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Scaling Technological Greenhouse Gas Removal: A Global Roadmap to 2050

Prepared by RMI | December 2024

Authors

This roadmap was developed through a collaboration between the Bezos Earth Fund and RMI. Following the announcement of the Bezos Earth Fund initiative on greenhouse gas removal and intent to accelerate technological removals towards scale via a global roadmap to guide future funding, the Bezos Earth Fund and RMI teams joined forces to design and publish the roadmap based on expert inputs from the February 2024 workshop hosted by the Earth Fund, U.S. Department of Energy, and Stanford University. In developing the roadmap, RMI initiated creation of the content and served as primary author, with the Bezos Earth Fund providing vision, shaping of content and analysis, and substantial editorial contributions, culminating in this joint effort.

RMI

Rudy Kahsar, Principal
Daniel Pike, Principal
Annina Sartor, Senior Associate
Gloria See, Senior Associate
Isabel Wood, Associate

Bezos Earth Fund

Noël Bakhtian,
Director of Technology Acceleration
(GHG Removal Initiative Lead)

Kelly Levin,
Chief of Science, Data and Systems Change
(GHG Removal Initiative Co-Lead)

Reviewers

Adina Abeles, Chan Zuckerberg Initiative
Brad Ack, Ocean Visions
Ramon Alatorre, 4 Corners Carbon Coalition
Jack Andreasen, Breakthrough Energy
Emily Averna, Bezos Earth Fund
Nikki Batchelor, XPRIZE
Paul Bodnar, Bezos Earth Fund
Tim Bushman, Carbon Removal Canada
Charithea Charalambous, RMI
Kyle Clark-Sutton, RMI
Gabrielle Dreyfus, Institute for Governance & Sustainable Development
Simon Freeman, Department of Energy — ARPA-E
Julio Friedmann, Carbon Direct Inc.
Susana Garcia, Heriot-Watt University
Maddie Hall, Living Carbon
Dave Hillyard, Carbon Technology Research Foundation
Jason Hochman, Direct Air Capture Coalition
Nicole Iseppi, Bezos Earth Fund
Andy Jarvis, Bezos Earth Fund
Marc von Keitz, Grantham Foundation
Anu Khan, Carbon180
Matt Kirley, RMI
Kelley Kizzier, Bezos Earth Fund
Charlotte Levy, Carbon180
Jack Lewnard, Department of Energy — ARPA-E
Cara Maesano, RMI
Arun Majumdar, Stanford University
Cecilia Martinez, Bezos Earth Fund
Jan Mazurek, ClimateWorks Foundation
Berta Moya, Carbonfuture
Sara Nawaz, American University — Institute for Responsible Carbon Removal
Meghana Palepu, Bezos Earth Fund
Aaran Patel, The Nand & Jeet Khemka Foundation
Lara Pierpoint, Prime Coalition — Trellis Climate
Erika Reinhardt, Spark Climate Solutions
Mitchell Rubin, Elemental Excelerator
Maki Tazawa, Grantham Foundation
Matt Villante, Pacific Northwest National Laboratory
Anya Waite, Ocean Frontier Institute / Dalhousie University
Frances Wang, Quadrature Climate Foundation
Eli Weaver, RMI
Lori Ziolkowski, National Science Foundation

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Contacts

GHGRemovalinitiative@bezosearthfund.org
GHGR@rmi.org

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Executive Summary

With our climate at a tipping point, technological greenhouse gas removals has emerged as a new frontier in the solution space. This report presents a roadmap of actions needed to scale greenhouse gas removal by 2050.

Greenhouse gas (GHG) emissions, predominantly from human activities such as the burning of fossil fuels and deforestation, have led to a host of environmental changes that threaten ecosystems, agriculture, water resources, and human health.[1] In the face of this challenge, the world has mobilized various emissions reduction strategies such as fossil fuel phaseout, the deployment of renewables, reducing deforestation, electrification of end uses, increases in energy efficiency, food system transformation, and industrial decarbonization. These efforts are critical to addressing climate change.

However, reducing emissions will not be enough. There is already a large volume of historical emissions in the atmosphere and oceans, and there are many ongoing emissions processes that will be difficult to fully abate. If the world is to constrain total atmospheric concentrations to levels that avoid the worst impacts to people and the planet (limiting long-term warming to 1.5°C), it will need to remove some of these emissions.[2] For these reasons, the Intergovernmental Panel on Climate Change stated in 2022 that carbon dioxide removal (CDR) — processes that ultimately remove carbon dioxide (CO_2) from the atmosphere — is unavoidable. Nature-based approaches have significant potential for removals, and in many scenarios they are expected to contribute significantly to the total amount of removals. However, the scale of the removal challenge will also require significant deployments of technological GHG removals, which are the focus of this roadmap. In addition, there are several other planet-warming gases that may also need to be removed.

There are two reasons this will be a major challenge:

1. **Technological greenhouse gas removal (GHGR) must achieve massive scale**: This roadmap establishes a scaling goal of 10 billion tons (gigatons) of technological carbon dioxide removal per year (10 Gt CO_2/y) by 2050 (see Section 4). This is larger by mass than any single current global commodity. For example, the entire global steel industry produces around 2 Gt/y of steel (see Figure 4).

2. **Technological GHGR must scale on a short time frame**: Past emissions have already put the world close to climatic tipping points, and future emissions may continue for decades despite efforts to decarbonize.[3] The need for scaled GHGR is therefore immediate and growing. To be on track for 10 Gt CO_2/y removed in 2050, this roadmap estimates that the world must achieve ~285 megatons of carbon dioxide per year (Mt CO_2/y) of removals in 2030 and ~4.5 Gt CO_2/y of removals in 2040, despite having removed less than 1 Mt CO_2/y in 2023 (4 orders of magnitude difference from 2023 to 2050).[4] Global scaling of new technologies often takes many decades, but this scaling must happen in 25 years without causing harm to communities. Furthermore, this roadmap includes goals for developing technologies to remove GHGs other than CO_2, and if these technologies prove viable, it may be necessary to deploy them on a short time frame as well.

This roadmap illuminates a path to achieving this ambitious but critical scaled deployment of greenhouse gas removal technologies. Meeting these goals will require a strategic path accounting for actions across many stakeholders, time-sensitive milestones, and complex interdependencies of deliverables. The objective of the roadmap is to work backward from the 2050 goals, to ensure a set of timed actions including urgent near-term deadlines, such that there is no "overshoot" with 2050 arriving without the necessary scaled removals in place. This document sets clear goals, outlines a path to achieving them, and serves to catalyze rapid action to enable success.

In addition to scaling and doing so quickly, the roadmap emphasizes the importance of prioritizing community and justice aspects of GHGR. Because GHGR is a new field, it has an opportunity to develop and deploy in a just way from the start. An emphasis of this roadmap is to set an example for the future of GHGR from the beginning so that the field can scale in a just and responsible manner.

This roadmap is a tool for aligning actions and investments across sectors and stakeholders. Accomplishing something of this magnitude will require buy-in, commitments, and execution from actors across the GHGR ecosystem. This includes government actors at all levels, funders, GHGR communities, industry, researchers, journalists and media, and nonprofits and civil society organizations.

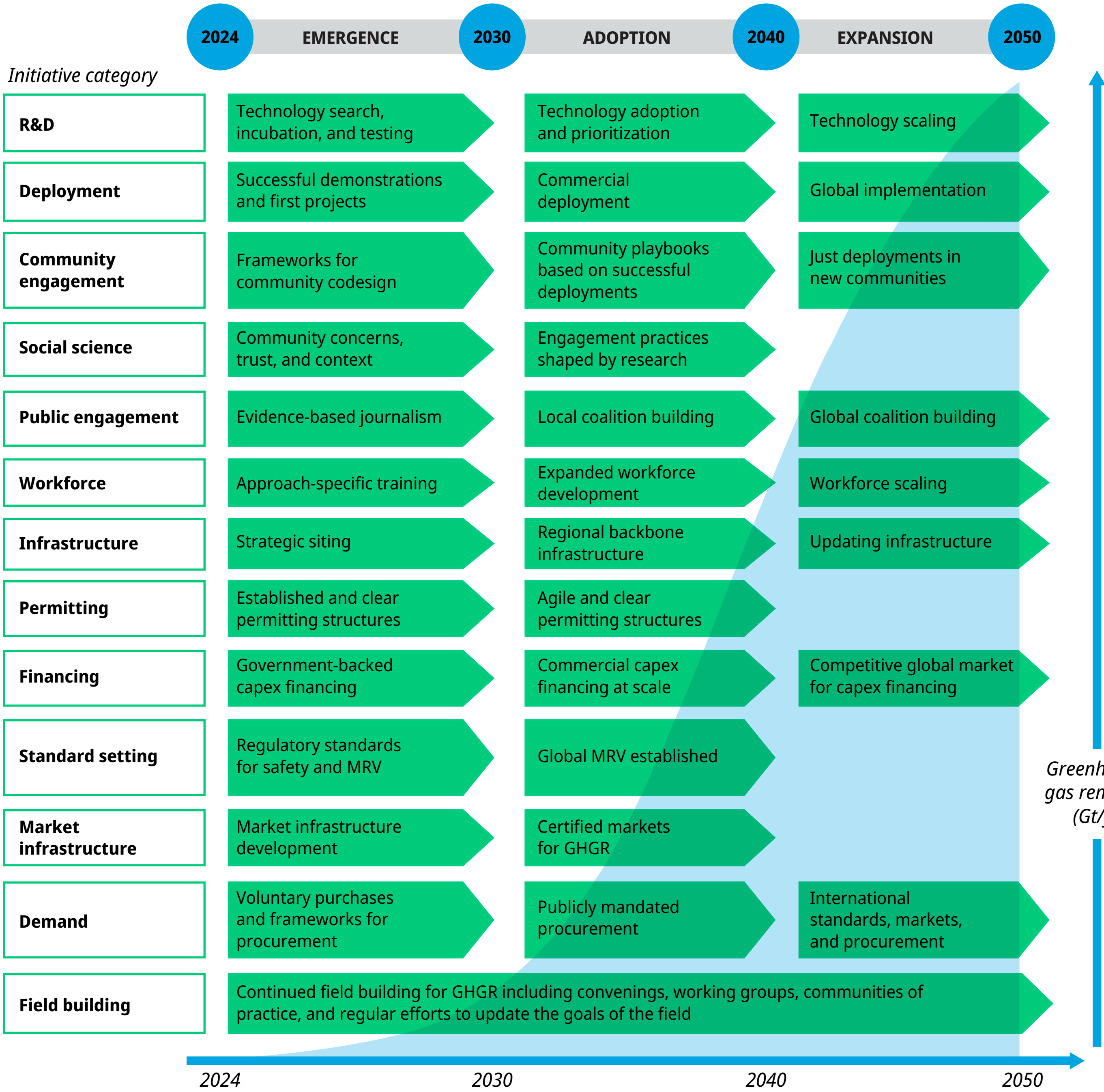
The roadmap is also a new addition to the already rich and burgeoning GHGR conversation because it is the first time a GHGR roadmap has taken a global, systems view to what is needed and included specific goals for both technological CDR and non-CO_2 gases in the years to 2050.

Box 1
How this roadmap is different

- It is global, rather than national or regional.
- It is inclusive of the broad range of stakeholders and actions required, including socio-behavioral and communities, finance and markets, and policy and regulation, alongside science and technical areas.
- It includes methane and nitrous oxide removal, in addition to carbon dioxide removal.
- It focuses on technological, rather than nature-based, GHGR.
- It excludes approaches that reduce emissions.
- It sets a specific goal for CDR in 2050.

The path forward is shared through multiple perspectives across this roadmap. There are sections on thematic areas for stakeholder engagement (Section 6) that describe how various stakeholders can get involved. There are also technology roadmap initiatives (Section 7) for describing what is needed in different technical areas. And, at the highest level, Section 8 tells a story of what actions are required to achieve the overall goals of the roadmap. It is a timeline view of the roadmap content, and it is described through three decadal periods. Simplified versions of the roadmap initiatives of these decadal periods are shown in Figure 1.

Figure 1 Roadmap for scaling technological greenhouse gas removal by 2050 (abridged)



Initiative category	EMERGENCE	ADOPTION	EXPANSION
R&D	Technology search, incubation, and testing	Technology adoption and prioritization	Technology scaling
Deployment	Successful demonstrations and first projects	Commercial deployment	Global implementation
Community engagement	Frameworks for community codesign	Community playbooks based on successful deployments	Just deployments in new communities
Social science	Community concerns, trust, and context	Engagement practices shaped by research	
Public engagement	Evidence-based journalism	Local coalition building	Global coalition building
Workforce	Approach-specific training	Expanded workforce development	Workforce scaling
Infrastructure	Strategic siting	Regional backbone infrastructure	Updating infrastructure
Permitting	Established and clear permitting structures	Agile and clear permitting structures	
Financing	Government-backed capex financing	Commercial capex financing at scale	Competitive global market for capex financing
Standard setting	Regulatory standards for safety and MRV	Global MRV established	
Market infrastructure	Market infrastructure development	Certified markets for GHGR	
Demand	Voluntary purchases and frameworks for procurement	Publicly mandated procurement	International standards, markets, and procurement
Field building	Continued field building for GHGR including convenings, working groups, communities of practice, and regular efforts to update the goals of the field		

Source: Author analysis. See Section 8 for more details on specific decadal initiatives. See figure notes in *Appendix C*.

The first decadal period, from 2024 to 2030, must enable the emergence of GHGR and lay a foundation on which a larger GHGR industry can be built and scaled. The roadmap goals will be met only if this first decadal period is a success, and as a result the roadmap initiatives of this decadal period must be considered of high urgency and begin immediately. Research and development will be needed to advance individual technologies, assess the safety of GHGR approaches with respect to environmental and public health, advance many types of CDR, and accelerate the basic science of non-CO_2 GHGR. First projects and demonstrations during this period will set the tone for future deployments and should seek community codesign and active workforce development. Additional activities will be necessary to inform clear permitting structures, validate safety, and establish market infrastructure. To be on track for 10 Gt CO_2/y by 2050, CDR must scale to ~285 Mt CO_2/y by 2030.

The second period, from 2030 to 2040, must then enable the widespread adoption of GHGR as it becomes a global, gigaton-scale industry. Technological GHGR must converge toward a portfolio of the lowest-cost, scalable, community oriented approaches, and these deployments must be accompanied by establishment of global measurement, reporting, and verification; local coalition building; workforce development; the build-out of backbone infrastructure; mobilization of supply chains; evolving and expanding permitting structures; and certification markets for GHGR. And, given that GHGR does not have a natural market of its own, this scale of deployment will be possible only with the establishment of stable, scaled demand through policy. Publicly mandated procurement, created through policy instruments such as compliance markets, tax incentives, pay for practice, and regulatory measures, must provide demand for at least ~4.5 Gt CO_2/y by 2040 to keep growth on track for the 2050 goal.

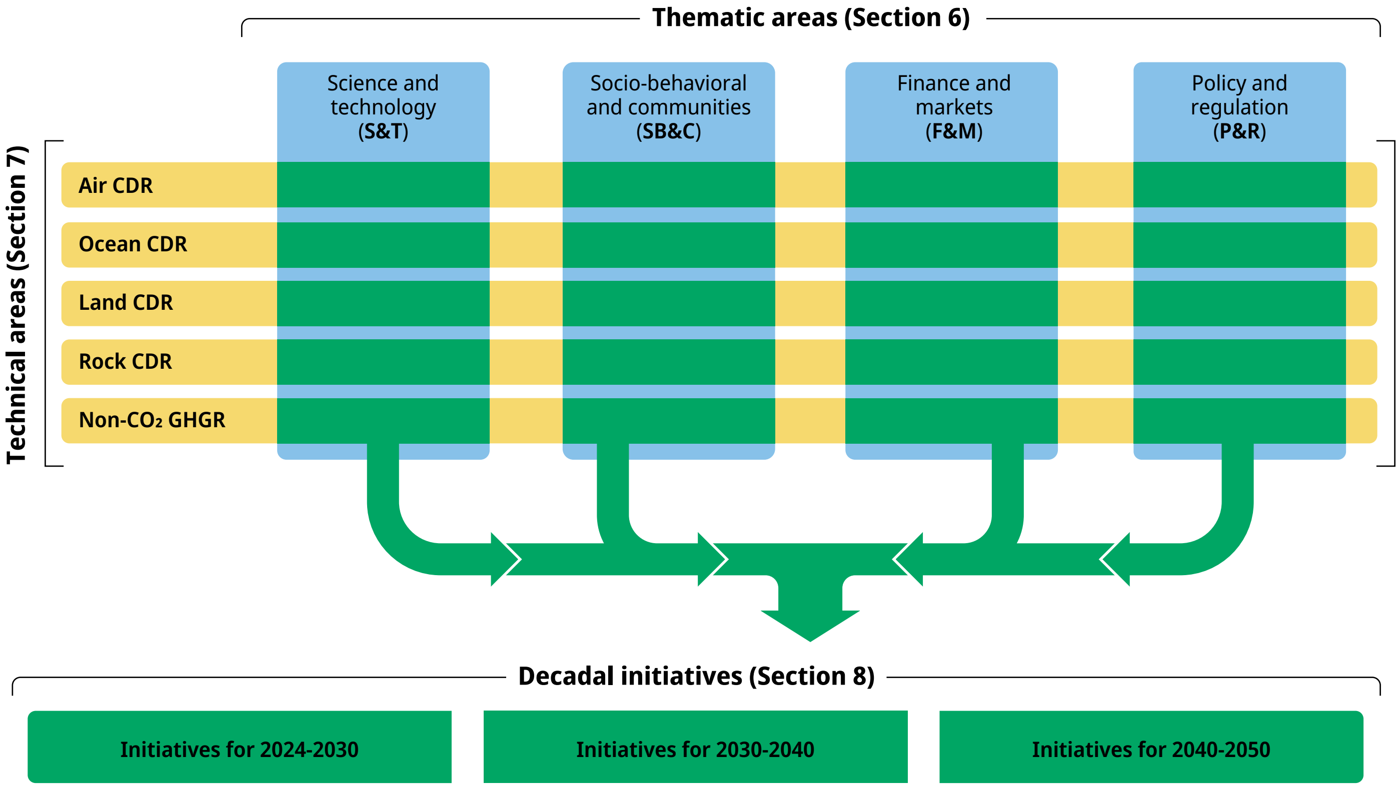
The final period, from 2040 to 2050, is characterized by the expansion of GHGR. To reach the goal of 10 Gt CO_2/y by 2050, it will be necessary to add between 500 and 800 Mt CO_2/y of additional capacity each year. This sustained expansion will test the limits of planetary resource constraints such as the availability of sustainable biomass, alkaline minerals, and low-carbon energy. It will require technology scaling, scaled manufacturing, global deployment, global coalition building, and international standards, markets, and procurement. To be a viable solution to protect ecosystems, GHGR will need to protect natural assets and be integrated into decarbonized industrial systems and infrastructures in a way that is as efficient and inconspicuous as possible. Ideally by 2050, GHGR will run efficiently around us, as a quiet background function of our lives, like a well-run utility.

