost $2 trillion annually on CDR. At some point in this progression, it's safe to say our required CDR spending *would* become unthinkable — and that's just for the US, the richest country in the world.

Still, it's important to recognize this spending would not be without benefits. Unthinkably high spending on CDR will create industries, jobs, and tax revenues (granted, while it also massively increases government debt and interest rates). And if all this spending creates millions of jobs worldwide and generations of spin-off industries, then this cash infusion might be a godsend for economies and labor markets lucky enough to be on the receiving end.[10] CDR spending might also

9. All these removals wouldn't necessarily be done inside the US. The argument here is that the US would pay for removing 25 percent.

10. Of course, if the economic multipliers from the CDR investments we make aren't

help avert trillions of dollars in future climate-related economic damage and adaptation costs. The Swiss Re Institute (2021), for example, estimated that severe, unmitigated climate-change could lop 18 percent off global GDP by 2050.

But hypotheticals aside, this spending may not be available anyway considering the coming capital needs of the global economy to make massive and ongoing investments in climate adaptation measures and alternative energy development, deal with the rising impacts of climate disruption, and feed our current infatuation with AI data centers. Annual spending of $13 trillion may be hugely catalytic in the end, but this amount of money may also be entirely unavailable to governments in the first place.[11]

MARKET & INVESTMENTS

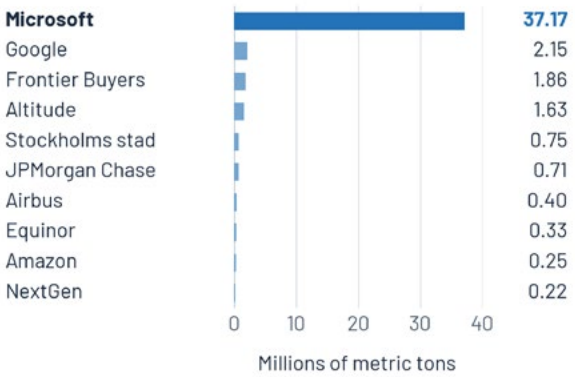
In the meantime, we're currently depending on the CDR marketplace to make our CDR scaling ambitions viable. But this marketplace, after an initial burst of enthusiasm, is transitioning today into a more cautious, sober phase.[12] Much of its early growth was driven by a handful of companies — namely Microsoft, whose large purchases of relatively inexpensive biochar removals helped establish and expand this fledgling market. Microsoft subsequently expanded into much larger agreements for BECCS, becoming by far the largest buyer of carbon removals worldwide.

This dominance has also made the industry vulnerable to shifts in Microsoft's priorities, however. As its AI spending has soared, the company cut its carbon removal purchases in early 2026 by 80 percent year on year (ESG News 2026). Industry-wide, buyers have also become increasingly wary of forest-based solutions due to their high reversal risks, while the high upfront capital costs of engineered solutions like DAC remain a major barrier.

Figure 4. Durable CDR contracted and delivered, 2020 to October 2026 (millions of metric tons)

Source: Adapted from CDR.fyimarket dashboard, accessed October 26, 2026

Figure 5. All-time top-10 purchasers of durable carbon removal (millions of metric tons contracted)



Source: Adapted from CDR.fyimarket dashboard, accessed October 26, 2026

large or are widely dispersed, then continued high levels of spending on CDR simply won't be sustainable for policymakers and economies. This is obviously a more complex discussion than can be covered in a few paragraphs; we may explore this topic in a future paper.

11. Not to pile on, but mobilizing this money will also require financial and institutional arrangements that don't yet exist, and sustaining these commitments through changing governments and economic conditions will be another challenge altogether.

12. Nemet et al. (2026) provides a detailed assessment of CDR demonstration projects, company investment, announced capacities, and commercial development. The chapter also examines investment by technology and the historical pace of technological scale-up. See CDR.fyi (2026a, 2026b) for additional data on commercial purchases and deliveries of durable CDR.

This friction has created a severe project financing gap across the industry. While corporate buying interest remains high on paper (World Economic Forum 2026), the physical deployment of new CDR projects and facilities remains limited. Developers face a tough, structural bottleneck: they cannot secure bank loans to build large-scale facilities without long-term buyer commitments, but corporations are hesitant to sign expensive, multi-year contracts for infrastructure that does not yet exist.

As well, the market cannot solve fragmented standards, unclear accounting rules, and risk-sharing failures on its own. These patterns are carefully tracked by industry insiders, but as far as the future of scaling CDR is concerned, this exercise is circling the drain because regardless of market stats, there are fundamental flaws in our portfolio design.

The first is that we're relying on a market-based approach to CDR, and markets naturally value immediate, high-certainty execution and near-term profit potential, rather than deep future capacity. Therefore, as long as our global climate strategy relies on private capital and voluntary carbon markets to dictate technology selection, our CDR portfolio will reflect solutions optimized for safe, high PR-potential investments and corporate balance sheets rather than the thermodynamic requirements of our atmosphere.

Biochar is the poster child of this appeal, accounting for the vast majority of durable CDR deliveries to date, but also being entirely unable to scale beyond a few gigatons per year at most. DAC is also attracting over 60 percent of all investments in CDR despite being priced too high to scale (CDR.fyi 2026), and being unlikely to reach climate relevant levels in the near future. Forest solutions are also a CDR red herring at hyperscale, highly popular with the public (Gonzalez-Coffin et al. 2026) but unable to scale very high before land use requirements become absurdly large (see the case study in the Feasibility section); as well, the storage capacity of forest can be quickly and catastrophically reversed through ever more intense forest fires.[13]

The second flaw in our CDR scaling ambitions is ambition. When we're designing a 10 Gt/y portfolio, solutions like biochar and forests are feasible and popular and will make a big difference. But when we're contemplating a hyperscale portfolio, our focus on low scale solutions could drain our capital and attention away from solutions capable of hyperscale removal. The investment needs for a 10 Gt/y solution where market forces and a portfolio approach makes sense are not the same as the investment needs for a hyperscale portfolio that will require highly scalable and affordable solutions subsidized by massive government spending.

A final caveat about investment patterns is that the current CDR industry is still overwhelmingly experimental, with relatively few technologies delivering meaningful quantities of verified removals. And while investment has been growing, it is also paltry. SOCDR reports that investment in CDR companies reached approximately $1.6 billion in 2025, which is approximately what the city of New York spent on road repair (Sherman 2024).

We should absolutely celebrate the progress being made in this field, but also keep this progress in perspective: The annual market activity and investments CDR needs to reach gigaton scale removals will measure in the low trillions of dollars, not low billions. If private investors can't summon this amount — and there's absolutely no reason to believe they can or will — then we need to figure out how to get governments more involved.

---

13. See NASA 2026 for a discussion of the increasing frequency and severity of forest fires. Canada's record-breaking 2023 wildfires released approximately 950 million tons of CO2 from managed forests alone — about 38% more than the country's total reported emissions from all other economic sectors combined that year (687 Mt). These wildfire emissions were also more than 12 times the reduction in Canada's annual emissions achieved between 2005 and 2023 (76 Mt), and nearly three times the annual reduction Canada has pledged to achieve under its 2030 NDC. See Environment and Climate Change Canada 2026a, 2026b.

At present, while there is some budding movement with regard to government involvement, the vast majority of public efforts remain confined to early-stage market building—such as localized research grants, technology prizes, and standard-setting. While these are welcome demand signals, they do not constitute a cohesive strategy. Nothing is happening yet at a climate-relevant scale because governments have not yet crossed the critical threshold into assuming true public responsibility for ensuring carbon removal actually occurs.[14]

FUTURE COSTS AND IMPLICATIONS

Will our current CDR costs come down? Table 5 summarizes estimates across various studies.[15] The pattern to note here is that the solutions with lower costs and lower potential cost floors also tend to have more limited removal potential (recalling Table 1), with the exception of OAE. Solutions with more durable storage potential are generally more expensive.

This is particularly true for DAC, which requires enormous up-front investments in industrial facilities, energy supplies, transportation networks, and storage infrastructure before meaningful removals can begin. A recent report from Harvard's Belfer Center concluded that because of the huge costs required to construct DAC facilities and maintain their operations, removal costs will likely still be between $200 and $500/ton by 2060, and are highly unlikely to ever drop below $100/ton (Al-Juaied and Whitmore 2023).

This is an important finding since DAC plays an outsize role in our hyperscaled CDR portfolio. If DAC is going to cost, at minimum, $200/ton by 2060, what does this mean for our plans? Affordability is one concern, obviously, but the Belfer report also noted the long timelines that financing, construction and permitting will create for DAC facilities, and estimates that because of these, DAC will make only a marginal contribution to our CDR goals over the next few decades — from a low of 64 megatons of CDR per year (Mt/y) in 2060 to a high of 1.4 Gt/y.

Indeed, the long-term prospects for any of our current CDR solutions to drop below $100/ton are uncertain since the marginal cost of securing additional resources may increase as deployment expands and resource competition increases. The question, therefore, isn't only whether these solutions will become significantly cheaper as they mature and our learning improves, but whether the cost improvements we'll see as a result will be able to outpace the increasing costs associated with increasing scarcity of the resources these solutions depend upon.[16]

What are the overall implications of these considerations at hyperscale? For one, our total costs will likely stay elevated. Particularly if DAC costs stay high and resource competition keeps other solution costs elevated, we may not see the economies of scale needed to significantly reduce

---

14. As tracked by the Vancouver Process secretariat (Governments & CDR tracking framework; see Vancouver Process 2026), contemporary public sector involvement in carbon removal is heavily weighted toward market building — creating the rules, standards, and pilot incentives for private entities to trade credits. Rare signs of strategic direction are emerging as a few states integrate these pilots into long-term climate modeling. However, true climate-relevant scale requires a transition to public responsibility, where sovereign states manage atmospheric carbon explicitly as a public waste management obligation underwritten by direct government procurement rather than leaving technology selection and deployment volume to voluntary market caprice.

15. For more detailed assessments of current and projected CDR costs, including the effects of technological learning, resource constraints, financing assumptions, and infrastructure requirements, see Fuss et al. (2026) and Kahsar et al. (2026). For an engineering-based assessment of DAC costs under different technological and geographic conditions, see IEAGHG (2021). The Howard and Sylvan 2024 survey also includes estimates from the CDR expert community on how low they think CDR prices can drop.

16. The argument across different solution sets is more nuanced, of course. DAC may benefit significantly from standardized production and technological learning. Biomass processing plants may become more efficient. Mining equipment may improve. As well, in a global marketplace, companies will look for low-cost labor and solutions. However, the marginal cost of securing additional resources may increase as deployment expands.

Table 5. Current and potential future costs of carbon dioxide removal

CDR APPROACH	OBSERVED MARKET PRICE (1)	CURRENT COST ESTIMATES OR SUPPLIER BREAK-EVEN (2)	POTENTIAL FUTURE COSTS (3)
Afforestation and reforestation	$20 (2024 average)	$5–53 in modeled at-scale assessments; comprehensive current costs uncertain	No reliable future floor; $5–53 represents favorable at-scale estimates
Soil carbon sequestration	$60–80 (2026 agreement)	–$45 to $105 in modeled assessments accounting for agricultural benefits	No reliable future floor
Biochar	$136	$143 supplier-reported 2025 break-even	$136 projected 2030 break-even; $70–360 in a longer-term cost assessment
BECCS	$220	$232 supplier-reported 2025 break-even; $75–300 in IEA current-cost estimates	$212 projected 2030 break-even; potentially $40–125 in longer-term assessments
Biomass burial/ direct storage	$61 for direct biomass storage	No comprehensive verified current-cost estimate; modeled at-scale costs $10–200, often excluding MRV	Low-end modeled costs around $10, but no established durable-removal cost floor
Enhanced rock weathering	$352	$272 supplier-reported 2025 break-even; current techno-economic estimates $50–300+, sometimes exceeding $1,000	$252 projected 2030 break-even; around $100 potentially achievable in favorable locations
Direct-air mineralization and mineral products	$392 for broader mineralization category	$316 supplier-reported 2025 break-even for mineralization generally; complete air-to-storage costs not established	$228 projected 2030 break-even for mineralization generally; no established floor for direct-air pathways
Ocean alkalinity enhancement (OAE)	$395	$100–150 in current techno-economic assessments; some approaches exceed $300–600	Costs expected to decline, but no reliable global-scale cost floor
Ocean iron fertilization (OIF)	No established commercial price	No verified commercial cost; modeled estimates range from <$10 to >$10,000	Potentially <$10 under optimistic assumptions, but highly uncertain
Direct ocean capture and storage (DOCCS)	$1,331 for the broader direct-ocean-removal category	$500–2,000 in systems-level estimates, sometimes excluding MRV and storage	No established mature cost floor
Cultivated seaweed sinking	No reliable comparable market price	Full CDR costs likely >$1,000; production costs vary enormously	Potentially around $100 under exceptionally favorable large-scale assumptions
DACCS	$516	$670 supplier-reported 2025 break-even; $400–2,500 in reviewed gross-removal cost studies	$341 projected 2030 break-even; potentially $100–600 at gigaton scale

All figures in US dollars per metric ton of CO2. Market prices are based on publicly disclosed transactions, not credits delivered.

Table sources and notes:

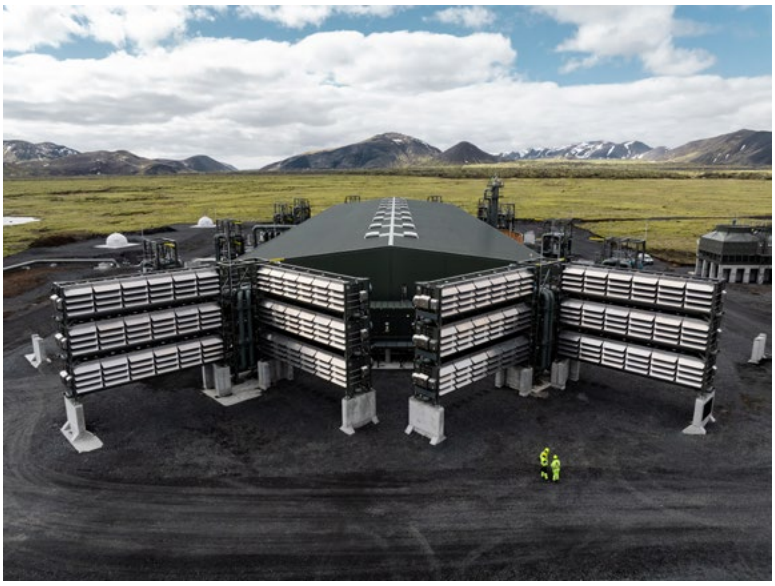
1. Most market prices are from CDR.fyi's publicly accessible database. These are reported contractual prices, not the costs suppliers incur or prices available to buyers today. For afforestation, the table uses Ecosystem Marketplace's $20.44 average transaction price in 2024. The soil-carbon estimate comes from Microsoft's January 2026 agreement with Indigo Carbon, whose reported pricing was approximately $60–80 per ton. These biological removals are not directly comparable with engineered CDR offering millennial storage. Sources: CDR.fyi (2026a); Ecosystem Marketplace (2025); Twidale and Jessop (2026).
2. Break-even figures come from the January 2025 CDR.fyi/OPIS supplier survey. They represent the average selling prices suppliers said they needed to cover costs, not independently audited production costs. These estimates are useful because they distinguish operating viability from the amount customers are willing to pay. Source: CDR.fyi and OPIS (2025).
3. Two different kinds of future costs projections are included here. The 2030 figures represent suppliers' expected break-even prices, as reported in the 2025 survey. The longer-term figures come from techno-economic assessments summarized in the 2026 State of Carbon Dioxide Removal. These shouldn't be interpreted as guaranteed technological cost floors. Sources: CDR.fyi and OPIS (2025); Fuss et al. (2026).