Sections 1 to 5 provide the backdrop for the roadmap, outlining the need for GHGR, describing the scope of GHGR technology covered in this roadmap, setting goals for GHGR to 2050, framing the GHGR scaling challenge, and describing the roadmap methodology. Sections 6–8 are the core roadmap content, and the initiatives in these sections are meant to overlap and reinforce each other. Section 6 provides an assessment of what is most needed across four thematic areas: (1) science and technology, (2) socio-behavioral and communities, (3) finance and markets, and (4) policy and regulation. Section 7 provides 51 technology-specific initiatives for advancing technological GHGR (e.g. rock CDR, ocean CDR, etc.). Section 8 unifies the preceding sections into a sequence of decadal activities for achieving GHGR goals in the years leading to 2050. Finally, Section 9 addresses uncertainties facing GHGR scale-up.

As shown in Figure 2, the roadmap is constructed as a highly cross-linked document. Technical areas and thematic areas overlap in various ways, and the roadmap includes guideposts so the reader can follow different threads through the various sections. All GHGR stakeholders are encouraged to explore the intersection of different areas of the roadmap, including in areas beyond their expertise, and to seek collaborative opportunities where possible.

Figure 2 Crosslinking of the core roadmap content in sections 6–8

These sections reference each other and are meant to reinforce each other.



Source: Author analysis.

This roadmap articulates key goals, areas of opportunity, and a path for action. It is a call to all stakeholders to step up, to innovate, to mobilize resources, and to cooperate on the many areas where collaboration and collective action are needed. The challenge of scaling GHGR on a short timeline is daunting, but with deliberate, coordinated effort, it will be possible to ensure that GHGR is ready to play its role in combating climate change and securing a thriving future for people and the planet.

Key Terms in the GHGR Roadmap

Terms related to roadmap path

Action: A specific activity undertaken to complete a GHGR roadmap initiative.
Checkpoint: A milestone that does not include a decision.
Decision point: A milestone that includes a decision.
Initiative: The assembly of an action, target, and milestone with the purpose of advancing GHGR to a target of 10 Gt CO_2/y of removals by 2050.
Milestone: Point in time at which an action is assessed against its targets.
Near-term action: A specific activity that can begin between 2024 and 2030.
Target: The metric against which an activity is measured.

Terms related to roadmap inputs

Barrier: A source of resistance to scaling GHGR.
Dependency: The start of one roadmap initiative requiring the completion of another.
Enabler: An accelerant to scaling GHGR.
Open question: An area of significant uncertainty where more information is needed.
Risk: The potential for danger, harm, loss, or failure.
Unintended consequence: Potential environmental, social, economic, or other impacts of a roadmap initiative that are unanticipated or outside the project's intended scope.

Terms related to technology scale-up

Adoption readiness level: A framework for representing the readiness of a technology to be adopted by an ecosystem.[5]
Applied research: Scientific research oriented toward identifying practical solutions to specific problems.
Basic research: Scientific research that aims to improve scientific theories and understand natural phenomena. For the purposes of this roadmap, this should be use-inspired basic research for GHGR.
Commercial deployment: A deployment of a GHGR approach that is fully functional in the market.
Compliance markets: Marketplaces where regulated entities can obtain and surrender emissions permits or offsets to meet predetermined regulatory targets.
Demonstration: A deployment of a GHGR approach at sufficient size for testing that approach's performance, impacts, or benefits under commercial conditions.
Field trial: A test of a GHGR approach under controlled or temporary conditions, taking place in the field as opposed to the lab. This is different from a pilot because it is focused on experimentation rather than validation.
Gigaton: Refers to 1 billion metric tons.
Industrial integration: Deployment of a GHGR technology within the value chains and operations of other industries.
Measurement, reporting, and verification (MRV): Includes (1) the measurement and monitoring of GHGR outcomes from discrete projects; (2) compiling and reporting that information to a relevant third-party system, program, or body; and (3) subjecting the reported data to a review and verification process.[6]
Pilot: A GHGR system that may be structured in a way that is pre-commercial or not under fully commercial conditions that is meant to test an approach at an intermediate stage between laboratory experiment and demonstration-scale operation.

Technical readiness level (TRL): A framework for representing the maturity of a technology on the path to commercial readiness, ranging from 1 (lowest) to 9 (highest).[i]
Voluntary markets: Marketplaces in which buyers voluntarily purchase and trade in credits generated from emissions reduction or removal projects.

Terms related to responsible and just GHGR deployment

Alternative ownership models: GHGR deployments that utilize innovative ownership schemes, such as those that are nongovernmental organization, municipality, community, or publicly owned, in part or in full.
Co-benefits: Economic, social, or environmental benefits from GHGR deployment that are beyond the primary benefit of removing greenhouse gases from the atmosphere and oceans.
Community engagement: Activities and methods in which communities that may be impacted by GHGR deployment are engaged through project planning, design, development, execution, and monitoring.
Disinformation: Information that is deliberately intended to mislead.[7]
Environmental justice pillars:[ii]

> **Procedural justice:** Actions that ensure participation and equitable inclusion in decision making processes for all impacted stakeholders.
> **Distributional justice:** Actions that lead to more equitable outcomes pertaining to benefits, risks, and other impacts across communities.
> **Restorative justice:** Actions and resource distribution that acknowledge, address, and remediate past harms or injustices.
> **Transformative justice:** Actions that spur changes in current social structures and systems to create a more equitable and just society.

GHGR communities: Communities that might host GHGR research and deployment activities in the future and/or could be impacted by the externalities of GHGR activities, whether geographically close to a project or not, especially those that have been overburdened in the past by economic or infrastructural development projects.
Misinformation: False or inaccurate information.[8]
Place-based: Term used to describe engagement and deployment processes that are tailored to the social, cultural, political, and economic qualities of geographic area.
Public engagement: Refers more broadly to engaging the general public, not only communities that are directly impacted by deployment.
Vulnerable populations: Groups of people who are more at risk of the impacts of climate change because of social, environmental, political, and economic factors such as poverty, race, ethnicity, age, gender, disability, and lack of healthcare, education, or a safe built environment.[9] The United Nations further outlines examples of vulnerable populations globally.[10] There are multiple sub-definitions of vulnerable populations that deserve consideration depending on the social context of a GHGR project.

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[i] TRLs are based on two well-established scales. The U.S. Department of Energy's **Technology Readiness Level scale**, which ranges from 1 to 9, and the U.S. Department of Energy's **technology risk scale,** which includes both technology readiness levels and market readiness levels. On this scale, TRL 6 refers to pilot-scale validation, TRL 7–8 to demonstration-scale deployment, and TRL 9+ to commercial-scale deployment. For more information on TRLs, see ***The Applied Innovation Roadmap for CDR*** (RMI, 2023, pp. 379, 387–390).

[ii] Based on energy justice definitions in M. Lacey-Barnacle, R. Robinson, and C. Foulds ("Energy Justice in the Developing World: A Review of Theoretical Frameworks, Key Research Themes and Policy Implication," ***Energy for Sustainable Development*** 55 [April 2020]: 122–138); and ***From the Ground Up***, XPRIZE and Carbon180, 2023.

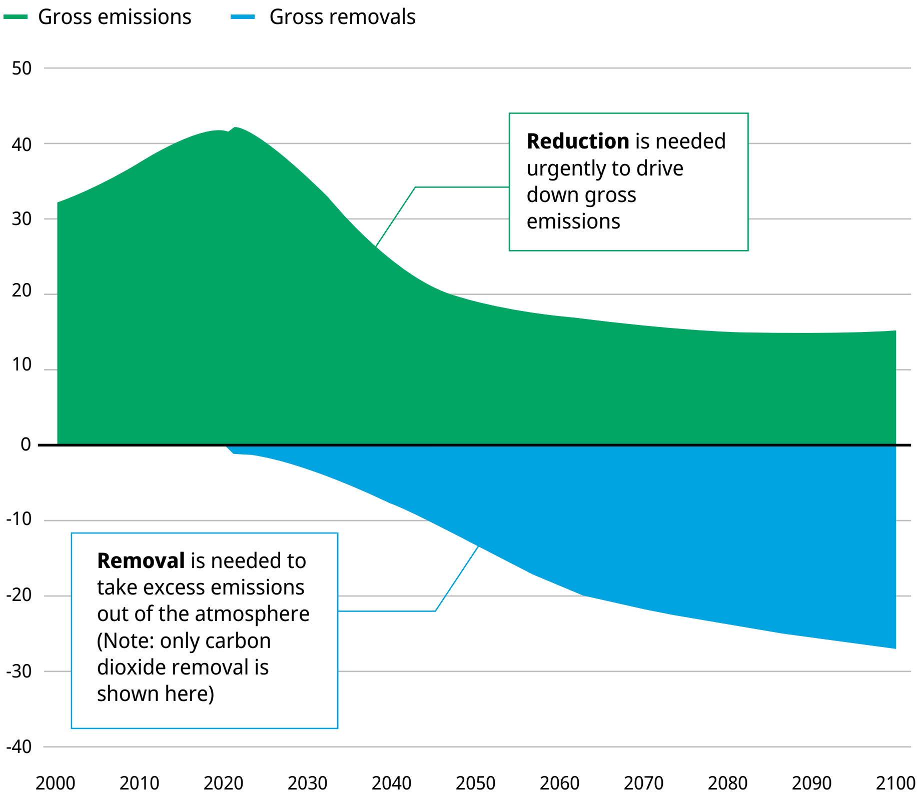
1. The Need for Greenhouse Gas Removal

In the past few hundred years, human activities, particularly the burning of fossil fuels and deforestation, have disrupted Earth systems by emitting greenhouse gases (GHGs) that are now accumulating in the oceans and the atmosphere. These gases trap heat, causing global temperatures to rise and triggering a cascade of other negative impacts such as extinctions, coral bleaching, melting ice, droughts, deadly storms, and wildfires.[11]

To mitigate global warming and the resulting impacts, the world has mobilized various efforts to reduce GHG emissions, including fossil fuel phaseout, the deployment of renewable energy generation, reducing emissions from agriculture and food, reducing deforestation, electrification of energy end uses, increases in energy efficiency, and decarbonization of industry. These efforts must remain the top priority for achieving long-term climate goals because achieving them will be possible only if there is a significant and rapid reduction of emissions as shown in Figure 3.

Figure 3 Removal of greenhouse gases is critical to achieving long-term climate goals

Emissions and removals of carbon dioxide (Gt CO_2/y)



CRITICAL BUT OUT OF SCOPE FOR THIS REPORT

Reduction includes strategies such as:

- Fossil fuel phaseout
- Deployment of renewable energy generation
- Reducing emissions from agriculture and food
- Reducing deforestation
- Electrification of energy end uses
- Increases in energy efficiency
- Industrial decarbonization

FOCUS OF THIS REPORT

GHG Removal (GHGR), which includes:

- Carbon dioxide removal (CDR)
- Methane removal, nitrous oxide removal, and any other non-CO_2 GHG removal

Source: Author analysis, based on data from International Institute for Applied Systems Analysis and **Integrated Assessment Modeling Consortium**. See figure notes in ***Appendix C***.

However, reductions of emissions will not suffice. Many industries are expected to produce residual emissions that will be difficult or expensive to abate, and these abatement activities might not be completed as quickly as needed. Furthermore, the air and oceans are already filled with excess legacy emissions that will continue to drive warming, even if future emissions are eliminated. As such, it will be necessary to ultimately remove GHG emissions from the atmosphere at scale, with approaches that are collectively referred to as GHG removal (GHGR).

The primary form of GHGR is carbon dioxide removal (CDR), which, as its name suggests, includes approaches for removing carbon dioxide (CO_2) from the air and oceans after it has already been emitted. CDR includes processes that take advantage of natural systems such as growing plants and then sequestering their biomass as well as approaches that make use of large industrial facilities such as direct air capture (DAC).

Most GHGR attention is currently focused on CDR, but there are other GHGs such as methane (CH_4) and nitrous oxide (N_2O) that also contribute to global warming and might also be removed with GHGR. The concentrations of these gases in the atmosphere are rising and the warming potentials are 27–30x (methane) and 270x (nitrous oxide) more potent than CO_2 over a 100-year period.[iii] As a result, the Intergovernmental Panel on Climate Change (IPCC) estimates that these two gases have contributed an additional 0.5°C (methane) and 0.1°C (nitrous oxide) to global warming to date.[12] Furthermore, as the climate continues to change, tipping points may accelerate the natural release of these gases.[13] For these reasons, removing these gases may also be an important part of a climate strategy.[iv] They are included in this roadmap under the category of non-CO_2 GHGR.

[iii] Warming potentials are a measure of the climate forcing of one unit mass of GHG. They are a combination of the ability of a gas to absorb energy (their radiative efficiency) and how long they stay in the atmosphere (also known as their lifetime) ("**Understanding Global Warming Potentials**," U.S. Environmental Protection Agency, accessed July 2024).

[iv] The scientific basis for the removal of these non-CO_2 gases is still very early stage, and it is not yet clear whether it is possible or desirable to remove them. For these reasons, the IPCC has not published scenarios that include the removal of these gases, and this roadmap sets goals intended to better understand the potential for non-CO_2 removals.

2. Scope of GHGR Technology Covered in This Roadmap

According to *The State of Carbon Dioxide Removal* report, the majority of GHGR currently being deployed around the world is nature-based CDR approaches.[v] These approaches have significant potential for removals, and in many scenarios they are expected to contribute significantly to the total amount of removals. However, the scale of the removal challenge will require us to supplement those approaches significantly with the deployment of technological GHGR removals, which are the focus of this roadmap.[vi]

Figure 4 Scope of GHGR technology approaches included in this roadmap

Approaches in blue belong in more than one category; they are **bolded** in their primary categories

SCOPE	CDR: Air[1]	CDR: Ocean[2]	CDR: Land[3]	CDR: Rock[4]	Non-CO_2 GHGR
In scope	• Direct air capture (DAC) • **Electrochemical CO_2 removal[10]**	• Nutrient fertilization for open ocean microalgae • Open ocean macroalgae • Coastal enhanced weathering • Electrochemical CO_2 removal • Microalgae in ponds • **Ocean alkalinity enhancement** *Alkalinity can also be added to rivers and inland waterways.*	• Bioenergy with carbon capture and sequestration (BECCS) • Biochar • Biomass direct storage[6] • Bio-oil • Other biomass building products • Technical breakthroughs for living biomass[7] • Timber building products[8] • Electrochemical CO_2 removal • **Microalgae in ponds** • Terrestrial enhanced weathering (TEW)	• Ex-situ mineralization[5] • In-situ mineralization[5] • Surficial mineralization • Synthetic storage in building materials[5] • **Coastal enhanced weathering** • Electrochemical CO_2 removal • Ocean alkalinity enhancement (OAE) • **Terrestrial enhanced weathering**	• Atmospheric methane removal • Atmospheric N_2O removal
Out of scope	• Point source carbon capture and sequestration (CCS)		• Living biomass approaches such as the management, conservation, and restoration of forests, agricultural and grazing lands, wetlands, mangroves, and peatlands[9]	• Conventional CO_2 storage	• Point source CH_4 removal • Point source N_2O removal

Source: Author analysis. Superscripts are described in the figure notes in *Appendix C*.

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[v] *The State of Carbon Dioxide Removal*, 2nd ed., University of Oxford Smith School of Enterprise and the Environment, 2024. This report refers to "nature based solutions" as "conventional CDR."

[vi] Note that there are also hybrid approaches that combine nature-based and technological GHGR.

The full list of technological GHGR approaches considered in scope is shown in Figure 4, where they are grouped into four CDR technology areas (CDR using air, ocean, land, and rock methods) plus a fifth category for non-CO_2 GHGR.[vii] For the purposes of this roadmap, the definitions of these approaches are as follows:

- **Air CDR** includes all technological CDR approaches that directly extract CO_2 from the atmosphere using a machine-based filtering process and then concentrate that CO_2 to be stored.
- **Ocean CDR** refers to any technological CDR approaches that take place in aquatic environments. This includes open-system approaches such as growing macroalgae (e.g., kelp) or cultivating microalgae in open water and sinking it, adding alkaline materials to water to reduce acidity and increase ocean capacity for CO_2 absorption from the atmosphere (an approach referred to as ocean alkalinity enhancement [OAE]), and approaches that use electricity to remove CO_2 directly from water, sometimes in conjunction with wastewater treatment or desalination facilities (referred to as indirect water capture [IWC]).
- **Land CDR** refers to technological CDR approaches that remove CO_2 through photosynthetic biomass production and then process that biomass to durably store the removed carbon. This includes approaches that process photosynthetic biomass into more stable forms such as bio-oil, biochar, or biomass construction materials. It also includes activities that convert photosynthetic biomass into CO_2 and then store that CO_2, including bioenergy with carbon capture and sequestration (BECCS). Land CDR also includes activities such as synthetic biology that enhance the plants themselves by making them grow faster, store more carbon, resist pests and pathogens, and exhibit increased durability.
- **Rock CDR** includes all technological CDR approaches that remove CO_2 from the atmosphere by reacting it with alkaline minerals. These approaches typically seek to accelerate naturally occurring reactions of certain types of rock, such as basalt or other alkaline materials, to form either solid carbonate minerals or dissolved bicarbonates. In a simplistic way, one type of rock is reacted with CO_2 to form another type of rock or dissolved mineral.
- **Non-CO_2 GHGR** is used to describe the atmospheric removal of methane and nitrous oxide.

These in-scope approaches are discussed across the roadmap, and initiatives related to their development are included in Section 7.

In addition to excluding nature-based GHGR solutions, qualities that make an approach out of scope for the purposes of this roadmap include activities that either offer insufficient durability, reduce rather than remove GHGs, or entail the removal of GHGs other than carbon dioxide, methane, or nitrous oxide. Each of these exclusions are discussed here in turn. Furthermore, storage and transportation are considered out of scope for the purposes of this roadmap.

Durability

Durability of technological GHGR is used to define the degree to which GHGs are permanently removed from the environment and securely stored with high confidence that they will not be rereleased. DAC with carbon storage (DACS) is an example of a high-durability approach for CDR. DAC captures CO_2 from the atmosphere and carbon storage sequesters it in geologic reservoirs, where it is expected to remain for thousands of years.

[vii] Note that the rock, ocean, land, and air taxonomy in this roadmap is based on the XPRIZE taxonomy. This XPRIZE taxonomy is not an exhaustive accounting of all possible CDR approaches. Additionally, some approaches specified here span several of the taxonomic categories ("**$100M Prize for Carbon Removal**," XPRIZE, accessed July 2024).

By contrast, living biomass or nature-based approaches such as the management, conservation, and restoration of forests, agriculture, grazing lands, wetlands, mangroves, and peatlands can be less stable. Many of these approaches can be prone to reversals, the rerelease of captured CO_2 into the environment, which can happen through natural disasters such as fires, or through human-induced changes such as deforestation.[14] Similarly, some forms of biochar and other land CDR approaches may be susceptible to rereleasing their stored carbon simply through natural decomposition.[15] Although these nature-based solutions might be an important part of the long-term removals portfolio, they are considered out of scope for this roadmap. However, this roadmap does include living biomass solutions when they include technological modifications such as cultivars with enhanced durability.

Although there is not yet a clearly agreed definition of durability,[viii] several organizations including the U.S. Department of Energy, RMI, and the crediting organization puro.earth believe the distinction between CDR methods that remove carbon for 100 years and those that do not is useful and meaningful.[16] Similarly, this roadmap assumes a durability of 100 years and focuses on technical CDR approaches as outlined in Figure 3.