Additional details:

- Where a commercially demonstrated removal cost or credible future estimate is unavailable, the table identifies this rather than substituting a theoretical minimum.
- Several literature estimates omit MRV, transportation, or final storage. Consequently, apparent low-cost options may become more expensive when evaluated on a consistent basis of verified net atmospheric removal. Comparisons are further complicated by differences in capital financing, equipment lifetimes, operating expenses, and revenues generated from commercial products.

average removal costs. In fact, expanding our portfolio could require progressively more expensive resources and greater reliance on higher-cost technologies, potentially increasing average costs even as individual solutions become more efficient.

Either way, reaching hyperscale CDR capacity could require multiple trillions of dollars annually. Lowering the cost of the solutions in our CDR portfolio starts to become increasingly important, whether this means looking for more efficiencies, putting more emphasis on the possibility of scaling non-DAC solutions, looking for new technologies that are less costly, or some combination of all these approaches.



Climeworks' Mammoth direct air capture facility, pictured at its May 2024 unveiling in Hellisheiði, Iceland. Powered by geothermal energy, Mammoth uses modular collectors to extract CO2 from ambient air. The captured CO2 is injected underground by Carbfix, where it mineralizes in basalt formations. Designed to capture up to 36,000 tonnes annually — roughly ten times the capacity of its predecessor, Orca — Mammoth represents an important milestone in DAC development. At this scale, however, removing 10 gigatonnes of CO2 annually would require approximately 278,000 Mammoth-equivalent facilities operating at full nameplate capacity, before accounting for operational losses. Photo credit: Climeworks

In this future, it is unlikely that OAE — the only other solution in our current portfolio capable of hyperscale — will be able to come to the rescue. The costs for OAE may only level off at $50-$160/ton in the future since this solution requires mining, crushing, and distributing billions of tons of alkaline rocks annually (NOAA 2023). It's also likely to scale much slower than initially forecast, with global removal potential of only 0.64 to 2.7 Gt per year by 2100 (Mack et al. 2025).

CONCLUSION

Our 10 Gt/y CDR solution portfolio will likely cost at least $1 trillion/year to operate by the year 2050 if all goes well (incorporating capital costs to the extent estimates include them). Beyond 10 Gt/y, high capital requirements, resource competition, and increasing reliance on DAC and OAE may prevent average costs from falling significantly with scale. Indeed, since DAC is substantially more expensive than most other CDR solutions, our overall costs per ton might even increase as our portfolio expands.

Therefore, reaching CDR capacities higher than 10 Gt/y will likely require multiple trillion dollar annual expenditures. While low trillion dollar levels of annual spending might integrate — albeit uncomfortably — into the global economic picture, higher levels of sustained spending would likely be unavailable, particularly if we expect markets to shoulder this burden alone without significant help from governments.

Meanwhile, as long as the CDR industry is guided by marketplace incentives, investors will continue to favor low-risk solutions like biochar and forests, regardless of their scaling potential, and investment in higher potential solutions like DAC will be hamstrung by high costs. There are no developments on the horizon suggesting these trends will suddenly change. The current CDR marketplace

is neither robust nor widespread enough to suggest that market forces alone will be sufficient to propel the CDR market to scale on its own to 10 Gt/y levels. Government involvement will likely be required, but governments are for the most part not yet looking at CDR as a civic responsibility — only as a marketplace that can benefit from additional support.

NON-COST FEASIBILITY

TRL, MRV AND OTHER ACRONYMS

Beyond costs, we also need to make sure our CO2 removal solutions are otherwise feasible — whether they can reach commercial scale in a reasonable period of time, sequester captured CO2 for a long period of time, measure this captured amount so we know removal is happening, operate reliably with minimal environmental impacts, and be trusted by governments and communities.

Table 6 summarizes several of these feasibility considerations for the same CDR solutions evaluated in Tables 1 and 5. As with our earlier comparisons of removal capacity and cost, there are no clear winners. Some solutions have excellent permanence but low readiness, others are technologically mature but vulnerable to reversal or hard to verify, and for others still we just don't know yet.[17]

But not all of these considerations are weighted equally. The Oxford Principles for Net Zero Aligned Carbon Removal considers durability to be the most important factor (University of Oxford 2024). Frontier — the world's largest corporate carbon removal buyer coalition — also considers permanence to be a mandatory "gatekeeper criteria": If permanence can't be guaranteed, then a CDR project is disqualified regardless of other feasibility scores (Frontier 2026). The EU's Carbon Removals and Carbon Farming Certification Framework (CRCF) defines permanent carbon removal as a process that captures and stores atmospheric or biogenic carbon for several centuries, while recognizing shorter-duration storage in products, forests, and soils as separate categories (European Parliament and Council 2024).

Many of the solutions in our current CDR portfolio are highly permanent. They tend to vary more widely around how well removals can be measured. Measurement, reporting and veri-

Feasibility case study: Afforestation @ 2 Gt/y

Suppose we wanted to remove two gigatons of CO2 annually through additional forest growth. How much forest would this require? If we assume a forest carbon accumulation rate of approximately 7.3 metric tons of CO2 per hectare annually (Waring et al. 2020), the land requirements become quite expansive.

MEASURE	REQUIREMENT
Annual CO2 removal target	2 billion tons
Assumed annual removal per hectare	7.3 tons
Required forest area	273 million hectares
Equivalent area	1.05 million square miles (4x size of Texas)
Estimated annual cost at $5–53/t	$10–106 billion

These calculations assume that all the land is suitable for forest restoration; that the resulting carbon uptake is additional; and that the forests maintain their assumed average growth rate. In reality, forest carbon accumulation varies substantially by location, forest age, species, and environmental conditions. Rates also change as forests mature. Climate-related disturbances could further reduce removal performance or release previously stored carbon. This model also excludes the potentially substantial costs of acquiring or managing land, monitoring removals, and protecting forests against reversal where these are not already included in the published cost estimates.

Source: Author calculations based on Waring et al. (2020).

17. Technology readiness assessments can also vary depending on whether they evaluate individual components or complete CDR systems. See RMI's Applied Innovation Roadmap (2023), Kahsar et al. (2026), and Nemet et al. (2026), Chapter 3 of SOCDR, for more detailed assessments of technological readiness, research, demonstration, and commercial development.

Table 6. Comparing the practical feasibility of CDR solutions

CDR APPROACH	PERMANENCE (1)	TECHNOLOGY READINESS (2)	MRV DIFFICULTY (3)	PRINCIPAL ENVIRONMENTAL/ RESOURCE CONCERNS (4)	PUBLIC ACCEPTANCE (5)
Afforestation and reforestation	Reversible; decades to centuries if protected	High	Moderate–high	Land competition, water, wildfire, ecosystem changes	Generally favorable; land-use conflicts possible
Soil carbon sequestration	Reversible; years to centuries	High	High	Carbon saturation, agricultural practices, soil disturbance	Generally favorable; depends on farmer participation
Biochar	Centuries to millennia for stable fractions	Moderate–high	Moderate	Sustainable biomass supplies, air pollution, soil effects	Generally favorable; industrial expansion may encounter opposition
BECCS	Potentially millennial with secure geological storage	Moderate	Moderate	Biomass demand, land, water, energy, pipelines and storage	Mixed; biomass and CCS concerns
Biomass burial/ direct storage	Potentially centuries or longer; uncertain	Low–moderate	Moderate–high	Biomass supplies, decomposition, storage-site management	Limited evidence; concerns about burial and waste
Enhanced rock weathering	Potentially millennial or longer	Low–moderate	High	Mining, grinding, transportation, soil and water chemistry	Uncertain; agricultural benefits may improve acceptance
Direct-air mineralization and mineral products	Millennial to geological timescales	Low–moderate (6)	Moderate	Mineral supplies, mining, processing, material handling	Uncertain; tangible products may help
Ocean alkalinity enhancement (OAE)	Potentially centuries to millennia	Low	Very high	Ocean chemistry, ecological impacts, mineral supply	Uncertain; marine intervention concerns
Ocean iron fertilization (OIF)	Variable; years to centuries or longer	Low	Very high	Ecosystem changes, oxygen depletion, food-web impacts	Controversial; substantial governance concerns
Direct ocean capture and storage (DOCCS)	Potentially millennial with secure storage	Low–moderate	High	Seawater processing, energy, marine discharge, storage	Uncertain; industrial and marine concerns
Cultivated seaweed sinking	Highly uncertain; potentially reversible	Low	Very high	Marine habitat alteration, sinking impacts, nutrient competition	Uncertain; ecological concerns
DACCS	Potentially millennial with secure geological storage	Moderate	Moderate	Energy, water in some designs, infrastructure, geological storage	Mixed; concerns about cost, energy and CO2 pipelines

Table sources and notes:

1. Sources: IPCC (2022); Edwards et al. (2026).
2. Sources: IPCC (2022); European Scientific Advisory Board on Climate Change (2025).
3. Sources: Smith et al. (2024); Hoffmann et al. (2026).
4. Sources: Edwards et al. (2026); IPCC (2022); National Academies (2022).
5. Source: Edwards et al. (2026).
6. The mineralization chemistry is relatively well established, but direct atmospheric capture coupled with mineralization varies substantially in technological maturity.

fication (MRV) is Frontier's second gatekeeper criteria. Can we verify how much CO2 is being captured and guarantee it's staying put? Every solution has its MRV challenges: verifying the amount of CO2 captured by DAC is easy, for example, whereas verifying CO2 capture by forests, OAE and enhanced rock weathering involves much more educated guesswork. Similarly, research has shown that basalt formations are incredibly effective at sequestering CO2 permanently since the gas becomes mineralized in these formations, whereas solutions like OIF require intricate monitoring protocols to verify permanence.

Our solutions also vary widely with regard to their technology readiness level, or TRL. The IPCC tracks TRL to understand how quickly solutions can scale and contribute to long-term climate pathways, whereas corporate buyers might use TRL as near-term feasibility gateways, reasoning that climate finance should prioritize solutions capable of working sooner rather than later (though some specialized catalytic funds explicitly seek out low-TRL solutions to accelerate their development). Meanwhile, the World Resources Institute notes that public acceptance acts as an ultimate checkpoint for technological scale-up, warning that even heavily funded solutions like DAC can't achieve widespread deployment if developers do not secure robust public and community trust (WRI 2026).

In short, a wide range of core non-cost feasibility factors like permanence, MRV, technology readiness and public acceptance (which we'll discuss again on the next page) are taken into account by policymakers who are trying to design the best CDR solutions portfolio possible. How these are weighted depends on the institution doing the assessment and what these assessments are trying to prove (e.g., commercial viability, environmental impact, long-term durability, and so on).

REGULATORY FEASIBILITY

Our current efforts to scale durable CDR are also restricted by a maze of regulatory and permitting frameworks that can cross many regions of governance. Whether CDR can scale will depend in no small part on how quickly and flexibly these frameworks can evolve.

For example, the main regulatory bottleneck for DAC (and also BiCRS) is how to safely transport and bury CO2. In the US, this requires navigating the EPA's rigorous Class VI Underground Injection Control permitting process under the Safe Drinking Water Act, alongside comprehensive National Environmental Policy Act reviews. Because the EPA backlog can stall projects for years, the regulatory landscape is shifting as states like Louisiana, Wyoming, and North Dakota secure "primacy" — taking over Class VI permitting to accelerate local approvals. Furthermore, developers must navigate a fractured network of state-level moratoriums on interstate CO2 pipelines, driven by local eminent domain and safety disputes. Even biochar, as it scales larger, will begin to face emerging compliance structures governing sustainable feedstock sourcing, regional air quality permits, and life-cycle supply chain traceability to ensure true net-negativity.

Marine CDR solutions probably face the most complex institutional barriers, however, since they must navigate both domestic regulations and international maritime law. The London Convention and London Protocol have established a precautionary approach to ocean fertilization, with resolutions adopted in 2008 and 2010 stating that activities other than legitimate scientific research should not be allowed. A 2013 amendment extending legally binding controls over marine geoengineering has not yet entered into force. However, in October 2026, the International Maritime Organization adopted new assessment frameworks for ocean fertilization, ocean alkalinity enhancement, and ocean biomass sinking. These frameworks clarify the requirements for conducting legitimate scientific research, including environmental assessments, monitoring, and risk management, but do not yet establish a pathway for large-scale commercial deployment (IMO 2026).

Furthermore, Article 6 of the London Protocol generally restricts the transboundary export of CO2 for offshore geological storage. Although a 2009 amendment would permit such exports under specified conditions, it has not yet entered into force. A 2019 resolution allows participating countries to apply the amendment provisionally, enabling cross-border CO2 storage arrangements subject to environmental safeguards and international agreements. These evolving regulations provide important protections but also illustrate the institutional complexity facing marine CDR. Establishing workable permitting procedures, demonstrating environmental safety, coordinating international governance, and developing reliable MRV protocols will remain major challenges to scaling these solutions.

PUBLIC ACCEPTANCE AND LONG-TERM SUSTAINABILITY

In a broad sense — without distinguishing between solutions like DAC and forests — some surveys have shown that the public supports CDR, once they learn about it (Data for Progress 2025; see Figure 6). At the same time, other surveys (e.g., Sovacool 2024) have shown wide differences in public support for natural solutions like forests and soil versus engineered solutions like DAC.[18] The public opinion landscape won't be easy to navigate. A CDR solution or project can satisfy every technical, legal, financial, and permanence requirement and still encounter fierce local opposition. Conversely, a solution might enjoy considerable public support but still fall short in other measures. Both considerations will influence how quickly CDR can scale, and whether deployments can be sustained over time.[19]

And while researchers have noticed that this dynamic is already important, public acceptance will become increasingly vital as our CDR solutions begin to scale. The negative impacts of the wrong operations writ large have the potential to weigh heavy on the public psyche: increased mining may have visible and controversial impacts, huge DAC deployments might compete ferociously for electricity and water, industrial waste streams will raise alarms, and every misstep will be amplified by disinformation outlets for a public that already has had a hard time accepting the reality of climate change. As well, unlike public works projects where we build dams that create electricity and irrigation, or ports and roads that move cargo, the multiplier effect of building DAC plants that remove and bury CO2 gas may be muted by comparison, and may struggle to maintain public support as a result.