Removal vs. Reduction

The second determinant of what counts as in scope as a form of GHGR covered in this roadmap is whether an approach provides reductions or removals. This roadmap is limited to the *removal* of GHGs from the atmosphere and oceans. As such, the roadmap excludes activities that capture GHGs from point sources because these activities are considered reduction and not removal. An example of an excluded activity is carbon capture and sequestration (CCS) on a fossil energy power plant. The reason for this exclusion from this roadmap is that capturing carbon from a fossil energy plant simply prevents new GHGs from entering the atmosphere; it does not draw down any volume of gases that are already in it.[ix] Similarly, this roadmap excludes methane abatement activities such as flaring because these are techniques that reduce methane emissions rather than remove them. Finally, this roadmap also does not include solar radiation management (SRM) because these techniques are intended to cool the Earth without removing GHGs.

Types of Gases Included

The final determinant of the scope of GHGR covered in this roadmap is in the types of GHGs that are considered for removal. The IPCC includes several categories of greenhouse gases that are reported under the common reporting format of the United Nations Framework Convention on Climate Change.[x] Most of these gases are present only in small concentrations in the atmosphere, but many of them have high warming potentials.[xi]

The two non-CO_2 gases with the most significant combination of warming potentials and atmospheric concentrations are methane and nitrous oxide. These gases are much different from CO_2, and therefore removing them requires a different set of approaches. In particular, they have different residence times, come from different sources, and are more reactive

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viii The *State of Carbon Dioxide Removal* notes that there is currently not a clearly agreed definition of durability. This roadmap includes several initiatives for setting international standards on durability including 1.11 and 2.10.

ix BECCS might be considered an exception. BECCS works by converting biomass into CO_2 and then sequestering it. This is considered in scope for the roadmap because the biomass is assumed to have removed CO_2 from the environment during its growth.

x These include CO_2 from fossil fuel combustion and industrial processes; net CO_2 emissions from land use, land-use change, and forestry; methane; nitrous oxide; and fluorinated gases comprising hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, as well as nitrogen trifluoride (***Climate Change 2022: Mitigation of Climate Change: Summary for Policymakers***, IPCC, 2022). According to the U.S. Environmental Protection Agency, there are 10 major GHGs including CO_2 ("**Overview of Greenhouse Gases**").

xi Warming potentials are a measure of the climate forcing of one unit mass of GHG. They are a combination of the ability of a gas to absorb energy (their radiative efficiency) and how long they stay in the atmosphere (also known as their lifetime) ("**Understanding Global Warming Potentials**," U.S. Environmental Protection Agency, accessed July 2024).

in the atmosphere, interacting with other gases in ways that are not fully understood. Because of these differences, it is still unclear whether it is possible to remove them. However, because their contribution to global warming is significant and growing, it may be desirable to remove them, if possible. This roadmap therefore includes methane and nitrous oxide removal and combines them in a category called non-CO_2 GHGR removal that is focused on advancing the science in order to determine their future potential for removals at scale.[xii] Removal approaches have not yet been proposed for other non-CO_2 GHGs, and therefore no other types of GHGR are included in this roadmap.

Box 2

Important ways in which non–CO_2 GHGR (methane and nitrous oxide removal) differs from CDR

1. **Potency:** Methane is 120x and nitrous oxide is 273x more potent than CO_2 on release.
2. **Concentrations:** Methane and nitrous oxide are respectively 200x and 1,200x less concentrated than CO_2 in the atmosphere.
3. **Residence time:** Methane and nitrous oxide have an average atmospheric life of 12 and 110 years, respectively.
4. **Sources:** There are direct releases, for example, from oil and gas or farming operations, as well as indirect releases, for example, of methane from wetlands and permafrost.
5. **Complexity:** Sources and sinks of methane and nitrous oxide are connected. These gases also interact with other GHGs in the atmosphere.
6. **Technological maturity:** CDR includes approaches with medium to high technical readiness level (TRL), whereas non-CO_2 GHGR approaches are at TRL 2 or below.
7. **Approach:** Whereas CDR removes CO_2 from the atmosphere, non-CO_2 GHGR typically seeks to convert the non-CO_2 gas into a molecule with lower warming potential, such as the oxidation of methane to CO_2.

These differences are described in more detail in Section 7.5.

[xii] Also in scope are non-CO_2 removals that convert GHGs into other gases with lower warming potentials. For example, rather than capturing methane gas from the atmosphere, it may be more effective to react that methane into other gases such as CO_2. Although CO_2 still has a warming potential, it is significantly lower than methane's, making this a valuable conversion (Nisbet-Jones, "**Is the destruction or removal of atmospheric methane a worthwhile option?**" 2021).

3. Goal Setting for GHGR

In order to create a path to the removals needed in 2050, it is necessary to set a goal, which is the intent of this section. In its *Sixth Assessment Report* (AR6), the IPCC stated that CDR is "unavoidable" if the world is to constrain total atmospheric CO_2 concentrations to levels that limit long-term global warming to 1.5°C and noted that 400–1,400 gigatons (Gt) CO_2 will need to be cumulatively removed by 2100.[17] The first edition of *The State of Carbon Dioxide Removal* used the same IPCC scenarios to refine that estimate to 590–1,300 Gt CO_2 by 2100.[xiii]

In the context of the AR6, these cumulative removal values are helpful for characterizing the scale of the challenge. However, to motivate the immediate action necessary to provide this scale of removal, the field of GHGR and its stakeholders need goals that come due much sooner than 2100 as well as a credible path to meeting those goals. What is needed is a roadmap. By providing a clear destination, a roadmap can enable relevant stakeholders to align their efforts, investments, and resources toward the most impactful solutions. Moreover, a well-defined roadmap can foster innovation and collaboration along the way by identifying research gaps, technical barriers, and policy needs.

Establishing specific goals is a difficult challenge for any type of strategy setting, which requires balancing ambition with practical limitations while also ensuring that the activities will deliver the intended product on time. CDR is still a relatively young field; however, it is well enough established and understood that it has been included by climate modelers in energy and climate systems models, including those that inform the IPCC, for more than 10 years. This makes it possible to define targets for its deployment.

By contrast, non-CO_2 GHGR is still in the very early stages of technical development, and it is not clear whether it is possible or desirable to deploy it. As a result, climate scenarios have not yet specified non-CO_2 removal deployment targets. For these reasons, this roadmap also refrains from setting non-CO_2 GHGR deployment targets.

Because of these critical differences between CDR and non-CO_2 GHGR, it is desirable to set different goals for these two gases: a deployment goal for CDR and a development goal for non-CO_2 GHGR.

Box 3
Roadmap goals for technological GHGR

1. **CDR:** Reach 10 Gt CO_2/y of durable technological removals by 2050.
2. **Non-CO_2 GHGR:** Advance the science of non-CO_2 removal such that decisions can be made by the early 2030s about future development and deployment.

Note: These goals may change as the science of GHGR advances, as energy and climate scenarios evolve, and as more information becomes available.

The goal for non-CO_2 GHGR is to advance the basic science to a point where the world has a better understanding of which processes are technically feasible, which approaches can be deployed safely, and what role, if any, removals of these gases should play in the overall portfolio of climate solutions. In short, the goal is to accelerate the technical understanding of these gases so that decisions can be made as to whether they can and should be deployed, and the

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[xiii] *The State of Carbon Dioxide Removal*, 1st ed., 2022. Numbers cited here are for IPCC AR6 C2 scenarios, those that limit warming to 1.5°C with overshoot. Note that models and scenarios assessed by the IPCC also do not consider changes in natural emissions of methane (e.g., Thomas Kleinen et al., "**Atmospheric Methane Underestimated in Future Climate Projections**," *Environmental Research Letters* 16 (2021): 119502).

extent to which the CDR goal might change as a result. To this end, this roadmap includes a series of initiatives in Section 7.5 that are tailored specifically to developing the basic science of non-CO_2 GHGR in the next decade.

Defining a strategic goal for CDR is more challenging. CDR has been proven to be technically viable, but it is also a relatively new field, and is still growing and evolving quickly.[xiv] According to *The State of Carbon Dioxide Removal*, there were only around 3,000 CDR-related publications in the years leading up to 2014, whereas there were 23,000 by 2022.[18] This is a growth rate of around 19% per year, faster than the growth in the literature on climate change.[19] These analyses continue to update and influence estimates of the amount of CDR that is considered *possible*.

Further complicating the goal setting for CDR is that there continues to be significant debate about the total amount of removals that will be *needed*. Simply dividing the removal estimate in the first edition of *The State of Carbon Dioxide Removal* of 590–1,300 Gt CO_2 over the 78 years from 2022 to 2100 — a crude estimate — yields an average of 7.6–16.7 Gt CO_2/y.[xv] However, individual IPCC scenario estimates of the amount of CDR needed by 2050 to limit warming to 1.5°C range from zero to more than 30 Gt CO_2/y.[20] Taking into account constraints, the Systems Change Lab estimates technological CDR needs to ramp up to 30-690 Mt CO_2/y by 2030, and 740-5,500 Mt CO_2/y by 2050.[21] Making sense of the range of scenario data can be difficult, but what is clear is that the world is likely going to need gigatons of CDR if it is to achieve its long-term climate goals. Most scenarios that achieve net zero by 2050 require at least 10 Gt CO_2/y of total removals by 2050.[22]

The removal values quoted here include both nature-based and technological CDR. The specific contribution of these two major types of CDR will depend on how the field evolves and which approaches turn out to be effective. The IPCC's AR6 suggests that nature-based CDR will supply more than half of all removals to 2050; however, it also indicates that these approaches are prone to reversals from human or natural disturbances.[xvi] New studies similarly suggest that nature-based CDR will struggle to supply these removals in a sustainable way and that far less nature-based CDR should be expected than what has been previously modeled by the IPCC.[xvii]

If nontechnological CDR approaches fail to supply their share of removals, more of the burden will fall on technological CDR. For this reason, this roadmap sets a goal of developing technological CDR so that it reaches 10 Gt CO_2/y of technological removals by 2050.[xviii] If a greater share of those removals can come from nature-based CDR, then technological CDR may not need to scale as much. But given the importance of removals to maintaining the climate at 1.5°C and the extent to which nature-based solutions can contribute to those removals at scale given other land use demands and durability, this goal aims the field of GHGR toward what may very well be required of technological CDR.[xix] It will be too late to determine in 2050 that the world needs more technological CDR.

[xiv] See ***The Applied Innovation Roadmap for CDR*** (RMI, 2023).

[xv] Cumulative removal numbers to 2100 are only provided in *The State of Carbon Dioxide Removal*, 1st ed. *The State of Carbon Dioxide Removal*, 2nd ed. estimates that total removals need to be 7–9 Gt CO_2/y by 2050.

[xvi] *Sixth Assessment Report. Working Group III: Mitigation of Climate Change*, 2022. The summary for policymakers states in C.11.3: "The removal and storage of CO_2 through vegetation and soil management can be reversed by human or natural disturbances; it is also prone to climate change impacts. In comparison, CO_2 stored in geological and ocean reservoirs (via BECCS, DACCS, ocean alkalinization) and as carbon in biochar is less prone to reversal. (high confidence)."

[xvii] For example, the portfolio of CDR deployed in AR6 scenarios is likely to be insufficient. BECCS and forestry approaches are a major source of removals, but recent research on the sustainable limits of these solutions indicate that they are likely to contribute removals well below the IPCC's mean technical potential estimates. If the world does not get as much CDR from these approaches as has been expected, then the burden will fall on other technical forms of CDR (Alexandra Deprez et al. "**Sustainability Limits Needed for CO_2 Removal**," *Science* 383, no. 6682 [February 2024]: 484–486).

[xviii] Because this is such a major scale-up beyond the current state, the next 10 years will look largely the same regardless of whether the industry ultimately scales to 1 or 30 Gt CO_2/y. It will require growing GHGR as quickly as possible. In the meantime, more work can be done to determine just how much GHGR is needed in 2050 and beyond. Uncertainties in GHGR requirements are further discussed in Section 8.

[xix] Furthermore, this deployment target will be needed to guide not only the physical deployment of CDR but also the nontechnical ecosystem, including the development of policy and financial structures to support this goal.

Box 4

Brief history of CDR potentials and targets in key energy and climate publications over the past decade

Note that these numbers include both technological and nature-based CDR. This includes all human activities to generate removals above the natural baseline.

The first mention of CDR in IPCC reports was in the ***Fifth Assessment Report*** **(AR5)** published in 2014. AR5 only included BECCS and afforestation approaches for CDR. It estimated a *potential* of 2–10 Gt CO_2/y from these approaches, based on the limited number of academic studies that were available at the time.[23, xx]

In 2018, the IPCC published a **special report on 1.5°C**, quoted the AR5, and shifted the language slightly to indicate that 10 Gt CO_2/y would be *needed* by 2100. Again, this value includes a blend of both technological and nature-based CDR. To quote the report, "In the IPCC Fifth Assessment Report, the vast majority of scenarios assessed with a 66% or better chance of limiting global warming to 2°C by 2100 included CDR — typically about 10 Gt CO_2/y in 2100 or about 200–400 Gt CO_2 over the course of the century."[24]

The **2019 National Academies report** *Negative Emissions Technologies and Reliable Sequestration* widened the aperture on potential CDR approaches and reinforced the message that the volumes required would be significant. It stated: "If the goals for climate and economic growth are to be achieved, negative emissions technologies will likely need to play a large role in mitigating climate change by removing ~10 Gt/y CO_2 globally by midcentury and ~20 Gt/y CO_2 globally by the century's end."[25] This report aligned the field around a goal of 10 Gt CO_2/y of CDR by 2050 as a waypoint.

Following the National Academies study, in the years from 2019 to 2022, CDR began receiving greater attention and funding. During this time, several organizations including ARPA-E, the ClimateWorks Foundation, the Columbia Center on Global Energy Policy, and the World Resources Institute cited the 2019 National Academies report as the benchmark for the amount of CDR that would be needed.[26]

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xx To quote the report, "Until 2050, bottom-up studies estimate the economic potential to be between 2–10 Gt CO_2 per year."

Box 4 (Continued)

These reports were superseded by the **IPCC's AR6 in 2022.** The AR6 is the most detailed compilation of climate scenario analyses published to date, but it only includes cumulative needed removals by 2100, which it lists as 400–1,400 Gt CO_2. The stated reason for only publishing a cumulative number and not a yearly removal number was that the scenarios in the report had poor alignment on how they treated forestry numbers.[xxi]

As of 2024, there continues to be significant debate in the climate community about the overall magnitude of residual emissions that will need to be removed and the amount of those removals that will need to come from nature-based solutions and from technological CDR solutions (see the main text of this section).[27] There are also uncertainties in the amount of CDR it will be possible to supply. The result is a current high degree of uncertainty regarding how much GHGR will be needed to achieve long-term climate goals. These uncertainties and more are discussed in detail in Section 9.

Furthermore, energy models, climate systems models, and integrated assessment models are continually being updated to reflect the latest science regarding what is needed and what is possible. As science and models evolve, better estimates will become available as to how much of those removals will need to come from nature-based CDR and how much will need to come from technological CDR. As the science of non-CO_2 GHGR is advanced, climate and energy systems models may potentially begin to include ranges for the removal of these gases as well.

There is no perfect number to set for 2050 removals, but the establishment of a specific and ambitious deployment target for CDR gives the field the necessary focus to understand what is needed and to develop a path to achieving it. With the destination established, the next step is to build a robust roadmap that describes the initiatives and milestones that must be accomplished along the way and that orient the GHGR community toward this common goal. Section 4 outlines the path needed to arrive there, at scale and on time.

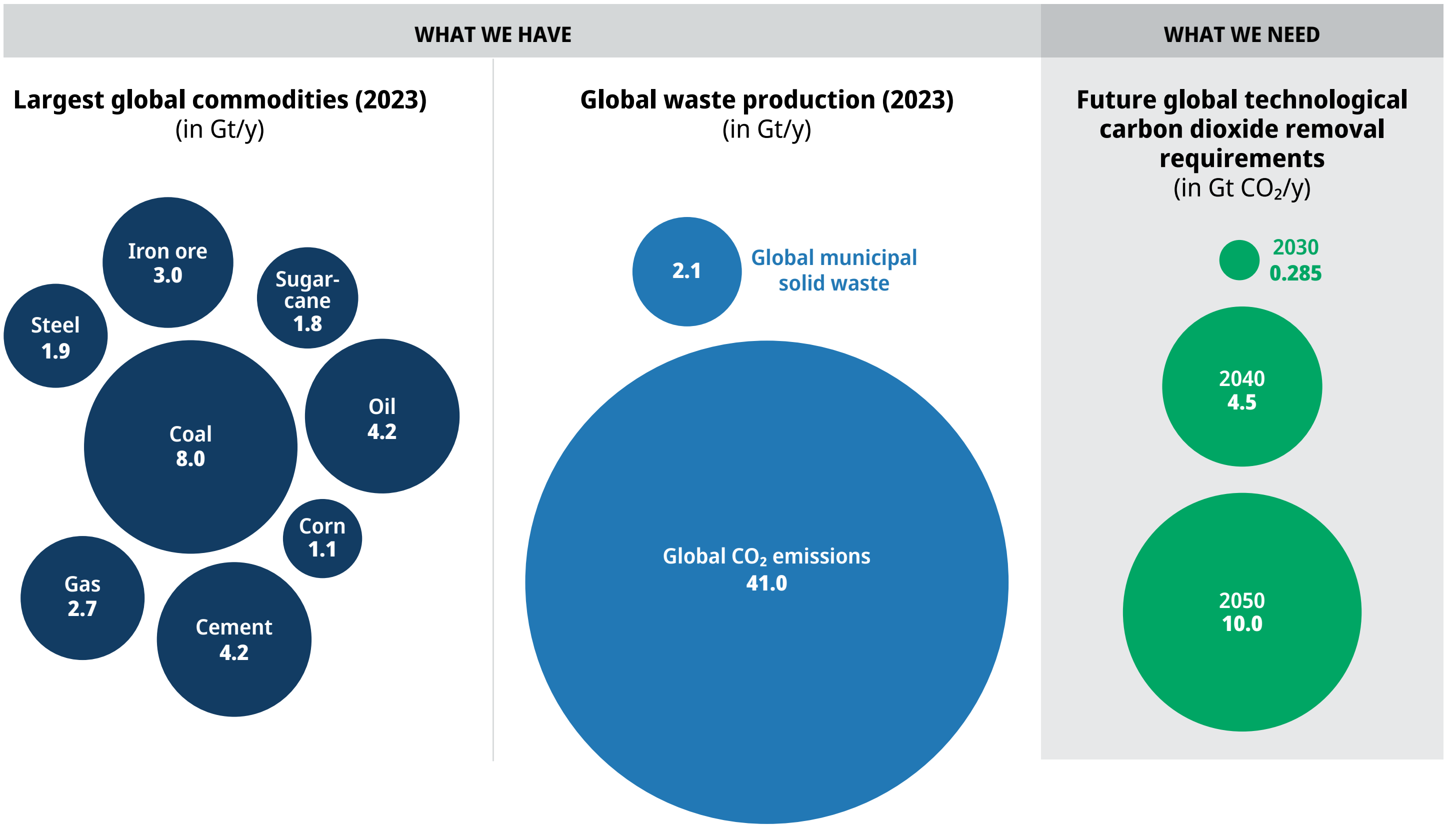
[xxi] *Sixth Assessment Report. Working Group III: Mitigation of Climate Change*, 2022. "Cumulative CDR from AFOLU [agriculture, forestry, and land use] cannot be quantified precisely because models use different reporting methodologies that in some cases combine gross emissions and removals and use different baselines."