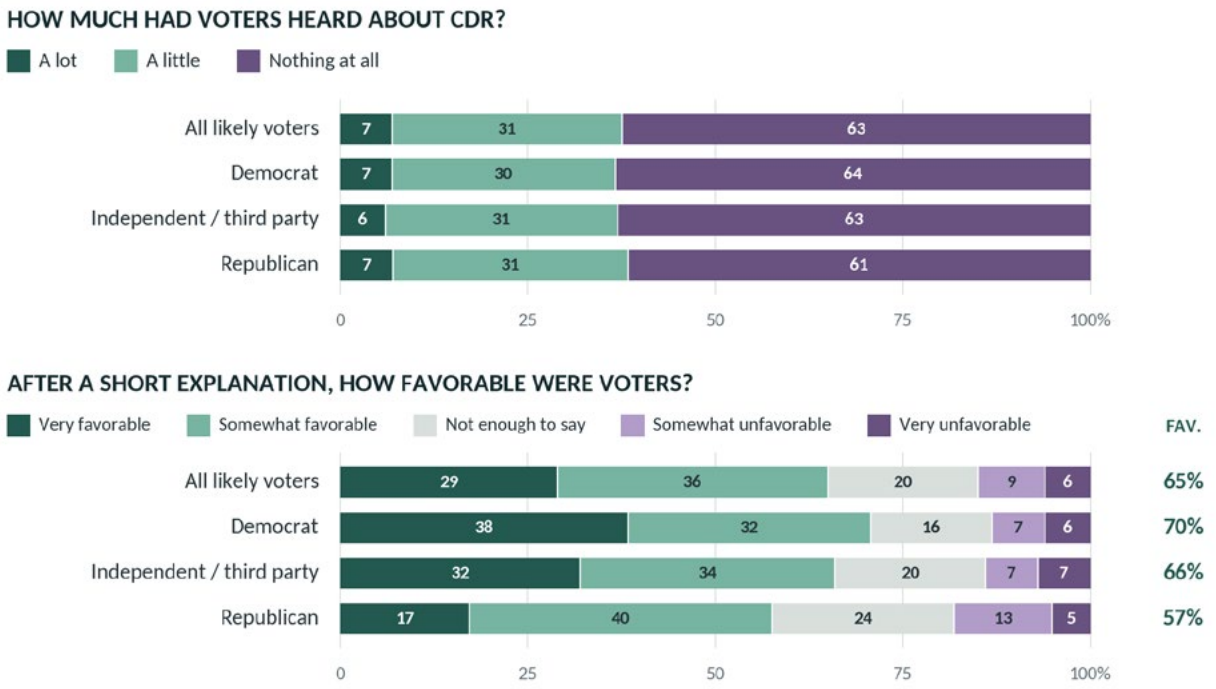
DAC might also be vulnerable because the public isn't particularly fond of pipelines and underground gas burial. In a recent public survey in regions where CO2 pipelines and underground storage were already happening — Norway, the Netherlands, Greece and Germany — respondents overwhelmingly felt at least some level of concern for these storage facilities and their long-term monitoring plans (Otto 2022). Whether these concerns disappear over time will depend on trust, familiarity and performance, but support may be precarious: one serious pipeline accident might permanently alter the trajectory of this industry the way Three Mile Island shuttered the US nuclear power industry in 1979.

If we're going to rely heavily on DAC then — at least in theory — it's possible we should start putting more emphasis on durable CO2 reuse than long-term storage. Drawing on society's experience with building public sewer systems in the 1850s, there might be a benefit to deploying solutions that have a strong connection between cost and benefit — solutions that can fill dump trucks with carbon or pump carbon into cement and pavement rather than filling reservoirs and accounting

18. Sovacool (2024) also reveals differences in opinion by region, age, gender and wealth status.

19. For a broader assessment of CDR governance and policy development, see Lebling et al. (2026), Chapter 5 of SOCDR. For the international governance of marine CDR, see the International Maritime Organization's guidance on marine geoengineering and the London Convention/Protocol. The 2008 and 2010 resolutions established a precautionary approach to ocean fertilization, while the 2013 amendment would introduce additional binding controls upon entry into force.

Figure 6. Estimating US public support for CDR



Source: Adapted from Fraser and Adcox (2025).

Figure note: Survey of 1,250 likely US voters in January 2025.

ledgers. Without this connection, public support for CDR spending may be difficult to sustain, not only because the impacts of our spending won't be felt for decades as the amount of CO2 in our atmosphere ticks down only slowly, but also because the ROI is less palpable. "This giant billion dollar factory that costs a billion dollars to operate every year is providing the raw materials to power a new industrial revolution," will be a much more supportable platform for policymakers in the year 2075 than "This giant billion dollar factory that costs a billion dollars to operate every year is burying CO2, and that's a good thing, even though you aren't noticing any benefit. Trust us."[20]

Long-term sustainability will also hinge on whether the CDR solutions we deploy can maintain their removal capacity over time. A solution capable of removing 10 Gt/y in 2050 might not be capable of maintaining that rate for another hundred years. Forests and soils eventually approach new carbon equilibria, favorable biomass and mineral resources may become progressively harder to obtain, and geological storage capacity is finite. At enormous scales, we need to evaluate not only how much CDR capacity we can realistically build and operate, but how long we can sustain such

20. Although there is not a body of research establishing that a more visible, visceral relationship with our carbon removal efforts will be important for sustainability, several studies tangentially support this hypothesis. For example, Friedmann (2019) identified the lack of immediate, tangible benefits as a challenge for public acceptance of engineered CDR. As well, the historical example of waste management is also telling (see Hampson 2026b): governments didn't design effective waste management solutions until the need for waste removal became so obvious that cities could no longer function. Surveys have indicated that other factors are also important for CDR deployment, such as fairness, community participation, public accountability, and the equitable distribution of benefits. While these will certainly help establish the social legitimacy of CDR, its long-term political durability may ultimately depend on demonstrating that removals are necessary and beneficial, and that the before and after comparisons are palpable. Sources: Scott-Buechler 2026; Kudrnáč and Fairbrother 2025; Arias and Schwartz 2026; Friedmann 2019; Fritz et al. 2026.

an effort physically, financially, and socially. And this sustainability map will grow extraordinarily complex over time. Over the next two decades, CDR will need to evolve from a smattering of small experiments to a permanent and highly visible fixture in society for at least the next 100 years. We need to begin thinking about how this effort will integrate into the human experience.

CONCLUSION

The non-cost feasibility profile for our CDR portfolio is mixed. We have a number of solutions with excellent permanence. However, the public prefers natural solutions like forests that rank low on permanence and scalability (biochar may at least be highly permanent). Meanwhile, the regulatory landscapes for both DAC and OAE are complicated, and will need to become substantially less so before these solutions can reach scale.

The biggest feasibility consideration though may be public acceptance. As our solutions increase in size, they will also increase in impact, and unless the public can make a strong connection between impact and benefits, the long-term sustainability of this work will be jeopardized.

THE ROAD AHEAD

WHERE ARE WE?

First, it's unlikely that $100/ton is a suitable target for the much higher levels of CDR we may need in the future. It's already hugely speculative to suggest the world will be willing and able to spend more than $1 trillion every year for 10 Gt/y of carbon removal by 2050; the prospect of paying multiple times this amount for the CDR we may actually need should give us pause.

Second, we'll need to change our formula for who's paying the bill. Spending at the hyperscale level shifts the responsibility squarely to governments; the marketplace alone — especially through voluntary measures — will never voluntarily commit to this burden, even if they could. Governments have an ethical reason to get involved anyway: governments need to stop thinking of carbon removal as a private-sector activity and start thinking of it as an essential public undertaking supported by an enormous network of private, public, and civic institutions. Governments are uniquely and historically capable of this task, possessing all the requisite tools to mobilize capital, clear regulatory hurdles, finance research, support first-of-a-kind demonstration projects, mandate compliance, and inspire virtuous cycles in a way that the private sector simply cannot — at least not at the scale required for this challenge.[21]

And third, technology development will be critical. While it's possible we might reach hyperscale CDR capacity using our current mix of solutions, this mix

21. See Hampson (2026b) for a much more developed analysis of this point.

will not get us there affordably or sustainably. We will either need to markedly improve the cost and effectiveness of these solutions (or at least the solutions like DAC that will carry most of the burden), or we'll need to keep looking for better ones.

Solutions that can scale through distributed deployment might be exceptionally helpful in this regard, so cities and even homeowners can deploy small-scale solutions that add up, rather than relying on a more limited deployment of mega-CDR facilities with huge costs and impacts. We wrote recently about solid carbon, for example. This is currently being investigated — hopefully more will be written about this option in the coming months.[22] A solution like this which can passively remove CO2 from ambient air at scale and for less than $5 per ton might be the type of solution we need, but it is also far too early to give up on our other options. More than likely, additional solution options like this will need to compete for inclusion in our CDR portfolio.

WHAT HAPPENS IF WE DON'T ACT?

It may end up being the case that no scalable CDR solutions emerge in a timely manner, which means we'll need to adapt to our changing climate as best we can until these solutions are developed and deployed. Global temperatures will be at 1.5°C above preindustrial levels by 2030, and without aggressive emissions reductions in the coming years, close to 3°C by 2100 (Climate Action Tracker 2026).

How long we take to deploy these solutions may depend at least in part on how bad things get and how much political influence the most deeply affected governments will be able to muster. A slowly unfolding climate disaster that just makes life inconvenient for the US, EU and China may never unlock the action the world needs; but when cities in the Global South start disappearing under waves, or food and energy supplies run out, maybe then we'll stop treating carbon dioxide removal as something we might want to deploy at limited levels in the distant future.

If we wait for widespread crises like these before acting on CDR, however, we may have no choice but to mandate geoengineering fixes like cloud brightening to attempt to lower global temperatures for a few decades while our CDR research and development continues. Many policymakers think we should do this now regardless, recognizing that our CDR solutions are likely still decades away from reaching the capacity we need. Carefully designed and managed geoengineering solutions won't change the amount of CDR we will eventually need, but they might extend our time horizons, and limit the damage our planet sustains until our scalable CDR solutions can be developed and deployed.

WHAT COMES NEXT?

Can our current portfolio of CDR solutions scale much higher than 10 gigatons per year? Probably not yet, and not reliably. There is merit in pursuing a diversified portfolio of solutions for 10 Gt/y of CDR deployment, including taking advantage of regional opportunities, distributing economic benefits, reducing dependence on any single technology, and creating opportunities for innovation. And there's no reason to assume that today's technologies won't improve considerably as investments increase and experience grows.

But there's also significant reason to doubt whether these improvements will be enough. The theoretical removal potentials of our current portfolio don't add up, costs are prohibitive and won't necessarily decline with scale, and many of our solutions face fundamental resource constraints

22. The concept has not yet been experimentally demonstrated, and its ultimate performance and costs remain unknown. But it illustrates the kinds of technological departures from today's CDR portfolio that may be worth investigating.

or won't be able to make climate relevant contributions to CDR for decades to come. And even if we can somehow assemble a portfolio capable of removing dozens of gigatons of CO2 annually, we still haven't established we can afford to operate it, sustain it for a century, or maintain the public and political support necessary to keep it running so we can not only keep temperatures under control but begin the long process of restoring global temperatures to their more historic levels.

None of this means we should abandon our current solutions. We need them, and we should continue investing in their development. But we also need to keep searching for more capable and lower cost solutions. If fossil fuel emissions stay high and we reach the point in the next few decades where our CDR goals need to increase to 25, 60 or even 100 gigatons of carbon dioxide annually, then scalability will need to become an essential requirement for the solutions we develop. We cannot afford — literally — to spend trillions of dollars over the coming decades on carbon dioxide removal solutions that won't be able to save us.

REFERENCES

Allen, Myles R., David J. Frame, Pierre Friedlingstein, et al. 2025. "Geological Net Zero and the Need for Disaggregated Accounting for Carbon Sinks." Nature 638: 343–350. DOI 10.1038/s41586-024-08326-8

Al-Juaied, Mohammed, and Adam Whitmore. 2023. "Prospects for Direct Air Carbon Capture and Storage: Costs, Scale, and Funding." Belfer Center for Science and International Affairs, Harvard Kennedy School, November 30. https://www.belfercenter.org/publication/prospects-direct-air-carbon-capture-and-storage-costs-scale-and-funding

Arias, Sabrina B., and Joshua A. Schwartz. 2026. "Think Globally, Act Locally: The Determinants of Local Policy Makers' Support for Climate Policy." Perspectives on Politics. Published online September 29. https://www.cambridge.org/core/journals/perspectives-on-politics/article/think-globally-act-locally-the-determinants-of-local-policy-makers-support-for-climate-policy/CC9FD2A14A1FA42AE9E136570030FC5A

Boyd, James, Emily Joiner, Alan Krupnick, and Michael A. Toman. 2024. Policy Incentives to Scale Carbon Dioxide Removal: Analysis and Recommendations. Report 24-03. Washington, DC: Resources for the Future. https://www.rff.org/publications/reports/policy-incentives-to-scale-carbon-dioxide-removal-analysis-and-recommendations

CDR.fyi. 2026a. "Carbon Removal Market Data." Accessed October 26. https://www.cdr.fyi

CDR.fyi. 2026b. "Durable CDR Market Update: From Ambition to Execution." June 12. https://www.cdr.fyi/blog/durable-cdr-market-update-carbon-unbound-east-coast-2026

CDR.fyi and OPIS. 2025. Bridging the Gap: Durable CDR Market Pricing Survey—Purchaser and Supplier Expectations in 2025 and 2030. https://www.cdr.fyi/reports/pricing-survey-jan-2025.pdf

Climate Action Tracker. n.d. "Climate Action Tracker." Accessed October 24, 2026. https://climateactiontracker.org

Climeworks. 2024. Global Optimal Portfolio for Carbon Dioxide Removal. Zurich: Climeworks AG. https://climeworks.com/uploads/documents/global-optimal-portfolio.pdf

Commonwealth Scientific and Industrial Research Organisation (CSIRO). 2025. Australian Carbon Dioxide Removal Roadmap. Canberra: CSIRO. https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/energy/cdr-roadmap

Ecosystem Marketplace. 2025. State of the Voluntary Carbon Market 2025: Meeting the Moment—Renewing Trust in Carbon Finance. https://www.ecosystemmarketplace.com/publications/2025-state-of-the-voluntary-carbon-market-sovcm