4. Framing the GHGR Scaling Challenge

The 2023 *State of Climate Action* report estimates that less than 1 megaton (Mt) CO_2/y was removed globally by technological CDR in 2023.[28] Scaling CDR to achieve the roadmap goal of 10 Gt CO_2/y by 2050 (Section 3) would therefore require deploying 10,000x more in only 25 years.

This combination of required scale and speed will test the limits of GHGR deployment. To put this challenge in perspective, the required 10 Gt/y removed is greater by mass than production of any of the world's largest global commodities, including coal, cement, oil, and iron. Additionally, any delay in global emissions reduction efforts would only make that number larger.[xxii] Likewise, scaling industries such as GHGR to the gigaton scale has historically taken 50 years or more, compared with the 25 years or less available for scaling GHGR.[29] Given these challenges, the question at hand is how to achieve the goals of this roadmap in the time frame to 2050.

Figure 5 Putting the scale of the global removal challenge into perspective



Source: Author analysis. Data from Pierre Fiedlingstein et al., "Global Carbon Budget 2023," *Earth System Science Data* 15 (2023): 5301–5369. See figure notes in *Appendix C*.

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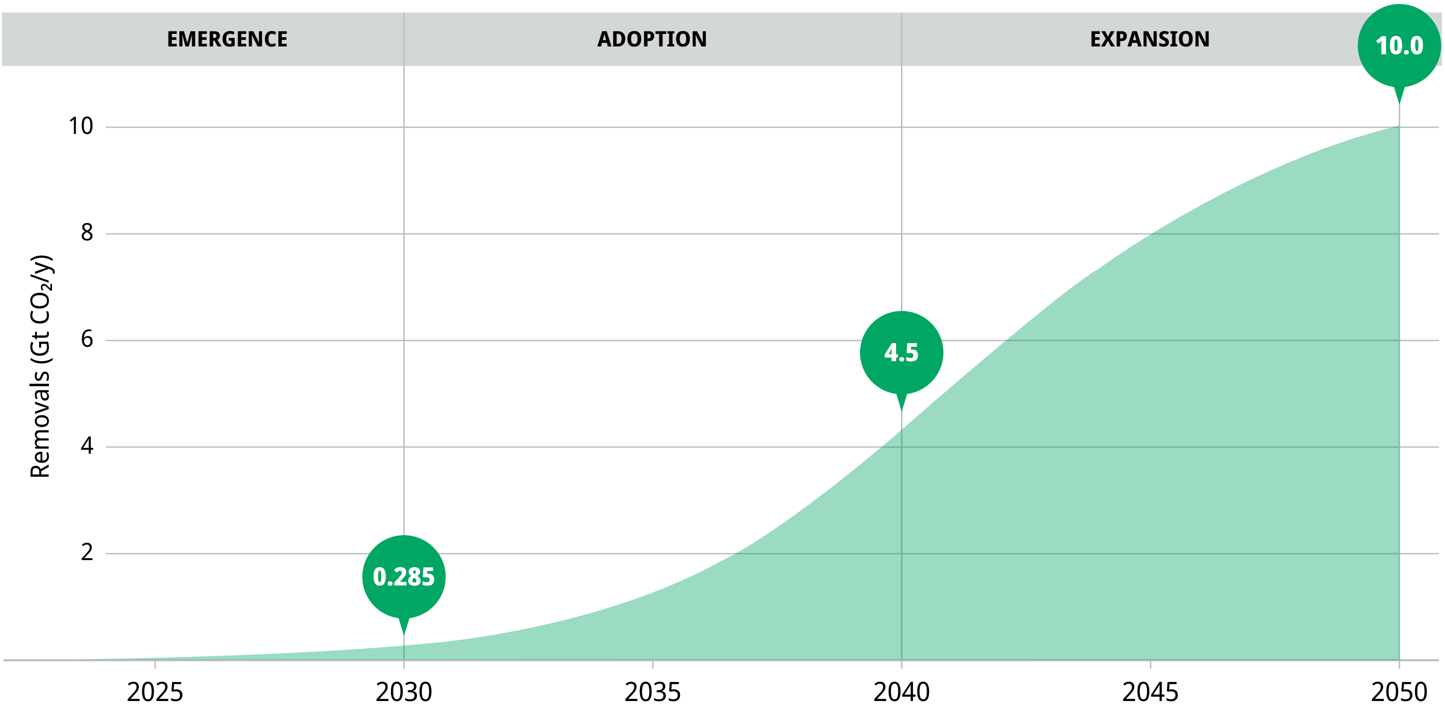
xxii *Sixth Assessment Report. Working Group III: Mitigation of Climate Change*, 2022. "If CO_2 emission levels stay around 40 Gt CO_2 until 2030, within the range of what is projected for current unconditional and conditional NDCs, rather than being halved to 20 Gt CO_2 until 2030, CDR deployment in the second half of the century would have to increase by 50%-100%, depending on whether the 2030-2050 CO_2 emissions reduction rate is doubled from 6% to 12% or kept at 6% per year. (3-77)."

Rapid scaling of new technologies often initially follows an exponential growth trajectory, whereby increases occur at an ever-increasing rate. However, as greater scale is achieved, most systems run into physical limits where it becomes more difficult for those increases to occur. Growth slows as demand is satiated, resources are consumed, or markets are saturated. This process — an initial period of rapid growth followed by reduced growth at scale — is the shape of an S-curve.

S-curve-shaped deployments have been demonstrated in multiple domains, including many across the energy transition.[30] However, they are not inevitable, and there is no guarantee that GHGR will follow this trajectory. For instance, CDR is currently in an initial exponential growth period, but continued growth to high levels of deployment will depend on demonstrated effectiveness and cost reductions across a suite of CDR approaches. Fortunately, a rapid rate of deployments often leads to decreases in costs, which in turn drive more deployments, but this relationship is not guaranteed. For CDR, demand is uncertain and there are still open questions about the upper physical limits of deployment. Therefore, continued growth to the scale of 10 Gt CO_2/y will require stable, scaled demand driven by policy, as well as strategies that overcome challenges in resource allocation across key inputs such as energy, alkaline minerals, and sustainable biomass.

Despite these challenges, there is a strong case to be made that stakeholders should look to replicate an S-curve for CDR deployment because it maximizes the rapid rate of year-on-year growth in early years while realistically accounting for scaling challenges in later years. This roadmap therefore proposes a series of initiatives designed to realize this S-curve trajectory to 2050.[xxiii] Figure 6 shows the hypothetical S-curve deployment trajectory used for the purposes of this roadmap, which would require achieving 285 Mt CO_2/y removed by 2030 and 4.5 Gt CO_2/y removed in 2040 in order to reach 10 Gt CO_2/y removed in 2050.[xxiv]

Figure 6 Hypothetical CDR deployment trajectory that takes the shape of an S-curve



Source: Author analysis. See figure notes in *Appendix C*.

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xxiii These are captured in Initiatives 2.12 and 3.8. One option for driving this shape of deployment is to create policy with an uncapped demand pull, similar to the 45Q tax credits currently offered in the United States. Another option would be to mandate public procurement in line with S-curve scaling.

xxiv This curve is only constrained by the end point of 10 Gt CO_2/y in 2050. The intermediary values are outputs from the modeled curve.

The hypothetical S-curve provides a model deployment trajectory from 2025 to 2050, but more details on specific actions along the way are needed to understand how to make the deployment trajectory a reality. For example, the early years of the S-curve will require a much greater emphasis on setting up the GHGR ecosystem, whereas the later years will require greater emphasis on large-scale deployment. To make sense of these different periods, this roadmap segments the deployment curve into three tractable phases of activity, emergence, adoption, and expansion, which each correspond roughly to the three decadal periods to 2050. Together, these three phases frame the high-level narrative of what successful technological removals will require from 2024 to 2050.

The **emergence** phase requires the coordinated development and testing of a variety of possible CDR technology options. Deployments in this phase start small and must grow to ~285 Mt CO_2/y by 2030. This will require yearly growth of 30%–50% and will be characterized largely by demonstrations and first deployments. The **adoption** phase requires the large-scale build-out of the most competitive CDR approaches. Deployments need to grow at 20%–30% per year and must reach ~4.5 Gt CO_2/y in 2040. In the **expansion** phase, growth rates slow to 5%–15% as CDR deployment is tempered by limitations of scaling, including market saturation, resource availability, supply chains, and access to capital. Still, absolute additions of removal technology deployments during this period are the highest of the entire curve, with some years adding 500–800 Mt CO_2/y of additional capacity in order to meet the target of 10 Gt CO_2/y capacity in 2050.

This S-curve framing, and the three decadal periods described here, provide the high-level structure of this roadmap. These three periods are used to unite the thematic areas for stakeholder action (Section 6) with the technology initiatives (Section 7) across time. They are also used to frame the decadal initiatives (Section 8) that cover the crosscutting needs of GHGR, as depicted in Figure 2.[xxv]

Achieving this will not be easy. As discussed in Section 9, there are physical limits to how much any one type of removal technology might be able to supply. For example, land CDR might be limited by the amount of biomass that can be sustainably sourced, rock CDR might be limited by the amount of cost-effective alkaline minerals that can be processed, and air CDR may be limited by the availability of low-carbon energy. The sheer physical size may also be a constraint. Reaching ~285 Mt CO_2/y by 2030 by DACS alone would require replicating the world's largest DACS plant 570 times and making all of them operational by 2030.[xxvi]

Realizing these scaling goals will require a significant increase in total funding for GHGR, which is still low in comparison to other realms of climate action. *The State of Carbon Dioxide Removal* estimates that global public investment in CDR research, development, and demonstration (RD&D) was only around $4.1 billion during the entire period of 2010–2022 compared with Organization for Economic Co-operation and Development spending of $17 billion on energy alone per year.[31] Furthermore, most of this CDR funding was specifically earmarked for DAC, and almost none was allocated to non-CO_2 GHGR. At a high level, one of the goals of the roadmap is to rightsize investment levels across three dimensions: first, for GHGR as compared with other fields; second, for non-DAC CDR as compared with DAC; and third, for non-CO_2 GHGR as compared with CDR.

[xxv] It is important to keep in mind that the deployment of technological removals from 2024 to 2050 will proceed in a fluid way and that these three decadal periods are artificial segmentations of the deployment curve. They were created as a way to break up the scaling challenge into manageable periods.

[xxvi] The world's largest planned GHGR plant to date, the 1PointFive Stratos facility, is expected to remove 500,000 tons CO_2/y when it becomes operational in mid-2025 ("**Stratos**," 1PointFive, accessed July 2024).

5. Report Methodology

The core roadmap content is contained in Sections 6, 7, and 8. These sections describe where stakeholders can engage to have the most impact in thematic areas across GHGR, initiatives for advancing GHGR technology to scale, and the major milestones that need to be met in GHGR by decade. These sections reflect original analysis based on four key inputs:

1. **Results from a GHGR workshop convened by the Bezos Earth Fund alongside the U.S. Department of Energy and Stanford University in February 2024.**[32] This two-day event included more than 500 experts and stakeholders from all areas of the GHGR ecosystem, including decision makers, researchers, industry, community advocates, government, think tanks, and philanthropies. It was convened under the Chatham House Rule. Thematic and technical breakout sessions were used to assess the most significant barriers and enablers, open questions and dependencies, and risks and unintended consequences. These outputs led to milestones, timelines, stakeholder touchpoints, and priorities.

2. **A public survey and expert feedback solicitation.** Surveys administered prior to the GHGR workshop further allowed participants and the public an opportunity to contribute. Takeaways from the workshop and the survey represent the latest expert thinking on how to advance GHGR and are woven throughout this roadmap.

3. **Previous roadmapping efforts.** An old proverb says, “To go fast, go alone; to go far, go together.” This roadmap is intended to build on and interlink with previous roadmapping activities in an effort to go far together. A nonexhaustive list of relevant roadmaps is included in Appendix A, and many of these are referenced throughout this roadmap.

4. **Review by GHGR experts.** Drafts of this roadmap were reviewed by GHGR experts, including those listed in the acknowledgments section.

The discussion of the roadmap initiatives begins in Section 6, which is dedicated to defining four thematic areas for action in GHGR: science and technology, socio-behavioral and communities, finance and markets, and policy and regulation. All four are critical pieces of the ecosystem that need to advance in a coordinated manner. That section shows how different stakeholders can work within these areas to advance GHGR. For example, government actors will be able to see where they can best contribute to these four areas.

Within these thematic areas, many of the most critical crosscutting issues facing GHGR are introduced. This includes a discussion of demand for GHGR, which is covered in Sections 6.3 and 6.4, as well as the role of measurement, reporting, and verification (MRV), which is covered in Sections 6.1, 6.3, and 6.4.

The roadmap also takes a comprehensive approach to addressing and incorporating justice and community engagement, which are of critical importance to any scaling effort. Because GHGR is a relatively nascent field, there is an opportunity, in contrast to scale-up in previous industries, to set a new paradigm with an exemplar approach to justice and community engagement from the beginning. As such, an entire thematic area, Section 6.2, is dedicated to these topics and is intended to provide a framework for applying these concepts to GHGR. The themes of this section are then intentionally woven into initiatives across the entire roadmap with particular focus on Sections 7 and 8.

Box 5

The crosscutting importance of MRV

MRV (measurement, reporting, and verification) is the quantitative accounting of a GHGR project. It includes measuring and monitoring the volume of removals, compiling and reporting that information to a system, program, or body, and then subjecting that reported data to a review and verification process.

MRV ensures that a removal has occurred. It enables accountability for project outcomes across project stakeholders, including payment for tons of carbon removed and the enforcement of contractual and regulatory obligations. Many parts of the GHGR ecosystem depend on MRV to function properly. Buyers and sellers of removal credits need effective MRV to ensure the validity of their transactions. MRV is also necessary for developing protocols that protect environments and communities and that meet financial and regulatory needs. All of this depends on advances in science and technology that provide reliable measurement and modeling.

Because MRV is such a crosscutting challenge, it is included in each section of the roadmap. The four thematic areas of Section 6 discuss how different stakeholders can interact with or advance MRV, Section 7 discusses MRV in the context of each technology area, and Section 8 discusses what is needed to advance MRV across the three decadal periods.

The roadmap provides a pathway to the GHGR goals of Section 3, revolving around 51 initiatives laid out in Sections 7 and 8, aligned with advancement of individual GHGR technologies and advancement of GHGR as a field across the three decadal periods from 2024 to 2050. The roadmap **initiatives** are collections of specific **actions**, **targets**, and **milestones** against which progress can be measured. **Actions** are activities undertaken to address an initiative. **Targets** are measurable goals against which actions are judged. **Milestones** are either checkpoints (status checks) or decision points (status checks plus decisions) on the path toward achieving an initiative's targets. Initiatives are meant to guide GHGR stakeholders as they seek to achieve the ambitious goal of scaling to gigatons removed by 2050.[xxvii]

Throughout the roadmap text, initiatives are referenced with their numbering or lettering in parentheses. Technical initiatives include a letter and number (e.g., A.1), where the letter corresponds to the technology area (A = air, O = ocean, L = land, R = rock, and N = non-CO_2 GHGR) and the number corresponds to the particular initiative. Decadal initiatives include two numbers (e.g., 3.7), where the first number indicates the decade (1 = to 2030, 2 = 2030–2040, 3 = 2040–2050) and the second number corresponds to the particular initiative in that decadal period.

An example of this is Initiative 1.2, an initiative in the first decadal period focused on accelerating new technology development through project demonstrations. The initiative includes an **action** to deploy demonstration-scale projects across varied geographies and technologies. The **target** is reaching 300-400 of these projects by 2030. And the **milestone** is a decision point in 2030 to proceed with future funding only for those technologies that demonstrate safe, durable, measurable, and cost-effective at scale.

[xxvii] The bolded words in this paragraph are more fully defined in the key terms section.

Box 6
Initiatives are meant to be:

- Inspirational by providing concrete guidance for the development of GHGR
- Based on current scientific understanding and prospective deployment scenarios
- Inclusive of actions that are SMART (specific, measurable, achievable, relevant, and time-bound)
- Implemented, learned from, iterated on, and updated as the field grows and evolves

Initiatives are not:

- Exhaustive of all initiatives that could be merited
- A prediction of what will happen

Note: All financial initiatives are reported in U.S. dollars unless otherwise noted.

The GHGR technology initiatives in Section 7 were developed based on a forward-looking assessment of what is considered ambitious but possible in the next 10 years. Given the speed and scale of deployments required, GHGR technology must progress and deploy as quickly as possible in the near term, and the technology initiatives were designed to push technological GHGR as fast as possible.

The decadal initiatives presented in Section 8 take a higher-level view of what is needed across all of GHGR and to extend that view to 2050. They are highly interdependent within their decadal period and are intended to be enacted in parallel, continually reinforcing each other; that is, they must all be implemented simultaneously. They should be seen as a collective set of actions focused on the same urgent goal where coordination and collaboration across the various stakeholders carrying out these activities is imperative. The overlap of the technical and decadal initiatives is shown visually in Figure 2.

One important way in which this roadmap differs from previous efforts is that it takes a global approach to GHGR, rather than a national approach, to first ensure a comprehensive understanding of the global GHGR scaling need. The goals defined in Section 3 are based on what is needed to achieve global climate alignment. From there, the thematic areas discuss what is needed by global stakeholders to advance GHGR, and initiatives in Sections 7 and 8 are designed with a global perspective, including targets and milestones that are specified in global terms.

This roadmap marks a further step toward ensuring that technological GHGR can meet the world's climate goals, but more work will also be needed. Growing an industry to the size required by 2050 will require continual and recurring planning and direction. There is an additional time-critical need for detailed convenings and roadmaps on individual GHGR technology areas, near-term initiatives, and planning at national, regional, and local levels. This may also include convenings and roadmapping efforts on subtopics of these areas, for example, roadmaps for specific ocean CDR approaches or subcomponents of the finance and markets thematic area or deepdiving on GHGR equity and justice plans and strategy. It will also be necessary to develop more clarity on what will be needed in the later periods of scale, including in the final decadal period, from 2040 to 2050, given the comparative challenge of the magnitude and speed of deployment needed. All of these areas and subareas will benefit from more near-term strategic planning and coordination.

It will be important to regularly update this roadmap to integrate the latest learnings, developments, and progress. GHGR is advancing quickly and improving each year, new companies are continually emerging, and the policy landscape is fluid and evolving. As the landscape changes, it will be important to revisit and update both the goals (Section 3) and the path for meeting those goals (Sections 6, 7, and 8). Given the rate of change, these updates may need to happen every one to four years and possibly even more frequently if there are major changes in GHGR or climate science in the interim.