Edwards, Morgan R., Oliver Geden, Matthew J. Gidden, et al., eds. 2026. The State of Carbon Dioxide Removal. 3rd ed. DOI 10.17605/OSF.IO/ZRD65

Energy Transitions Commission. 2022. Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive. London: Energy Transitions Commission

Environment and Climate Change Canada. 2026a. "Land-Based Greenhouse Gas Emissions and Removals." Canadian Environmental Sustainability Indicators. Government of Canada. https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/land-based-greenhouse-gas-emissions-removals.html

Environment and Climate Change Canada. 2026b. "Executive Summary of the Report: Greenhouse Gas Sources and Sinks in Canada: 2026." Government of Canada. https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/sources-sinks-executive-summary-2026.html

ESG News Editorial Team. 2026. "Microsoft Cuts Carbon Removal Buying 80% Amid AI Push." ESG News, August 17. https://esgnews.com/microsoft-cuts-carbon-removal-buying-80-amid-ai-push

European Parliament and Council of the European Union. 2024. Regulation (EU) 2024/3012 of 27 November 2024 Establishing a Union Certification Framework for Permanent Carbon Removals, Carbon Farming and Carbon Storage in Products. Official Journal of the European Union, December 6. http://data.europa.eu/eli/reg/2024/3012/oj

European Scientific Advisory Board on Climate Change. 2025. Scaling Up Carbon Dioxide Removals: Recommendations for Navigating Opportunities and Risks in the EU. Luxembourg: Publications Office of the European Union. https://www.ecologic.eu/20005

Fraser, Catherine, and Grace Adcox. 2025. "Most Voters Have Heard Nothing About Carbon Removal, but Support Investing in It After Learning More." Data for Progress, February 25. https://www.dataforprogress.org/blog/2025/2/25/most-voters-have-heard-nothing-about-carbon-removal-but-support-investing-in-it-after-learning-more

Friedlingstein, Pierre, Michael O'Sullivan, Matthew W. Jones, et al. 2026. "Global Carbon Budget 2025." Earth System Science Data 18: 3211–3288. DOI 10.5194/essd-18-3211-2026

Friedmann, S. Julio. 2019. "Engineered CO2 Removal, Climate Restoration, and Humility." Frontiers in Climate 1: 3. DOI 10.3389/fclim.2019.00003

Fritz, Livia, Lucilla Losi, Christine Merk, et al. 2026. "Public Support for Novel Carbon Removal Hinges on Procedural and Distributive Fairness." Nature Climate Change 16: 1152–1161. DOI 10.1038/s41558-026-02741-7

Frontier Climate. n.d. "Apply." Accessed October 24, 2026. https://frontierclimate.com/apply

Fuss, Sabine, Abby Lunstrum, Ruben Prütz, and Friedemann Gruner. 2026. "Costs and Potentials." Chap. 10 in The State of Carbon Dioxide Removal, 3rd ed., edited by Morgan R. Edwards et al. DOI 10.17605/OSF.IO/FBZ4X

Gidden, Matthew J., Joana Portugal-Pereira, Raphael Apeaning, et al. 2026. "Paris-Consistent CDR Scenarios." Chap. 8 in The State of Carbon Dioxide Removal, 3rd ed., edited by Morgan R. Edwards et al. DOI 10.17605/OSF.IO/JZDQM

Gonzalez-Coffin, Sarah, Shahzeen Z. Attari, Holly Buck, Amanda R. Carrico, Yoel Inbar, Ezra Markowitz, Kaitlin T. Raimi, Jonathon P. Schuldt, Trisha Shrum, and Leaf Van Boven. 2026. "Naturalness Catalyzes Public Support for Carbon Dioxide Removal and Low-Carbon Energy Technologies." Communications Earth & Environment. Published July 20. DOI 10.1038/s43247-026-03829-w

Hampson, Glenn. 2026a. "When 10 Gigatons Isn't Enough." Global CDR Action Network, August 15

Hampson, Glenn. 2026b. "Building Empires, Saving Cities." Global CDR Action Network, September 24

Hoffmann, Linn J., Lennart T. Bach, Kohen W. Bauer, et al. 2026. "Monitoring, Reporting, and Verification of Marine Carbon Dioxide Removal: Exploring Scientific Consensus and Divergences across Continents." Elementa: Science of the Anthropocene 14 (1): 00113. DOI 10.1525/elementa.2025.00113

Howard, Peter, and Derek Sylvan. 2024. Consensus on Carbon Dioxide Removal: A Large-Sample Expert Elicitation on the Future of CDR. New York: Institute for Policy Integrity, New York University School of Law. https://policyintegrity.org/files/publications/CDR_Consensus_Report.pdf

IEAGHG. 2021. Global Assessment of Direct Air Capture Costs. Technical Report 2021-05. Cheltenham: IEAGHG. https://ieaghg.org/publications/global-assessment-of-direct-air-capture-costs

International Energy Agency (IEA). 2024. Strategies for Affordable and Fair Clean Energy Transitions. Paris: IEA. https://www.iea.org/reports/strategies-for-affordable-and-fair-clean-energy-transitions

International Maritime Organization (IMO). n.d. "Marine Geoengineering." https://www.imo.org/en/mediacentre/hottopics/pages/marine-geoengineering.aspx

International Maritime Organization (IMO). 2026. "IMO Adopts Frameworks to Assess Marine Geoengineering Research Activities." October 9. https://www.imo.org/en/mediacentre/pressbriefings/pages/imo-adopts-marine-geoengineering-frameworks-for-research-activities.aspx

Intergovernmental Panel on Climate Change (IPCC). 2022. Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report. Cambridge: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3

Kahsar, Rudy, Daniel Pike, Gloria See, and Isabel Wood. 2023a. The Applied Innovation Roadmap for CDR. RMI. https://rmi.org/resources/the-applied-innovation-roadmap-for-cdr

Kahsar, Rudy, Daniel Pike, Isabel Wood, Silvan Aeschlimann, and Cara Maesano. 2023b. "Creating a Diversified Solutions Portfolio to Meet the Scale of the Carbon Removal Challenge." RMI, November 30. https://rmi.org/resources/creating-a-diversified-solutions-portfolio-to-meet-the-scale-of-the-carbon-removal-challenge

Kahsar, Rudy, Daniel Pike, Annina Sartor, Gloria See, and Isabel Wood. 2024. Scaling Technological Greenhouse Gas Removal: A Global Roadmap to 2050. RMI, in collaboration with the Bezos Earth Fund. https://rmi.org/resources/scaling-technological-greenhouse-gas-removal-a-global-roadmap-to-2050

Kahsar, Rudy, Annina Sartor, and Eli Weaver. 2026. The New Frontiers Report for CDR. RMI. https://rmi.org/resources/the-new-frontiers-report-for-cdr

Kudrnáč, Aleš, and Malcolm Fairbrother. 2025. "Perceived Costs and Benefits and Public Support for Climate Policies." npj Climate Action 4: 93. DOI 10.1038/s44168-025-00301-x

Lebling, Katie, Elina Brutschin, Oliver Geden, et al. 2026. "Policymaking and Governance." Chap. 5 in The State of Carbon Dioxide Removal, 3rd ed., edited by Morgan R. Edwards et al. DOI 10.17605/OSF.IO/62548

Mack, Connor, Ryan Hanna, Daniela Dias, and David G. Victor. 2025. "The Scalability and Carbon Removal Potential of Ocean Alkalinity Enhancement." Preprint, Research Square, December 1. DOI 10.21203/rs.3.rs-7956805/v1

McKinsey & Company. 2023. Carbon Removals: How to Scale a New Gigaton Industry. New York: McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/carbon-removals-how-to-scale-a-new-gigaton-industry

McKinsey & Company. 2024. Matching Durable Carbon Removal Supply and Demand by 2030. New York: McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/sustainability-blog/matching-durable-carbon-removals-supply-and-demand-by-2030

Moyer, Jonathan D., Barry B. Hughes, Mohammod Irfan, et al. 2026. "Broadly Quantifying SSP Elements for 188 Countries to 2150 in International Futures." Nature Communications 17: 7209. DOI 10.1038/s41467-026-73836-0

National Academies of Sciences, Engineering, and Medicine. 2022. A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration. Washington, DC: National Academies Press. https://www.nationalacademies.org/read/26278

National Aeronautics and Space Administration (NASA). 2026. "Wildfires and Climate Change." NASA Science. Last modified May 14. https://science.nasa.gov/earth/explore/wildfires-and-climate-change

National Oceanic and Atmospheric Administration (NOAA). 2023. Strategy for NOAA Carbon Dioxide Removal Research: A White Paper Documenting a Potential NOAA CDR Science Strategy as an Element of NOAA's Climate Interventions Portfolio. NOAA Special Report. Washington, DC: NOAA. DOI 10.25923/gzke-8730

Nemet, Gregory F., Morgan R. Edwards, Oliver Akeret, et al. 2026. "Demonstration and Upscaling." Chap. 3 in The State of Carbon Dioxide Removal, 3rd ed., edited by Morgan R. Edwards et al. DOI 10.17605/OSF.IO/82XV6

Neumann, Rebecca B. 2026. "How Carbon Dioxide Removal Lost Its Way: Tracing the Origin and Transformation of the 10-Gt Durable CDR Target." SSRN preprint, July 16. https://ssrn.com/abstract=7119306

Otto, Danny, Marit Sprenkeling, Ruben Peuchen, Åsta Dyrnes Nordø, Dimitrios Mendrinos, et al. 2022. "On the Organisation of Translation—An Inter- and Transdisciplinary Approach to Developing Design Options for CO2 Storage Monitoring Systems." Energies 15 (15): 5678. DOI 10.3390/en15155678

Our World in Data. 2026. "United States: CO2 and Greenhouse Gas Emissions Country Profile." https://ourworldindata.org/profile/co2/united-states

Pett-Ridge, Jennifer, et al. 2023. Roads to Removal: Options for Carbon Dioxide Removal in the United States. LLNL-TR-852901. Lawrence Livermore National Laboratory. DOI 10.2172/2301853

Ritchie, Hannah, and Pablo Rosado. 2025. "Global CO2 Emissions from Fossil Fuels Are Likely to Increase This Year, While Those from Land-Use Change Will Fall." Our World in Data, November 13. https://ourworldindata.org/data-insights/global-co2-emissions-from-fossil-fuels-are-likely-to-increase-this-year-while-those-from-land-use-change-will-fall

Scott-Buechler, Celina. 2026. "Removing Carbon, Governing Deployment: Public Perceptions of Industry and Community Roles in U.S. Carbon Dioxide Removal Policy." Climatic Change 179: 112. DOI 10.1007/s10584-026-04177-6

Sherman, Michael. 2024. Report on the Fiscal 2025 Preliminary Plan and the Fiscal 2024 Preliminary Mayor's Management Report for the Department of Transportation. New York: New York City Council Finance Division. https://council.nyc.gov/budget/wp-content/uploads/sites/54/2024/03/841-DOT.pdf

Smith, Stephen M., et al., eds. 2024. The State of Carbon Dioxide Removal. 2nd ed. DOI 10.17605/OSF.IO/F85QJ

Sovacool, Benjamin K., Darrick Evensen, Chad M. Baum, Livia Fritz, and Sean Low. 2024. "Demographics Shape Public Preferences for Carbon Dioxide Removal and Solar Geoengineering Interventions across 30 Countries." Communications Earth & Environment 5: 642. DOI 10.1038/s43247-024-01800-1

Swiss Re Institute. 2021. The Economics of Climate Change: No Action Not an Option. Zurich: Swiss Re Management Ltd. https://www.swissre.com/dam/jcr:5d558fa2-9c15-419d-8dce-73c080fca3ba/SRI_%20Expertise_Publication_EN_LITE_The%20economics_of_climate_change.pdf

Twidale, Susanna, and Simon Jessop. 2026. "Microsoft in Record Deal for Soil Carbon Credits as Data Centres Surge." Reuters, January 15. https://www.reuters.com/sustainability/climate-energy/microsoft-record-deal-soil-carbon-credits-data-centres-surge-2026-01-15

United Nations Environment Programme (UNEP). 2025. Emissions Gap Report 2025: Off Target—Continued Collective Inaction Puts Global Temperature Goal at Risk. Nairobi: UNEP. https://www.unep.org/en/publications/report/emissions-gap-report-2025

University of Oxford. 2024. The Oxford Principles for Net Zero Aligned Carbon Offsetting (Revised 2024). Oxford: Smith School of Enterprise and the Environment. https://www.smithschool.ox.ac.uk/sites/default/files/2024-02/Oxford-Principles-for-Net-Zero-Aligned-Carbon-Offsetting-revised-2024.pdf

U.S. Department of Energy. 2025. Carbon Negative Shot Strategy. Washington, DC: U.S. Department of Energy. https://www.energy.gov/hgeo/carbon-negative-shot-strategy

U.S. Government Accountability Office. 2026. Carbon Capture Tax Credit: Actions Needed to Improve Federal Administration and Evaluation of Tax Expenditure. GAO-26-107711, August 6. https://files.gao.gov/reports/GAO-26-107711/index.html

Vancouver Process. 2026. "Governments & CDR." Accessed October 26. https://vancouverprocess.org/governments-and-cdr

Waring, Bonnie, Mathias Neumann, Iain Colin Prentice, et al. 2020. "Forests and Decarbonization—Roles of Natural and Planted Forests." Frontiers in Forests and Global Change 3: 58. DOI 10.3389/ffgc.2020.00058

Wear, David N., and Matthew Wibbenmeyer. 2023. Prospects for Land Sector Carbon Dioxide Removal in the United States. Report 23-05. Washington, DC: Resources for the Future. https://www.rff.org/publications/reports/prospects-for-land-sector-carbon-dioxide-removal-in-the-united-states

World Data Lab. 2026. "Consumer Spending Categories." https://worlddatalab.com/categories

World Economic Forum. 2026. Carbon Dioxide Removal Technologies: Market Overview and Offtake. White paper in collaboration with Oliver Wyman and ClimeFi. Geneva: World Economic Forum, March 31. https://reports.weforum.org/docs/WEF_Carbon_Dioxide_Removal_Technologies_2026.pdf

World Resources Institute. n.d. "Direct Air Capture Measures in U.S. Climate Policy." U.S. Climate Policy Resource Center. Accessed October 24, 2026. https://www.wri.org/us-climate-policy-implementation/sectors/direct-air-capture

Zhu, Yuqi, and Aaron Bergman. 2025. Policies for Building the Technology Performance Insurance Market. Report 25-03. Washington, DC: Resources for the Future. https://www.rff.org/publications/reports/policies-for-building-the-technology-performance-insurance-market

SCI

CDRANet

VANCOUVER
PROCESS