6. GHGR Thematic Areas for Stakeholder Action

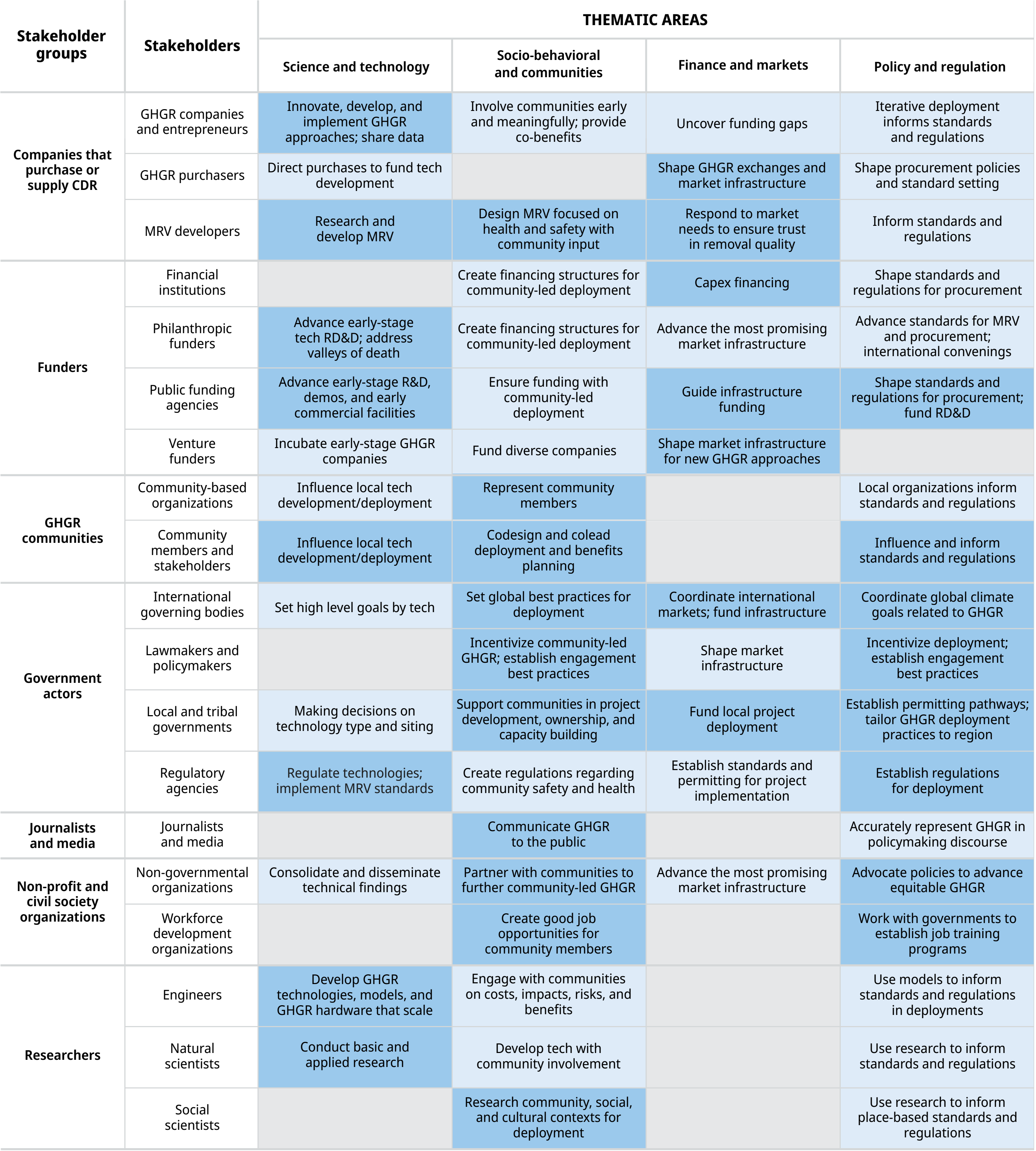
The purpose of this roadmap is to define initiatives necessary to reach the targets identified in Section 3 on goal setting for GHGR. However, these initiatives rest on an enabling environment created by GHGR stakeholders. For the entire GHGR endeavor to succeed, stakeholders across society will need to lead and cooperate. Relevant stakeholders include (alphabetically):

- **Companies that supply or purchase CDR** to develop the commercial ecosystem of GHGR, including the production of GHGR removals and the market mechanisms necessary to buy, sell, and verify those purchases.
- **Funders,** including philanthropic funders and public funding agencies, to advance early-stage research and development (R&D), incubate early-stage companies, and advance promising approaches.
- **GHGR communities** to influence the development and deployment of technology and to inform standards and regulations.
- **Government actors** to develop deployment practices, establish GHGR targets and scaled demand, ensure that GHGR is developed equitably and safely, and help develop and streamline the permitting frameworks, regulatory structures, public data sets, and government programs necessary to enable GHGR.
- **Journalists and media** to communicate an accurate story of GHGR, including long-term scaling goals and crosscutting issues and challenges, which are each critical to informing local audiences and to ensuring accountability, transparency, and trust.
- **Nonprofit and civil society organizations** to organize GHGR deployment goals, partner with community members, and highlight areas where additional engagement can help advance GHGR.
- **Researchers** to conduct basic and applied research to advance GHGR technologies and to better understand GHGR in community, social, and cultural contexts.

Figure 7 provides an overview of each of these stakeholder groups and how they can engage to advance GHGR.

Figure 7 Critical roles for GHGR stakeholder groups across four thematic areas

Relevance of actors: 🟦 High □ Medium ▒ Low



Stakeholder groups	Stakeholders	THEMATIC AREAS			
		Science and technology	Socio-behavioral and communities	Finance and markets	Policy and regulation
Companies that purchase or supply CDR	GHGR companies and entrepreneurs	Innovate, develop, and implement GHGR approaches; share data	Involve communities early and meaningfully; provide co-benefits	Uncover funding gaps	Iterative deployment informs standards and regulations
	GHGR purchasers	Direct purchases to fund tech development		Shape GHGR exchanges and market infrastructure	Shape procurement policies and standard setting
	MRV developers	Research and develop MRV	Design MRV focused on health and safety with community input	Respond to market needs to ensure trust in removal quality	Inform standards and regulations
Funders	Financial institutions		Create financing structures for community-led deployment	Capex financing	Shape standards and regulations for procurement
	Philanthropic funders	Advance early-stage tech RD&D; address valleys of death	Create financing structures for community-led deployment	Advance the most promising market infrastructure	Advance standards for MRV and procurement; international convenings
	Public funding agencies	Advance early-stage R&D, demos, and early commercial facilities	Ensure funding with community-led deployment	Guide infrastructure funding	Shape standards and regulations for procurement; fund RD&D
	Venture funders	Incubate early-stage GHGR companies	Fund diverse companies	Shape market infrastructure for new GHGR approaches	
GHGR communities	Community-based organizations	Influence local tech development/deployment	Represent community members		Local organizations inform standards and regulations
	Community members and stakeholders	Influence local tech development/deployment	Codesign and colead deployment and benefits planning		Influence and inform standards and regulations
Government actors	International governing bodies	Set high level goals by tech	Set global best practices for deployment	Coordinate international markets; fund infrastructure	Coordinate global climate goals related to GHGR
	Lawmakers and policymakers		Incentivize community-led GHGR; establish engagement best practices	Shape market infrastructure	Incentivize deployment; establish engagement best practices
	Local and tribal governments	Making decisions on technology type and siting	Support communities in project development, ownership, and capacity building	Fund local project deployment	Establish permitting pathways; tailor GHGR deployment practices to region
	Regulatory agencies	Regulate technologies; implement MRV standards	Create regulations regarding community safety and health	Establish standards and permitting for project implementation	Establish regulations for deployment
Journalists and media	Journalists and media		Communicate GHGR to the public		Accurately represent GHGR in policymaking discourse
Non-profit and civil society organizations	Non-governmental organizations	Consolidate and disseminate technical findings	Partner with communities to further community-led GHGR	Advance the most promising market infrastructure	Advocate policies to advance equitable GHGR
	Workforce development organizations		Create good job opportunities for community members		Work with governments to establish job training programs
Researchers	Engineers	Develop GHGR technologies, models, and GHGR hardware that scale	Engage with communities on costs, impacts, risks, and benefits		Use models to inform standards and regulations in deployments
	Natural scientists	Conduct basic and applied research	Develop tech with community involvement		Use research to inform standards and regulations
	Social scientists		Research community, social, and cultural contexts for deployment		Use research to inform place-based standards and regulations

Source: Author analysis. This table is meant to indicate priority areas for certain stakeholder groups, but it is not comprehensive. See figure notes in *Appendix C*.

To suggest the best ways for each of these stakeholder groups to engage, this section identifies four thematic areas for action and shows how different stakeholders can work within these areas to advance GHGR. The four thematic areas are science and technology, socio-behavioral and communities, finance and markets, and policy and regulation.

- **Science and technology** refer to the foundational RDD&D activities that create new knowledge, innovations, and technical solutions. This encompasses basic scientific research, applied research, and the development of prototypes and pilot projects for GHGR, through to deployment. It is critical for advancing the technical capabilities and maturity of GHGR, ensuring that the field progresses from conceptual stages to practical, scalable solutions.

- **Socio-behavioral and communities** focus on understanding the human and social dimensions of the adoption and use of GHGR. This includes cultural factors, community engagement, and the impact of GHGR on society. It is about ensuring that GHGR technologies are designed and deployed responsibly and with social impacts in mind.

- **Finance and markets** involve the economic and commercial aspects of GHGR development and deployment. This includes securing funding and investment, and developing business models, market analysis, and commercialization strategies. Access to capital, financial incentives, and a clear understanding of market dynamics are essential to bring GHGR to market, scale operations, and achieve economic viability.

- **Policy and regulation** encompass the legal and regulatory frameworks that govern the development, deployment, and use of GHGR. This includes crafting and enforcing laws, standards, and guidelines that ensure safety, security, environmental protection, and ethical considerations. Effective policy and regulatory support can facilitate innovation, remove barriers to market entry, and provide a stable environment for technology growth and adoption.

Specific stakeholder groups may interact with several or all of these thematic areas, and each of the four thematic area sections (6.1, 6.2, 6.3, and 6.4) includes a table to help clarify where and how stakeholders can engage for high impact. Moreover, this thematic section is intended to help stakeholders understand activity areas outside of their area of expertise, given that cooperation and collaboration will be critical to achieving the overall GHGR scaling goals outlined in Section 3. Finally, this section provides a grounding for the technical initiatives of Section 7 and the decadal initiatives of Section 8, which reference these four thematic areas.

6.1 Science and Technology (S&T)

Science and technology are the foundation of technological GHGR; they are what enable humans to characterize the problem of excess GHG concentrations, to physically remove climate-warming gases from the environment, and to quantify and compare impacts. Science and technology initiatives are intended to advance the technical viability of GHGR approaches through use-inspired basic research, applied research, field trials, pilots, and demonstrations, as well as technical analyses such as life-cycle assessments (LCAs), technoeconomic assessments (TEAs), climate modeling, process design, equipment configurations and systems design, developing and implementing MRV, and industrial cluster planning.

One of the biggest barriers to advancing the science and technology of GHGR at a pace required for reaching climate goals is the lack of pilot-scale projects.[xxviii] Pilot-scale projects as well as field trials and other deployment-led learning can help researchers test and refine the basics of an approach, including the engineering, logistics, and infrastructure challenges and operating conditions of how a GHGR approach will function at scale. This will require running pilots in a variety of geographic conditions including in the global south. Pilots also allow for the collection of data to determine how well the process works under different conditions and to evaluate any externalities, including positive or negative environmental or human health impacts. This has direct impacts on the financial risks of GHGR projects, as discussed in Section 6.3, because successful field trials in different contexts enable new technologies to advance past the valley of death toward successful implementation at scale.[33]

Given this key barrier, the most important near-term GHGR priority for science and technology is to focus on deployment-led learning, specifically pilot projects, with the intent to share learnings with relevant stakeholders so that rapid and iterative decisions can be made on where to direct new research efforts.[xxix] Many CDR startups are already doing these types of pilots, but because they are private companies, they are not required to share their learnings, and as a result their experiences are not available to advance the field as a whole. Future funding for these startup activities, where possible, should incentivize data sharing to advance the field of GHGR. Besides startups, the U.S. Department of Energy's Carbon Negative Shot Pilots funding announcement seeks to provide $100 million over five years for pilot projects, and according to the second edition of *The State of Carbon Dioxide Removal*, there are several other ongoing GHGR pilot activities around the world.[34]

These activities are a great start, but far more is needed to advance GHGR to where it needs to be by 2030 (see Section 8.1). This roadmap estimates that $8 billion needs to be spent on technology search, incubation, and testing (1.1) and that this needs to be accompanied by 300–400 demonstration-scale projects (1.2), all by 2030. This roadmap also establishes GHGR technology initiatives for achieving these goals (A.4, O.6, O.10, L.2, L.3, R.4), notes projects that explore opportunities for industrial integration (O.11, L.5, R.5), and sets targets for the deployment of over 350 field trials, pilots, and demonstrations across varied geographies and operating conditions.

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xxviii For more information on project scope and TRLs as defined in this roadmap, see ***The Applied Innovation Roadmap for CDR*** (RMI, 2023 , pp. 379, 387–390).

xxix Note that this is only true for CDR. The focus of non-CO_2 GHGR is to resolve basic scientific uncertainties.

The second key S&T barrier is the technical readiness of many GHGR approaches. Many technological GHGR approaches are still at low maturity levels and have technical capabilities yet to be refined and optimized. Depending on the approach, and after ensuring that any negative human and environmental impacts have been identified and addressed, the TRL can be advanced with applied research targeted to addressing specific barriers or open questions. This type of research can also facilitate assessments of which approaches are most viable for safe, durable, measurable, and cost-effective scaled deployment. Through the GHGR technology initiatives in Section 7, this roadmap identifies critical applied research opportunities in process innovation, synergistic siting, standards to inform MRV, field trials, LCA and TEA development, biomass sourcing, and ways to integrate CDR approaches with other processes (A.1, A.3, O.2, O.4, L.8, L.9, R.1, R.2, N.1).

Another area that can help advance applied GHGR research is approach-specific field coordination and rapid data sharing. This includes the sharing of innovations in process development, measurement and mitigation of environmental impacts, and safety. If successful, this type of collaboration can help transmit shared learnings from both successes and failures (A.11, O.13, L.12, R.10). The GHGR approaches that succeed through the TRL scale are those that will be most likely to move up the S-curve described in Section 4.

The final major priority area for science and technology is in advancing use-inspired basic research for GHGR. Because GHGR is still in the early stages of technical maturity, basic research will be critical to understanding the foundational science behind technological GHGR as well as in expanding and uncovering new approaches. This will require an increase in overall funding as well as directing a greater share of funding toward non-DAC technological GHGR approaches. Advances in basic science are especially critical for the enablement of non-CO_2 GHGR, which is still largely theoretical and requires more work to better understand the complex interactions of gases in the atmosphere and how to remove them. Similarly, open-system GHGR interventions require an improved understanding of their interactions with complex natural systems in order to assess their climate impacts and environmental safety. Across GHGR, this roadmap identifies use-inspired basic research initiatives in material development, biogeochemistry research, systems modeling, MRV, efficiency improvements, and Earth systems modeling (A.1, O.1, O.3, L.11, R.1, R.2, N.1, N.3).

Putting all of this together, the story across the thematic area of science and technology begins with real-world testing. Most GHGR approaches are simple, and what is needed most to advance their technical readiness is to begin testing them at the pilot scale. This should be the focus of the next 10 years. Crucially, it should be accompanied by applied research for tactically solving specific technical barriers and challenges of individual GHGR approaches. Meanwhile, use-inspired basic research should continue to build out a foundation of scientific knowledge. By 2035, and earlier if possible, approaches demonstrating the ability to achieve safe, durable, measurable, and cost-effective removals that contribute meaningfully to the 10 Gt CO_2/y goal should begin to outcompete other GHGR approaches (2.1, 2.2). This means prioritizing approaches that have the potential for gigaton scale (1.1). By this point, the GHGR ecosystem will have accumulated an additional decade of technical understanding, and new roadmaps and tools will be needed to make decisions about which approaches to fund and how.

Finally, the GHGR field should expect the innovation process to be highly nonlinear across invention, translation, adoption, and diffusion. History shows that most technologies follow an iterative process of learning by doing, continuous improvement, and major breakthroughs.[35] Given that the field is still at such an early stage of technical readiness, it would be prudent not to preemptively pick winners and losers at this time due to the high likelihood of unexpected curveballs and breakthroughs.

Stakeholders for advancing science and technology (S&T) initiatives

Stakeholder groups (alphabetical)	Stakeholders	Role
Companies that purchase or supply GHGR	GHGR companies and entrepreneurs	Enable breakthroughs in more established GHGR approaches from learning by doing, with problems and solutions discovered during project implementations being fed back into process improvement research. Integrate MRV standards into measurement and modeling for GHGR projects and provide data for accurate and transparent LCAs.
	MRV developers	Develop LCAs and TEAs based on process data from GHGR deployments and develop appropriate and trustworthy carbon accounting mechanisms and standards.
Funders	Philanthropic funders	Fill gaps including funding use-inspired basic science, early-stage technology R&D, and first-of-a-kind projects.
	Public funding agencies	Fund use-inspired basic science, early-stage technology R&D, pilots, and early-stage commercial facilities.
GHGR communities	Community advocates and organizers	Contribute to early-stage research and deployment that may affect community members (e.g., research on the safety of a technology, deployment siting decisions, and overall impacts and cost of the technology).
Government actors	Regulatory agencies	Regulate implementation of new technologies and MRV standards for the benefit of people and the environment.
Researchers	Engineers and researchers focused on deployment	Perform innovative research and engineering to study and develop GHGR systems, equipment configurations, site designs, and process designs. As GHGR scales, many breakthroughs will come from systems improvements and successful integration into existing processes rather than novel science.
	Natural scientists	Advance basic science and applied research across technological GHGR, including interdisciplinary Earth systems studies and modeling.

6.2 Socio-Behavioral and Communities (SB&C)

Science and technology will determine which tools are available for GHGR, but how those tools are used should not be determined only by scientists and engineers. Stakeholders across society will need to deliberate and decide. As discussed in Section 3, the scale of GHGR required is beyond anything humans have ever done before. Achieving this scale will require a wide variety of natural resources, infrastructures, technologies, and workforces, presenting communities across the world with significant economic opportunities. And, because of potential technology co-benefits, GHGR may also provide opportunities for additional environmental and health benefits to communities.[xxx]

[xxx] For more specifics on these potential co-benefits, see the technical roadmaps in Section 7.

However, GHGR will also place potential risks, costs, and burdens on different communities. Without deliberate and preemptive attempts to counter these potential downsides, GHGR development risks perpetuating inequities and injustices. For this reason, socio-behavioral and communities initiatives are vital. These include activities around social acceptance, community engagement, and the impact of technologies on society. Effective strategies in this area ensure that technologies are designed with user needs and societal impacts in mind, facilitating broader acceptance and integration into daily life. This is true in the global north, where GHGR deployment is likely to occur in existing industrial corridors, as well as the global south, where GHGR deployment is more likely to occur on greenfield sites.

Actors across the field must be held responsible for championing and supporting equity and justice across GHGR activities. Citizen participation in engagement practices can range from nonparticipation to citizen control and includes communities from a local to a regional or state level as well as tribal and Indigenous communities. This roadmap proposes that all projects conduct two-way engagement with communities and that they avoid nonparticipation or tokenism in engagement.[36] Stakeholder mapping is vital to defining communities for individual projects.[37]

Communities at risk include those that might host GHGR research and deployment activities in the future and those that could be affected by the externalities of GHGR activities, whether they are geographically close to a project or not. This especially includes communities that have been overburdened in the past by economic or infrastructure development projects. The socio-behavioral and communities initiatives in this roadmap are intended to ensure that these GHGR communities shape GHGR development to their benefit as opposed to the development being shaped solely by external actors.

Box 7

GHGR roadmap initiatives with socio-behavioral and community elements

In order to ensure sufficient focus on these goals, this roadmap includes socio-behavioral and community initiatives across all five technology areas (Section 7) as well as all three decadal periods (Section 8). This includes:

1. Assessments of potential impacts of GHGR research and deployment to communities as well as actions that mitigate these risks (A.3, O.4, R.1)
2. Accountability and enforcement mechanisms that protect communities from potential harms (O.9, L.1, R.6)
3. Building capacity and support for local and regional organizations to shape GHGR activities in their localities and regions (A.11, O.13, L.12, R.10, 2.5, 3.6)
4. Exploration and demonstration of community governance and alternative ownership models for deployment (A.5, L.6, 1.3, 2.3, 3.3)
5. Local and regional workforce development (1.6, 2.6, 3.5)
6. Social science research (1.4, 2.4)
7. Support for dialogue and deliberation by the public through well-resourced independent journalism, science communication, civil society organizations, and enablement of evidence-based efforts to counter mis- and disinformation (A.11, O.13, L.12, R.10, 1.5, 2.5, 3.4)
8. Tracing impacts, costs, and risks through the supply chain to ensure that the community-level impacts of upstream activities such as biomass sourcing, energy generation, and mining are understood and managed, alongside the impacts of GHGR deployment itself (1.7, 2.7, 3.6)
9. Two-way engagement with GHGR communities to shape specific GHGR research and deployment projects in line with justice principles (see key terms) and aimed at producing co-benefits tailored to communities

Box 8
GHGR roadmap initiatives in the four pillars of environmental justice

In addition to the socio-behavioral and communities initiatives, this roadmap also includes initiatives related to the four pillars of environmental justice. These initiatives shed light on the ways in which GHGR research and deployment activities, laws, policies, and regulations could, depending on how they are configured, advance justice or perpetuate injustice.

Procedural justice refers to participation and fairness in decision-making processes. Initiatives that further procedural justice focus on the early engagement of GHGR communities for decisions related to on-site research, siting, deployment, and MRV practices (A.9, A.11, O.5, O.13, L.12, R.7, 1.3, 2.3, 3.3).

Distributional justice refers to the equitable allocation of resources, risks, impacts, and benefits across communities. Initiatives that further distributional justice are focused on both reducing harms to GHGR communities and producing co-benefits that have been tailored to and agreed upon by GHGR communities (A.3, A.5, A.6, O.4, L.1, L.5, L.8, R.8, R.9, 1.3, 1.10, 2.3, 3.3). Workforce development is an important piece of this pillar, which emphasizes the creation of high-quality, well-paying, safe, and local jobs, as well as programs that aid in training for job transitions in the face of the climate crisis.

Restorative justice involves acknowledging, addressing, and remediating past harms or injustices. Initiatives focused on restorative justice may, for example, aim to clean up pollutants or integrate GHGR into legacy infrastructure in ways that mitigate harms and pollutants (A.9, O.12, R.3).

Transformative justice refers to spurring changes in current structures and systems to create a more equitable and just society. Transformative justice exists at the intersection of procedural, distributional, and restorative justice. This roadmap includes mention of community governance and alternative ownership models, which may be one way to work toward transformative justice in GHGR (A.5, L.6, 1.3, 2.3, 3.3).

Initiatives related to socio-behavioral and communities also include funding for social science research. This funding is needed to better understand and address community concerns, trust, power dynamics, and social and cultural contexts for deployment. Climate change is a global challenge, and GHGR must be deployed as a global solution. Given the global variety of social and cultural contexts, GHGR governance and ownership structures will necessarily vary across geographies. Localized social science research will be necessary to shed light on this variation and to identify innovative ways that GHGR can be shaped by communities for their benefit and to improve the adoption readiness level of GHGR technologies.

Finally, the socio-behavioral and communities thematic area includes initiatives designed to support well-informed public debate and deliberation about GHGR. This is important because debate can shape policy, regulation, and the business environment independent of specific research or deployment projects. Deployment done right means that projects reflect significant community engagement and are seen as beneficial, effective, equitable, just, and trusted. In time, this may spur community-based organizations and local governments to become advocates for responsible and successful GHGR as a local and global solution to the climate crisis in the same way that local groups advocate for public transportation, renewable energy, and other climate change solutions. This type of outcome will be accomplished only if GHGR correctly includes community engagement practices from the beginning. And, if it is accomplished, communities might one day be eager to host GHGR activities because of their community benefits, such as wealth, economic prosperity, and jobs.

Stakeholders for socio-behavioral and communities (SB&C) initiatives

Stakeholder groups (alphabetical)	Stakeholders	Role
Companies that purchase or supply CDR	MRV developers	Emphasize ecosystem and human health impacts when developing technologies and standards to inform MRV. Ensure processes are codesigned and trusted by communities and that data is transparent.
	Project developers	Engage communities early and thoroughly, continually iterating on project design based on input (A.9, O.5, L.6, R.7).
GHGR communities	Community members and stakeholders	Contribute to assessments of risks, impacts, and benefits of these technologies and maintain this engagement up through the codesign and coleading of GHGR deployments (A.9, O.5, L.6, R.7).
Government actors	International governing bodies	Set global best practices for deployment. Establish standards that ensure international supply chains do not overburden vulnerable populations.
	Local government	Support communities during project development, especially during negotiations with project developers. Build community capacity through training programs and funding. Oversee CDR deployments with partial or full ownership by local municipalities or governments.
	Policymakers	Incentivize community-led CDR and CDR with co-benefits. Establish stringent engagement best practices in permitting pathways. Provide funding for local capacity building.
Journalists and media	Journalists and media	Provide independent, accurate coverage of GHGR activity to continually inform local audiences and ensure accountability, transparency, and trust.
Nonprofit and civil society organizations	Community-based organizations (CBOs)	Represent community members in engagement processes. Advocate for business practices and policies that center on community codesign and co-benefits.
	NGOs	Partner with communities and advocate for policies to advance community-led GHGR.
	Workforce development organizations	Create good job opportunities and training programs for community members; this could include unions.
Researchers	Social scientists	Research community concerns, trust, institutional and political dynamics, and the social and cultural contexts that shape deployment.

Note: All GHGR stakeholders, including those not listed in this table, should prioritize efforts that do not perpetuate but rather mitigate existing inequities and that center around community health, safety, and economic vitality.

6.3 Finance and Markets (F&M)

Finance and markets involve the economic and commercial aspects of GHGR development and deployment. These include the creation, development, and scaling of GHGR market infrastructure as well as the creation and scaling of GHGR demand through voluntary markets, compliance markets, public procurement, and other mechanisms for incentivizing, mandating, or directly deploying GHGR. They also include public and private financing for GHGR projects, funding for the build-out of critical infrastructure, the development of traceable global supply chains, and initiatives designed to support effective MRV upon which much of the GHGR ecosystem rests.

One of the biggest financial barriers to realizing the goals of this roadmap is in achieving sufficient, scaled demand for GHGR. In 2023 only around 4.5 Mt CO_2 of durable CDR were purchased for around $2 billion.[38] But, as described in Initiative 1.12, purchases of CDR will need to reach $40–$60 billion/y by 2030 to keep track with the goals of this roadmap. Furthermore, the Boston Consulting Group estimates that CDR market size could reach hundreds of billions of dollars by 2040, and BloombergNEF estimates that CDR could reach a trillion dollar per year industry by 2050.[39] Reaching these numbers will require a dedicated effort to scale up demand.

Currently, regulations and incentives do not substantially incentivize GHGR. Therefore, demand is expected in the near term to come primarily from voluntary carbon markets (VCMs), where companies and individuals purchase CDR in the absence of any policy or regulatory requirements or incentives. They do this to offset or remove their legacy emissions but also out of an expressed interest in scaling up the industry so that it can be ready for larger-scale deployments in future years.[40] For example, Microsoft voluntarily purchased 3.2 Mt CO_2 in 2023.

Other voluntary activities such as advance market commitments and buyers clubs can also be used to advance CDR; for example, Frontier has committed to buying over $1 billion of durable carbon removal between 2022 and 2030.[41] Voluntary activities help incubate frameworks, standards, and tools that can be picked up by governments in pilot procurement programs. For these reasons, voluntary markets merit further investment as a vector for funding GHGR directly and as an environment for developing tools, protocols, and standards that can be picked up by policymakers and governments in the future (1.12).

Although voluntary purchases through VCMs will be necessary to pay for GHGR in the near term, these purchases will fall well short of what is needed to achieve global climate goals. Long-term scaling under the current GHGR market paradigm will require the establishment of significant demand through some form of mandated procurement. This roadmap therefore includes initiatives that establish publicly mandated procurement and grow it to 10 Gt CO_2/y by 2050 (1.12, 2.12, 3.8). Work must begin immediately on Initiative 1.12 to develop frameworks for public procurement because it will take several years to develop the best approaches and to build social and political support. These plans must then be adopted in the first half of the 2030s at the latest and grow to a collective, global purchase requirement of more than ~4.5 Gt CO_2/y by 2040 (1.12, 2.12). Section 6.4 discusses some of the mechanisms for achieving this.

Box 9
Potential alternatives to carbon markets

As the field of GHGR evolves and grows, the GHGR market may begin to operate differently than VCMs have historically operated. VCMs have historically aspired to trade carbon credits that are comparable and fungible across project and credit types, typically by using ton-based accounting. But there are a number of challenges to scaling this approach, even with strong government procurement, compliance regimes, or other policy backing in place. First, because different forms of GHGR (especially CDR and non-CO_2 GHGR) have differences in measurement uncertainty, durability, and risk of reversal, making GHGR comparable and fungible will be challenging. Second, as with avoidance-based carbon credits, GHGR will face questions of additionality and leakage. Strategies exist to compensate for these differences, including ton-year-based accounting, insurance products, and regional or jurisdictional accounting, but these methods also have methodological challenges, and each add cost and complexity.

Given these challenges, it may be desirable to broaden the mechanisms for paying for GHGR beyond traditional market mechanisms and to develop fit-for-purpose standards. These may include carbon accounting mechanisms that meet jurisdiction-specific public goals and that do not assume the primacy of ton-denominated credit generation. This is especially relevant for open-system interventions and non-CO_2 GHGR. One possibility is to create policy incentives that require emitters to buy removal credits. Another option is to account for GHGR at the jurisdictional or national level, which could potentially enable credit trading between nations. Governments can also leverage pay-for-practice techniques to generate removals alongside other economic activity (e.g., farming, mining, forest management). Finally, if governments come to view climate change and its destabilizing effects as a global security issue, GHGR may be viewed through a similar lens and funded accordingly.

Another key barrier to GHGR deployment is in unlocking scaled capital expenditure (capex) financing for first-of-a-kind (FOAK) projects and commercial-scale deployments. Many CDR approaches — and this would be expected of non-CO_2 GHGR approaches as well — require significant up-front capital for infrastructure and deployment. In early stages, this may require significant funding from development banks, concessional capital providers, venture funders, government lenders, or other early-stage capital. Further advancing these approaches will require unlocking larger volumes of lower-cost private financing to enable growth and scale. However, large lenders are often reluctant to fund large-capex projects if these projects do not have a well-trodden path to predictable cash flows. This poses a challenge to all new and emerging climate technology. It is particularly acute right now for DAC companies on the cusp of commercial deployment.[42]

Intentional financing programs and interventions can unstick the development of FOAK projects. For example, the U.S. Department of Energy's Loan Programs Office seeks to solve this problem by providing debt financing for the commercial deployment of large-scale projects. This type of funding is not meant to single-handedly scale the industry; it is instead meant to get early projects built so that later ones can be funded by private markets. This roadmap includes similarly structured initiatives to fund and finance demonstration projects and advance promising approaches to commercial deployment (A.4, O.6, L.3, R.4, 1.9).

Achieving all of these goals will require leadership and action by a large variety of stakeholders who work in market-facing roles. This includes people who work in financial services, development finance, industry, private-sector purchasing, and delivery of GHGR as well as in standard setting, regulation, trading, and offtakes (1.11, 2.11). Additionally, financial stakeholders such as credit purchasers and funders will be critical in identifying and specifying acceptable standards for MRV. These stakeholders should work alongside policymakers and regulators in shaping the creation of effective MRV protocols in line with financial and regulatory needs. Several initiatives in this roadmap are aimed at establishing MRV with third-party verifiers and standard bodies to provide trusted accountability and fungibility of removal credits (1.10, 2.10).

Stakeholders for advancing finance and markets (F&M) initiatives

Stakeholder groups (alphabetical)	Stakeholders	Role
Companies that purchase or supply CDR	GHGR companies	Uncover and communicate funding gaps.
	GHGR purchasers	Voluntary credit purchasers build early demand in carbon markets for the next 5–10+ years and provide revenues. This includes aggregated purchasers such as buyers' alliances as well as advance market commitments. For the CDR market to reach gigaton scale before 2050, compliance credit purchasers can provide strong demand signals, fund infrastructure and growing commercial operations, and support bankability of projects.
	MRV developers and standard-setting bodies	Respond to market needs to ensure trust in quality of removals.
Funders	Financial institutions	Support early development projects to underwrite large-scale infrastructure investments. Institutions include commercial and investment banks, development banks, insurers, asset managers, venture capital, and private equity.
	Philanthropic funders	Support finance and market incentives and other essential activities not being otherwise supported, such as activities that help unlock funding for large scale projects.
	Public funding agencies	Provide funding to advance commercial viability, including through loans for early-capex projects, and potential innovative mechanisms such as demand-pull activities (e.g., prizes, advance market commitments).
	Venture funders	Provide funding and shape market infrastructures to support new GHGR approaches.
Government actors	International governing bodies	Coordinate international markets and fund global market infrastructures.
	Local government	Fund local project development.
	Regulatory agencies	Provide regulatory support to mitigate first-mover risks.

6.4 Policy and Regulation (P&R)

Policy and regulation include all initiatives that leverage public governance mechanisms as a tool for advancing the field of GHGR. They include activities that advance regulatory clarity, fund RDD&D, enable government-backed markets, and provide provisions for safe, just, and equitable deployment. In this way, the thematic area of policy and regulation should also be used to advance each of the three other thematic areas.

As discussed in Section 6.3, one of the biggest barriers to scaled GHGR is establishing sufficient, scaled demand. Unlike many energy transition activities, GHGR has no inherent value to most potential buyers, and therefore, in the absence of policy and regulation, demand is likely to remain low.[xxxi] This is because GHGR is inherently a public good, similar in many ways to the waste management industry. As a result, significant political decisions and policy interventions will be required to pay for GHGR at scale (1.12, 2.12, 3.8). These might include both incentives and penalties, including compliance regimes or other government-backed markets, tax schemes, procurement programs, direct investments in GHGR infrastructure by governments, or other incentives. One example of a publicly mandated procurement program was put forward by The Energy Futures Initiative's CO2-Secure Program, which proposes the creation of a new CDR purchasing agency.[43] Other approaches might consider legislation to make CDR purchases a mandatory part of corporate climate reporting.

Because of the cost and scale, the programs themselves will require significant investment to stay abreast of the latest scientific evidence and to manage risks, costs, and benefits to society. These interventions will also need to be available globally because of the required scale of GHGR. Finally, stable, scaled demand will depend on a willingness to pay by societies and governments. Country-level and regional political concerns and international negotiations will influence what is politically viable, where, and when.

This roadmap includes initiatives from 2024 to 2030 that, if implemented, would see total purchases of GHGR credits grow to more than $40–$60 billion/y in 2030 via a combination of voluntary corporate buyers and early government procurement (1.12). Spending on GHGR would need to grow from there because the required increase in demand would far outstrip any decrease in cost per ton removed. To pay for this, this roadmap outlines several initiatives that lead toward larger-scale government procurement (1.12, 2.12), including activities in the 2020s that develop frameworks and build support for publicly mandated procurement that can be adopted in the first half of the 2030s (1.12). However, as discussed in Section 6.3, achieving a global target of ~4.5 Gt CO_2/y by 2040 and 10 Gt CO_2/y by 2050 may also require other, novel policy measures for purchasing GHGR.

The second critical role of policy is in establishing governance, permitting, and regulatory structures for GHGR. Clarity in each of these areas will reduce deployment barriers and provide guardrails that ensure safety, integrity, and equitable deployment. Governments should begin by establishing GHGR removal targets. National and subnational governments should tailor these targets to their local needs and strengths. International agreements should call on countries to specify GHGR deployment goals and to do so separately from their decarbonization targets. Separate GHGR deployment goals for reductions and for removals will ensure that both continue to receive adequate support.

Governments should also clearly define the parameters around which removals are measured and counted. For example, the establishment of a law-based regulatory structure requiring GHGR to verify durability of 100 years would align the ecosystem toward producing and verifying removals of only the highest durability. It would give providers, verifiers, and purchasers a clear set of target parameters. Finally, governments can advance GHGR by clarifying regulations

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[xxxi] GHGR can provide important co-benefits that do have value to buyers. For example, farmers might under some conditions benefit from enhanced soil quality and productivity from terrestrial enhanced-weathering CDR projects. But, by and large, most forms of GHGR offer limited co-benefits or direct value to private buyers.

for deployment and monetization of removals. This includes everything from clarifying pore space ownership for geologic carbon storage and developing permitting pathways for ocean CDR to ensuring supply chain transparency and establishing standards to inform MRV.

Some of these efforts are already underway in countries around the world, but much more work is needed. This roadmap includes initiatives that call on countries to clarify permitting for GHGR by 2030 (1.8, 2.8). It also includes initiatives that call for permitting and regulatory clarity in specific GHGR technology areas (A.8, O.8, L.10, R.8). As an example, the air CDR section calls for standards and permitting pathways for CO_2 transportation and storage methods to be established in all DAC deployment regions in the next 10 years.

Box 10
The global nature of GHGR

Climate change is a global problem. Because climate change pollutants are distributed and are emitted across the planet, they can also be removed anywhere on Earth. This is an opportunity for countries around the world, including those in the global south, to contribute to the deployment of a set of widespread and diverse GHGR approaches.

Countries vary dramatically in political, social, and economic structures as well as in terms of wealth, resources availability, and influence over global systems. Every country has different strengths when it comes to talent and resources availability, and different constraints of physical and social geography. Additionally, interactions between countries including technology transfer, finance flow, international regulations, and supply chains for materials need to be taken into account. Although this makes roadmapping GHGR across the globe very complex, it also provides opportunities for strategic and creative deployment shaped by the cultural, social, and economic traits of individual countries. As a result, funding should be directed toward ideas, expertise, and leadership across the globe that are focused on building out technological removals in a place-based and equitable way.

International governing bodies will have some overlap with national bodies; however, their main goal should be coordination among countries, specifically on MRV standards, market coordination, and alignment on the role of GHGR in international climate goals. It is vital that this global coordination includes countries that have historically been excluded from global governance and climate conversations, especially those that will be most impacted by the climate crisis and those with favorable resources and economic opportunities to deploy technological GHGR.

The third critical role of policy is in ensuring funding for RD&D, including scientific research, tests at pilot scale, and commercial-scale demonstrations. Government funding is especially critical because most GHGR approaches are still nascent and lack a clear market for long-term success, raising the risk profile for private investors. This roadmap identifies funding needs across the GHGR technology landscape. For example, for ocean CDR, it identifies a need for $500 million of investment focused on researching ocean biogeochemistry and activities focused on understanding the impacts of viable ocean CDR technologies by 2035 (O.1). For land CDR, it identifies the need for 40 land CDR demonstrations across geographies that provide at least 30 Mt CO_2/y of removals (L.3).

Finally, policy is needed to protect people and the environment, ensure that GHGR communities are actively engaged, and shape GHGR research and deployment projects. In the United States, federal standards attached to government grants for DAC projects have started to establish a useful framework for project development that incorporates community engagement, environmental justice, and equity considerations, and these programs should be continued. Policymakers can also get more creative and seek to enable and engage in projects that have elements of public codesign, co-ownership, or oversight on behalf of represented communities. This includes crafting GHGR policy in consultation with communities to ensure their concerns and preferences are integrated into policy design and implementation (A.6, O.5, L.6, R.7, 1.3, 2.3, 3.3).

Policy and regulation will require actors from every level to engage. This includes local siting decisions, regional planning, national funding and mandates by federal governments, and global standard setting by international bodies. As a result, these different levels of government should assume different roles in developing the GHGR field.

Stakeholders for advancing policy and regulation (P&R) initiatives

Stakeholder groups (alphabetical)	Stakeholders	Role
GHGR communities	GHGR communities	Inform relevant standards and regulations related to GHGR.
Government actors	International governing bodies	Coordinate global GHGR goals, financing, siting, MRV standards, and governance, and include countries that have historically been excluded from global governance and climate conversations.
	National governments	Create regulations on risks and impacts, establish best practices for engagement and deployment, incentivize deployment through grants and other programs, create data sets and standards to support MRV development, and include CDR in national climate plans and goals.
	Policymakers	Develop policies to incentivize deployment and establish best practices for community engagement. Make funding programs to support GHGR development.
	Regulatory agencies	Establish regulations and permitting processes to ensure public environmental safety and facilitate rapid deployment.
	Subnational governments	Establish permitting pathways and tailor GHGR deployment practices to local regions to ensure community engagement and safe deployment.
Nonprofit and civil society organizations	NGOs	Advocate for policies to advance effective, safe, and equitable GHGR.
	Workforce development organizations	Work with governments to establish job training programs.

7. GHGR Technology Initiatives

Meeting the roadmap goals of Section 3 will require the rapid development of GHGR technology in the next 10 years. CDR must reach ~285 Mt CO_2/y deployment by 2030 on its path to 10 Gt CO_2/y by 2050, and the basic science of non-CO_2 removal must advance to a point by 2035 where it is possible to make decisions about whether it can and should be deployed. By 2050, CDR will need to grow to a scale that is larger (by mass per year) than any single commodity in use on Earth. One single GHGR approach will not be enough to accomplish this; instead, it will require a portfolio of technological approaches. This section outlines a path for advancing a suite of technological GHGR approaches, each of which has the potential to contribute to that portfolio.

At a high level, this roadmap divides the technology landscape of GHGR into five major areas: air CDR, ocean CDR, land CDR, and rock CDR as well as non-CO_2 GHGR, which each contain a subset of individual GHGR approaches.[xxxii] Comprehensive details on the scope of approaches included in this roadmap are provided in Section 2, while this section identifies initiatives with actions, targets, and milestones that are necessary to advance each of these five technology areas in the critical decade to 2035.[xxxiii]

Box 11

Current cost and TRL of the five major GHGR areas

	Air CDR	Ocean CDR	Land CDR	Rock CDR	Non-CO_2 GHGR
TRL of most established approaches	3–9	4–7	5–9	6–7	1–2
Current cost per ton CO_2	\$600–\$1,200 per ton CO_2	\$100–\$1,300 per ton CO_2	\$100–\$500 per ton CO_2	\$100–\$400 per ton CO_2	Unknown

Note: The TRL data reflects known active companies and does not include the myriad early stage technological approaches that need to be developed to reach the goals of this roadmap. Data is based on ***The Applied Innovation Roadmap for CDR***, RMI, 2023.

Technology-specific initiatives beyond 2035 are not included in this roadmap because they will depend significantly on the outcomes leading up to that year. The assumption is that, by 2035, deep investments in R&D will generate new information on which approaches are demonstrated to be safe, durable, measurable, cost-effective, and scalable, and that these findings will inform new, updated strategies that drive further progress in the most promising technology areas. Moreover, for GHGR to meet its scaling goals, it may be necessary by 2035 for funders of CDR to explicitly begin diverting funding only toward those approaches best suited to contribute to the 10 Gt CO_2/y goal. As the field grows and evolves, this roadmap and other strategic planning efforts will need to be continually updated, including regular updates in the years to 2035.

[xxxii] As discussed in Section 2, air CDR, ocean CDR, land CDR, and rock CDR are based on categories used by XPRIZE.

[xxxiii] Given the necessary speed of deployment, all of these initiatives should either be already underway or should be started in the next few years.

Finally, it is important to note that the scope of this section is focused on GHGR technology area initiatives — those focused on accelerating the technology of air CDR, rock CDR, etc. Crosscutting needs, such as demand for GHGR, are included in decadal initiatives in Section 8. Likewise, additional details on the specific contributions of stakeholders across thematic areas can be found in Section 6.

7.1 Initiatives for Air CDR

Air CDR includes all carbon dioxide removal approaches that directly extract CO_2 gas from the atmosphere.[xxxiv] This is typically done by using machines that suck in atmospheric air and then selectively separate out the CO_2 molecules from the rest using a filtering process. Because the atmosphere has no borders, this process can be done anywhere on Earth for the same effect. The most common air CDR approach is DAC.

To date, air CDR has received more funding support than many other technological CDR approaches, but more funding is still needed to develop it.[44] According to the International Energy Agency (IEA), 27 DAC plants have been commissioned worldwide and an additional 130 plants are at some stage of development.[45] The United States currently has the strongest policy support for DAC, largely through the U.S. Department of Energy's $3.5 billion in funding for regional DAC hubs.[xxxv] This early support is encouraging, but more work is needed.

Figure 8 presents technology roadmap initiatives that are needed to advance air CDR toward scale, to determine what approaches have the greatest potential, and to enable the field to focus on the most promising approaches by 2035. These initiatives are focused on scaled deployment, energy efficiency and cost improvements, attention to community concerns, and careful siting of projects.

[xxxiv] Different air CDR approaches, including definitions and examples, and the innovation needed to advance them, are described in ***The Applied Innovation Roadmap for CDR*** (RMI, 2023).

[xxxv] "**Regional Direct Air Capture Hubs**," U.S. Department of Energy, accessed July 2024. Reports tracking current and projected future deployment of DAC projects in the United States include ***The Landscape of Carbon Dioxide Removal and US Policies to Scale Solutions*** (Rhodium Group, April 2024).

Figure 8 Initiatives for advancing Air CDR technology to 2035

Costs: $ <$100M $$ $100M-$1B $$$ >$1B **Timeline:** 🟨 Work ongoing 🔷 Checkpoint 🔶 Decision point

INITIATIVE	ACTION	COST	2025 2030 2035	ASSESSMENT OR MILESTONES
A.1	Improve energy and process efficiency through research on materials (sorbents, solvents, membranes, etc.), regeneration processes, and process optimization.[1]	$$	🟨 🔷 🔷 🔶	Research portfolio for improving DAC is identified and funded by 2025. The most promising process and capture innovations are deployed in both new and existing facilities by 2030. Efficiency improves to 2.5 GJ/t CO_2 or less by 2035.[2]
A.2	Expand financing structures to enable demonstration and commercial scale projects.	$	🟨 🔷	Mechanisms such as offtake agreements are in place by 2026 to ensure sufficient funding for DAC.[3] This funding must enable 100 Mt CO_2/y scale deployment by the early 2030s.
A.3	Identify and execute on DAC demo sites that optimize power, water use, CO_2 transportation or storage infrastructure, and synergies from co-location with industrial processes or other CDR approaches.[1]	$$	🟨 🔷 🔷	DAC siting plans are developed by 2026 and updated by 2030. Siting plans are based on local resource requirements to avoid energy shortfalls, material constraints, and increased risks for local environments. Siting also involves community input beginning in early project stages. Siting plans should also be developed alongside permitting processes as described in Initiative A.8.
A.4	Develop >100 global demonstration-scale DAC projects,[3] passing the 100 Mt CO_2/y removals threshold[4] by the early 2030s.[1]	$$$	🔷 🟨 🔷 🔷	>100 DAC demos are announced by 2026, operational by the early 2030s, and on track to achieve[4] 180 Mt CO_2/y by 2035. These demos are developed with siting considerations described in A.3, A.5, and A.6.
A.5	20-50 demonstration projects from Initiative A.4 should employ alternative ownership models (e.g. community, municipal, nonprofit, or public).	$	🟨 🔷 🔶	By the late 2020s, 50 demonstration projects have documentation of having explored alternative ownership models.[5] Of these, 20 projects are in some stage of design or operation by the early 2030s. Results of these projects should be distributed to inform future deployments.
A.6	Develop tailored co-benefits for the DAC projects described in Initiative A.4.	$$	🟨 🔷 🔷	All new commercial-scale DAC projects provide documented employment, financial, and other co-benefits to communities. DAC projects should not proceed without community support. Co-benefit plans should be updated regularly.
A.7	Ensure scaling of material production and relevant supply chains in line with 2030 deployment goals defined in Initiative A.4. These supply chain goals should also look toward gigaton-scale deployment of DAC by 2050.[1]	$$	🟨 🔷 🔷 🔷	Sufficient supply chains for necessary materials and equipment (e.g., sorbents, solvents, membrane materials, air contactors) and material disposal and reuse are established. These supply chains should be identified by 2026 and must be on track by 2030 to enable the deployment of 180 Mt CO_2/y scale by 2035. Specific production targets should be determined based on which DAC approaches are most likely to scale as well as geographic site potential.
A.8	Establish and enforce international standards and rapid permitting pathways for CO_2 transportation and storage in DAC deployment regions.[1,6]	$	🟨 🔷 🔷 🔷	Pipeline and storage infrastructure should seek draft regulatory permitting by 2026 with <5 year permitting timeline and regular updates to permitting regimes. These permitting standards should be developed with communities as described in A.3.
A.9	Develop location-specific community engagement processes for locations with new or converted CO_2 transportation or storage infrastructure.[1]	$$	🟨	Communities are regularly engaged to provide input into appropriate transportation mechanisms — trucks, pipelines, etc. — in their region. Communities are involved in planning process from project start, and projects do not proceed without finalized agreements negotiated between project developers and community
A.10	Establish country or regional standards to inform MRV for validation of DAC removals,[7] including relevant long-term monitoring, across DAC and CO_2 storage approaches.	$$	🟨 🔷 🔷	By the late 2020s, LCA and MRV methodology development is on track to validate all DAC projects that are planned, under development, or operational. Methodologies and data from these analyses are transparent to inform MRV process improvements. All deployments by the early 2030s use a public MRV methodology.
A.11	Field coordination across air CDR stakeholders to engage in iterative target setting and problem solving across all relevant thematic areas.[1, 8]	$	🟨 🔷 🔷	The field of DAC should continually be aligned on priorities and next steps to advance the pathway. This includes disseminating critical information and updates across Initiatives A.1 – A.10. Every five years, funders and field builders should update strategies to drive the most promising technology areas forward.

Source: Author analysis. See figure notes in *Appendix C*.

One of the top barriers facing air CDR is its current cost, driven in large part by its significant energy consumption. Increased R&D, advancing new innovations and moving these swiftly to lab- and pilot-scale (A.1), can help bring down energy requirements and make DAC much less expensive. This includes work on system design improvements and on materials breakthroughs to reduce energy demand and enhance CO_2 uptake. It also includes identifying strategies for co-siting with processes that produce geothermal or industrial waste heat. This type of co-siting can reduce demand for low-carbon electricity and thus conserve that electricity for other climate solutions. This is especially urgent for geographies and regions with high energy burdens and low or slow-growing access to clean energy. By 2035, successful DAC approaches should seek to demonstrate total energy requirements of 2.5 gigajoules (700 kilowatt-hours) or less per ton CO_2.[xxxvi] Approaches that demonstrate the lowest projected electricity demand while also avoiding negative environmental impacts are better positioned to proceed toward larger-scale deployment.

Box 12
Research priorities for air CDR

- Materials breakthroughs, including novel or improved sorbents
- Process energy efficiency, design, and feasibility improvements (e.g., to reduce energy requirements)
- Novel, scalable approaches for removing CO_2 from the atmosphere
- Process integration, including co-location with heat sources to reduce electricity demand
- Improved monitoring and verification of removals, including accounting mechanisms
- Improved understanding of the impacts, benefits, risks, and costs of DAC development and deployment in communities

Another significant cost driver for DAC is the significant up-front capex cost of new facilities. Overcoming this barrier will require unlocking sufficient financing (A.2). However, unlocking private financing for these facilities requires first de-risking these approaches from a technical, environmental, and economic perspective. Like other high-capex technical demonstrations and deployments, air CDR faces a chicken-and-egg problem where more successful facilities are needed to unlock financing, but financing is needed to build those facilities. This cycle can be jump-started with small-scale financing and offtake agreements that unlock funding for midsized (<100 kilotons [kt] CO_2/y) facilities, enable learning by doing, and eventually lead to larger facilities.

Because air CDR requires significant infrastructure and materials, the long-term costs and scalability of these approaches will also depend on the establishment of robust supply chains for equipment such as air contactors and for recycling, reuse, or end-of-life plans for solvent and sorbent materials (A.7). Here, DAC may compete with other growing industries for material inputs. As research narrows in on the most promising materials (A.1) and demonstration projects highlight which air CDR approaches will be most likely to scale (A.4), it will be important to invest in relevant supply chains so they do not become a bottleneck to growth. Ongoing collaboration and data sharing (A.11) can also help the field identify and overcome barriers that may arise due to the future availability of material and energy inputs.

[xxxvi] See ***The Applied Innovation Roadmap for CDR*** (RMI, 2023, pp. 198–202, 224–325). This benchmark was also informed by expert review as part of the GHGR roadmap review process.

Development of CO_2 transportation and storage technologies is beyond the scope of this roadmap; however, it is a key dependency for air CDR. Rapid DAC project deployment will require clear standards and permitting pathways for safe CO_2 transportation and storage (A.8, A.10). Siting all DAC demonstrations to optimize locally available power, water, CO_2 transportation, and storage infrastructure can help avoid energy or material shortfalls or increased risks for local environments and communities (A.3). As the number of successful deployments grows, it will become possible to formalize standards and learnings and build on these successes. For example, scaled deployment of projects for carbon capture and storage, a related field, has already established a precedent of safe and verified CO_2 storage on which future projects can be built.

Among technological CDR approaches, DAC is relatively visible in the public eye because it is the first approach with a large number of commercial-scale projects being deployed. This visibility provides some financial and policy support, but it also means that DAC plays an important role in setting precedents for responsible, successful CDR deployment and in shaping how the public views CDR as a whole. DAC projects that engage communities and provide benefits are vital to establishing the rapport of the industry, and documentation of best practices on co-creation with DAC communities can benefit other GHGR technology development that comes after.

Not all DAC needs to or should be company led. Actors in the field should explore alternative models for project initiation and ownership, including municipality- or publicly owned projects (A.5; see key terms for more examples) and projects with community codesign. New commercial-scale DAC deployments should prioritize engaging communities in the planning stages to understand and address location-specific needs, concerns, and opportunities (A.6, A.9). Synergies specific to chosen locations, including the availability of resources and existing infrastructure, should be incorporated into project siting (A.3) and communications. Mechanisms to ensure human and environmental safety of CO_2 transportation and storage infrastructure (A.8) need to be put in place before DAC approaches are implemented at scale. Global funding and financing structures should be developed to ensure under-resourced countries and localities have the opportunity, if desired, to deploy DAC under local leadership in ways that deliver benefits to local communities.

DAC facilities are closed systems, meaning their CO_2 capture and storage happens within the system. This is in contrast to open-system CDR such as enhanced rock weathering where the CO_2 capture occurs in the open environment. Because of this difference, reliable MRV will be easier for DAC, but by no means guaranteed. It will be necessary to develop MRV standards that utilize transparent LCAs that include process and reversal risks from CO_2 transportation and storage, account for net carbon removal, and monitor cradle-to-grave environmental impacts (A.10). These activities should be developed alongside regulatory structures such as permitting processes and should become standard practice across all DAC projects by the early 2030s to provide trusted and traceable carbon removal.

Finally, in order to enable rapid learning across air CDR development areas, the field needs increased coordination (A.11). Greater collaboration can allow DAC providers to learn from each other's successes and failures in project siting, permitting, financing, community engagement, and industrial integration. Field coordination can also create open lines of communication between the scientists and engineers who develop and optimize DAC processes, the standard setters, the MRV developers, and the community members who are experts on concerns that are specific to potential deployment sites. Data sharing on innovations in materials and process design as well as measurement and mitigation of environmental risks will help the field advance quickly and safely. Therefore, it should be a goal of the air CDR community to develop incentive structures for rapid data sharing, to continue to update deployment targets based on the growth of the field, and to support the development of transparent MRV implementation across all DAC approaches.

Box 13
Biggest barriers facing air CDR

- **Cost of removals:** DAC currently costs more than \$600/t CO_2, making it one of the most expensive CDR approaches.[xxxvii]
- **Energy consumption:** DAC is currently highly energy intensive. Energy use is a large driver of DAC's operational costs and contributes to the high cost of removals. Moreover, high energy consumption can lead to competition with other energy transition activities for low-carbon energy and will amplify the climate challenge given the additional global energy that will be required to power the removal plants.
- **Capex financing:** DAC plants are large industrial facilities that require significant up-front capital. Unlocking financing is an immediate barrier to scaling DAC.
- **Establishment of supply chains:** Sufficient supply chains are needed for equipment such as air contactors as well as for solvent, sorbent, and membrane materials.
- **Enabling infrastructure:** DAC units are large industrial processes that will require ancillary infrastructure such as new CO_2 transportation and storage facilities.

7.2 Initiatives for Ocean CDR

Ocean CDR refers to any CDR approach that takes place in aquatic environments. This includes open-system approaches such as growing macroalgae (e.g., kelp) or cultivating microalgae in open water and sinking it, adding alkaline materials to water to reduce acidity and increase ocean capacity for CO_2 absorption from the atmosphere (an approach referred to as OAE), and using electricity to remove CO_2 directly from water, sometimes in conjunction with wastewater treatment or desalination facilities (referred to as IWC).[xxxviii]

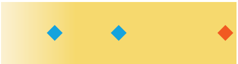
Figure 9 presents technology roadmap initiatives that are needed to advance ocean CDR toward scale, to determine what approaches have the greatest potential, and to enable the field to focus on the most promising approaches by 2035. These initiatives are focused on field trials, the development of MRV, clarification of regulatory frameworks, and assessment of potential environmental impacts.

[xxxvii] Current cost of DAC is estimated at \$600/t CO_2 (***The Landscape of Carbon Dioxide Removal and US Policies to Scale Solutions***, Rhodium Group, April 2024). It is estimated that costs as low as \$100–\$300/t CO_2 are achievable (Lukas Kung et al., "**A Roadmap for Achieving Scalable, Safe, and Low-Cost Direct Air Carbon Capture and Storage**," *Energy & Environmental Science* 16, no. 10 [2023]). The U.S. Department of Energy Carbon Negative Shot sets a target of < \$100/t CO_2.

[xxxviii] These and other ocean CDR approaches, including definitions and examples, and the innovation needed to advance them, are described in ***The Applied Innovation Roadmap for CDR*** (RMI, 2023). Most are at low to medium TRL. Other recent reports offering information on the state of the field and proposed advances include "**Depending on the Ocean: Research and Policy Priorities for Responsible Ocean Carbon Removal**" (Carbon 180, 2023), ***A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*** (National Academies, 2022), and **Ocean-Based Carbon Dioxide Removal: Road Maps** by Ocean Visions.

Figure 9 Initiatives for advancing Ocean CDR technology to 2035

Costs: $ <$100M $$ $100M-$1B $$$ >$1B **Timeline:** 🟨 Work ongoing 🔹 Checkpoint 🔸 Decision point

INITIATIVE	ACTION	COST	2025 2030 2035	ASSESSMENT OR MILESTONES
O.1	Fund $500M of R&D to establish an ocean baseline, understand biogeochemistry, and characterize ocean CDR technology interventions.[1,2,3]	$$		Funding identified by 2026. Research results are regularly incorporated into ongoing MRV model efforts (O.3 and O.4). By the late 2020s, ocean baselines are established that enable MRV for ocean CDR and ensure ocean safety.
O.2	Develop, manufacture, and test hardware for ocean CDR approaches including drones, sinking tech, sensors, and other monitoring technology.[1,2]	$$		Within each ocean CDR approach, component technologies that prove most efficient and effective become standard. New hardware needs identified in 2025. Progress on hardware development evaluated by late 2020s. New technology is developed to enable efficient biomass sinking and ocean measuring.
O.3	Develop robust ocean systems models for characterizing ocean CDR safety and MRV.[3]	$$		A complete ocean system model is developed by 2030 that reliably characterizes ocean CDR interventions and activities. Research and field trial data are regularly incorporated into the model.
O.4	Develop risk assessments, LCAs, and standards to inform MRV for each ocean CDR approach and to characterize human health and environmental impacts.[1,3]	$$		LCAs are developed for each approach. By the late 2020s, approaches with unclear impacts or harms are deprioritized. By the early 2030s, government-backed MRV standards are established based on LCAs.
O.5	Meaningfully involve communities in initial siting and project design process for 100% of field trials and demos.[1,4,5]	$		Processes used to engage with communities are regularly iterated based on feedback and project success. MRV and research results are disseminated to communities to inform deployment decisions (O.4).
O.6	Conduct >60 field trials[6] across ocean CDR approaches.[1,2]	$$		Field trials are scoped by 2026 and underway by the late 2020s. The most successful approaches are evaluated in the early 2030s and their results are used to advance to pilots and prioritize demonstrations.
O.7	Develop global ocean CDR deployment models by the late 2020s. Utilize global models of shipping routes, coastal land use, marine protected areas, and existing industry for demo siting.[7]	$		Ensure the development of global ocean models by late 2020s and then update these models at least every five years. Demo siting should be influenced by local needs and should incorporate community input beginning in early project stages.
O.8	Clarify and revise regulatory frameworks for at least one ocean approach per country in 40+ countries.[8]	$		Countries undergo processes to clarify permitting for field trials and pilots, moving to permitting larger deployments as CDR approaches mature and are deemed safe. Draft regulatory frameworks by 2026 and established permitting for 40+ countries by early 2030s.
O.9	Establish or revise international regulations that allow for open ocean deployment with a permitting process of <2 years for approaches deemed safe and effective.	$		An international working group[9] to increase global knowledge sharing convenes by 2026. By 2030, an existing or new international body is established to govern ocean CDR. Regulations are revised and iterated based on MRV developments and environmental safety assessments.
O.10	Operate >40 standalone ocean CDR demonstration projects for a removals total of >16 Mt CO_2/y.[5,10]	$$$		Demos are scoped by 2027 and at least half begin operation by 2030. By 2035, only tech that can scale safely should proceed. Some demonstration projects trial alternative (e.g., community or municipal) ownership models.
O.11	Operate >20 demonstration projects with industrial integration. These projects should have total removals of >8 Mt CO_2/y.[5,10]	$$		Demos (e.g., integrated with shipping, mining, or wastewater treatment) are scoped by 2026 and at least half are operational by 2028. By early 2030s, only tech that can scale safely should proceed.
O.12	Dedicated sourcing of alkaline minerals for OAE increases to 100 Mt of material.[11]	$$		Materials should be procured based on global and local resource demands and should factor in energy costs of transportation. New mine deployment should be avoided by using waste materials when possible.
O.13	Field coordination across ocean CDR stakeholders to engage in iterative target setting and problem solving across all relevant thematic areas.[1,12]	$		The field should regularly align on priorities and next steps to advance ocean pathways. This includes disseminating critical information and updates across Initiatives O.1 – O.12. Every five years, funders and field builders should update strategies to drive the most promising technology areas forward.

Source: Author analysis. See figure notes in *Appendix C*.

Technological ocean CDR approaches vary greatly in their TRLs, research needs, and resource use.[xxxix] However, one of the most common threads across ocean CDR is the need to better understand ocean baselines and ocean biogeochemistry (the physical, biological, chemical, and geological processes of the ocean) and to characterize ocean CDR technology interventions (O.1).

Ocean CDR interventions are challenging to understand because they take place in open systems, outside of human control. This also makes them particularly challenging to quantify. Properly characterizing ocean CDR approaches will require new hardware approaches for measuring ocean systems (O.2) and the development of robust ocean systems modeling for characterizing ocean CDR safety and MRV (O.3). Once these interventions are better characterized, it will be possible to develop risk assessments, LCAs, and standards to inform MRV for each ocean CDR approach and to characterize human health and environmental impacts (O.4).

Box 14
Research priorities for ocean CDR

- Materials innovations and improvements in electrodes, bi-polar membranes, and membrane materials for electrochemical ocean CDR approaches
- Novel approaches for extracting dissolved inorganic carbon from seawater
- New processes or process design and improvements for electrochemical ocean CDR technological approaches, including pilot scale tests and process integration with existing industry (e.g., desalination). Process designs should also consider novel disposal or use of byproducts such as chlorine gas and hydrogen.
- Open ocean microalgae and macroalgae growth processes and sinking, including hardware development, field studies, and related in-field measurements
- Advances and breakthroughs for microalgae in ponds
- Measurement and monitoring of environmental ocean metrics to establish an ocean baseline, including modeling ocean systems and biogeochemistry in the ocean
- Development of an open-source, global documentation system for studies, trials, and results of ocean CDR projects
- Measurement and monitoring of the short- and long-term impacts of ocean CDR approaches on environmental ocean metrics and ocean communities (impacts, costs, risks, and benefits). This includes the environmental, economic, health, and social effects of adding alkalinity to the ocean, adding biomass to the ocean, cultivating biomass in the ocean, sinking biomass in the ocean, and/or removing biomass from the ocean. This includes approaches such as micro-algae and macro-algae (kelp) cultivation and sinking as well as approaches that add alkalinity to the ocean, including mineral alkalinity and electrochemical alkalinity enhancement.
- Improved hardware and sensor development of open ocean CDR for understanding environmental impacts and developing MRV.
- New and improved software and modeling for characterizing CDR durability, MRV, LCA, and the final destination of carbon in ocean CDR
- Pilot-scale field tests to research environmental, ecosystem, and human health impacts as well as the effectiveness of electrochemical ocean CDR approaches
- Pilot-scale tests of mineral alkalinity enhancement to understand reaction kinetics, dispersal, and dissolution rates, interactions with biological and chemical cycles, and end destination of formed caronates. Pilot-scale tests may also study the sourcing, transportation, and distribution of alkaline materials, particularly as it pertains to scaling of these approaches.
- Improved understanding of sustainable ocean CDR potential by region, including community impacts, costs, risks, and benefits

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[xxxix] For more information on project scope and TRLs as defined in this roadmap, see ***The Applied Innovation Roadmap for CDR*** (RMI, 2023, pp. 379, 387–390).

Ocean CDR approaches also have a number of R&D questions that are specific to each approach. For example, for algae-sinking approaches, both growth and sinking processes need to be further studied to understand the impacts of fertilization and sunk biomass on the ocean environment.[xl] Environmental impact assessments of these approaches require measurement and monitoring of ocean metrics such as nutrient levels, oxygen content, and carbon content.

For electrochemical ocean CDR approaches, R&D efforts should focus on process development and materials innovation for electrodes and membranes as well as on environmental impact studies and quantification of removals through modeling, systems research, and field testing. OAE requires additional studies to better understand the impacts of adding alkaline materials to ocean systems, including pilot-scale tests of reaction kinetics, dispersal and dissolution rates, interactions with biological and chemical cycles, and the end destination of formed carbonates.

In addition to R&D, field trials will also be needed to optimize ocean CDR approaches and to understand impacts (O.6). This can be done through specifically designated field trials and test beds in locations identified through stand-alone demonstration projects (O.10) or through integration with existing industries (O.11).[46] Siting decisions should make use of global ocean use models that include shipping routes, marine protected areas, and other relevant information (O.7). Such models could also be used to identify regions where additional ocean observation and measurement efforts may be needed.

[xl] Many studies question the viability of these approaches (*A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*, 2022).

For field trials, pilots, and demonstrations, community involvement will be vital (O.5). Communities should be engaged through ongoing conversations about project design, and results from ocean systems modeling and other research from Initiatives O.1, O.3, and O.4 should be disseminated to communities to inform them about deployment decisions. Through community engagement, projects should seek to reduce negative impacts and provide co-benefits to those who will be most affected by deployment. Finally, these processes should be regularly iterated based on feedback and project results. Clarity on permitting pathways and regulatory frameworks for ocean CDR is also important to ensuring its success (O.8). Ocean approaches are relatively new ideas, which creates two problems: (1) there are not yet sufficient permitting pathways or regulatory frameworks for ocean CDR, and (2) it is not yet clear how ocean CDR activities will affect ocean systems. As described above, field trials can be used to understand ocean impacts, and these field trials can be used to shed light on what is needed to develop new permitting pathways and regulatory frameworks. However, care must be taken to ensure that these field trials are done in ways that minimizes any negative impacts.

In projects that occur along the coast or in an exclusive economic zone, the results from early pilots and demonstration projects can be used to set precedents for permitting pathways. In the open ocean, permitting structures are more difficult. Legal frameworks for the open ocean, namely the London Protocol and London Convention, restrict what can be put in the ocean.[47] Over the next 10 years, these legal frameworks should be revised to account for ocean CDR, and an existing or new international body should be created to lead on international coordination and standard setting (O.9). Clarity in these areas can also act as a key enabler for ocean CDR by accelerating the process elsewhere and providing success stories for policymakers in other locations.

The results of these ongoing field trials should then be used to inform the development of ocean systems models, quantification standards, and MRV (O.3, O.4). In order to be deemed safe for deployment, ocean CDR projects should demonstrate safety under a wide range of geographies and operating conditions, including stand-alone facilities and as existing operations, such as desalination plants (O.10, O.11).

Deployment increases in line with Initiatives O.6, O.10, and O.11 will also require major shifts in supply chains. Two primary examples of this are the allocation of low-carbon electricity for IWC and the allocation of alkaline materials such as basalt for OAE (O.12).[xli] To minimize the effects of these deployments, the focus should be on opportunities for integration with other industries such as wastewater treatment and desalination. Such coordinated deployment can help avoid massive infrastructure build-out and instead focus on CDR that takes advantage of integration into existing efforts that are already moving significant quantities of water and minerals. This type of integration can reduce additional energy demands and include co-benefits to local ecosystems.

Field coordination will also help ocean CDR stakeholders align on priorities and prioritize funding (O.13). These activities should involve community members, scientists, funders, NGOs, companies, and anyone else that could affect or be impacted by deployment. Activities should also create open lines of communication between scientists who are experts in ocean systems, companies that are experts in CDR technology, and community members who are experts on their history and needs. Proactively exploring and addressing concerns from these three groups will enable ocean CDR that is sized, designed, and implemented based on shared understandings of safety and community wants and needs. Similarly, open-source global documentation for studies, field trials, and their results can enable shared learning and support independent impact assessments.

[xli] For more information, see ***The Applied Innovation Roadmap for CDR*** (RMI, 2023).

Box 15
Biggest barriers facing ocean CDR

- **Ocean systems science:** Ocean CDR approaches interact with complex and interconnected physical and biological ocean systems, making it difficult to predict and model ocean CDR impacts. The knowledge base of these systems and their interactions with marine biogeochemistry must be developed.
- **MRV:** The net carbon removal effect of open-system approaches is difficult to quantify. MRV will rely on both measurement technologies and systems modeling.
- **Deployment and monitoring hardware:** Ocean CDR approaches require a variety of new hardware. For example, electrochemical approaches require new materials and process equipment, and biomass sinking approaches need new machines to enable these processes.
- **Potential environmental impacts:** Beyond net carbon removals, other impacts of open-system ocean CDR approaches on ecosystems, good and bad, are often poorly understood. Approaches should be scaled only after careful assessment of their impacts on human and environmental health.
- **Legal frameworks:** Due to the international nature of ocean waters and the potentially impacted living ecosystems, international and national legal frameworks are critical. However, regulation is currently being executed through proxy legal frameworks that were not intended for ocean CDR. There is a need for either new or updated policies that cover research and deployment of the variety of ocean CDR approaches.

7.3 Initiatives for Land CDR

Land CDR refers to technological CDR approaches that remove CO_2 through photosynthetic biomass production and then process that biomass to durably store the removed carbon. This includes approaches that process photosynthetic biomass into more stable forms such as bio-oil, biochar, or biomass construction materials. It also includes activities that convert photosynthetic biomass into CO_2 and then store that CO_2, including BECCS. Land CDR also includes activities such as synthetic biology that enhance the plants themselves by making them grow faster, store more carbon, enable deeper and better rooting in crops, burial of carbon through biological sequestration (e.g., mycelium, bacteria), survive pest and pathogen attacks, and exhibit increased environmental durability.[xlii]

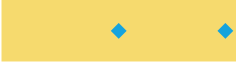
For the purposes of this roadmap, which focuses on scaling technological removals, land CDR does not include nature-based living biomass solutions, such as land management, conventional agricultural practices, and reforestation. Most of these out-of-scope approaches remove CO_2 through photosynthesis during the growth of biomass; however, they do not durably store the removed CO_2. A more detailed explanation of this scoping decision is included in Section 2. Note also that land CDR may overlap with other CDR approaches that use land, such as terrestrial enhanced weathering (rock CDR), DAC (air CDR), and electrochemical ocean CDR approaches (ocean CDR).

Figure 10 presents technology roadmap initiatives that are needed to advance land CDR toward scale, to determine what approaches have the greatest potential, and to enable the field to focus on the most promising approaches by 2035. These initiatives are focused on enabling the safe and rapid deployment of new activities for durably removing CO_2 from the atmosphere with land-based biomass.

[xlii] These and other land CDR approaches, including definitions and examples, and the innovation needed to advance them, are described in ***The Applied Innovation Roadmap for CDR*** (RMI, 2023).

Figure 10 Initiatives for advancing Land CDR technology to 2035

Costs: $ <$100M $$ $100M-$1B $$$ >$1B   **Timeline:** 🟨 Work ongoing ◆ Checkpoint ◆ Decision point

INITIATIVE	ACTION	COST	2025 2030 2035	ASSESSMENT OR MILESTONES
L.1	Establish and enforce regulations to minimize negative ecosystem impacts and land-use change. Use these to inform removal quality certification, leverage local expertise to avoid harms, and maximize ecosystem co-benefits.[1,2]	$$		International regulations, permitting, and enforcement are used to avoid CDR-driven monocultures, changes to crop rotations and land-use, native ecosystem conversion, invasive species, even aged forests, and other negative ecosystem impacts. All operations utilize these best practices. Standards in place by 2030 (L.2, L.3, L.4, L.5, L.6).
L.2	Perform >20 field trials for novel biomass building materials, biomass direct storage,[3] and other low TRL stabilized biomass approaches.[1,4]	$$		Field trials are underway by the late 2020s to answer open questions on removal durability, biomass sourcing, and project implementation. The most successful approaches advance to pilots, the results of which determine prioritization for demonstrations. Results utilize MRV and LCA best practices, in line with Initiatives L.8 and L.9.
L.3	Successfully operate 50 demonstrations of biochar, bioliquid, biomass direct storage, and microalgae in ponds across different geographies. These demos should provide at least 30 Mt CO_2/y of combined removals.[1,4]	$$$		Demonstrations should be sited by 2026 and operational by 2030. Demos should assess commercial viability across removal types and deployment conditions, with demonstration projects utilizing alternative (e.g., community or municipal) ownership models, per L.8. By mid-2030s, only tech that can scale safely should advance to larger scale.
L.4	Implement >12 commercial projects for timber buildings, biochar, and BECCS that integrate CDR.[1,4,5]	$$$		New commercial operations determine best practices for providing CDR as a primary or co-product and are performing at full capacity with >150 Mt CO_2/y combined removals. Projects are identified by 2026 and implemented by 2030. Operations should be sited to support communities and maximize co-benefits.
L.5	Deploy >20 industrial integration projects to leverage existing operations that can incorporate CDR at scales greater than 1 Mt CO_2/y.[1,2,4,6]	$$		New projects integrate CDR into existing industry processes, such as construction, agriculture. Projects should be sited by 2026 and should optimize co-location with existing supply chains. Efficacy of these projects should be assessed in the early 2030s.
L.6	Deploy 15-25 demonstration projects with alternative (e.g., community, municipal, nonprofit, or public) ownership models that generate local community benefits.[1,7]	$		Demonstration projects and deployments from Initiatives L.3, L.4, and L.5 employ distinct ownership models. Projects are identified by 2026. By the early 2030s, impacts and results are shared and used to inform future project implementation. Past projects inform best practices that are used to guide future deployments.
L.7	Fund and implement 3-5 pilot scale biomass cultivation projects to increase arable land and biomass production.[1,3,8]	$$		Projects should be scoped to safely provide new areas and methods for biomass production including reverse desertification, environmental remediation, and synthetic biomass. Projects are identified in 2025 and funded by 2027.
L.8	Establish standards for MRV, including long-term monitoring, to validate removals across approaches and biomass sources.[1,9,10]	$		Baselines and removals can be validated in the short term and long term for all projects, while accounting for potential reversals, additionality, and counterfactuals; results are shared with project communities and land-owners to inform continued project decisions.
L.9	Develop robust LCAs to determine the removal benefit of land CDR approaches and to optimize sustainable biomass sourcing.[10]	$$		Biomass utilization, land use, and process conditions can be accurately assessed for carbon efficiency across varied land CDR project types and biomass sources. LCA work should be funded by 2025. The results should be made public by 2030 and used to inform investments in future land CDR approaches.
L.10	Establish and enforce standards and permitting that inform removal quality for projects that store and utilize biomass and derivative materials.[1,11]	$$		Biomass storage, pyrolysis products, building materials, etc. have appropriate regulation for safe and sustainable CDR deployment, storage, and integration into relevant industrial processes and materials. Standards should be drafted at state, regional, or relevant jurisdictional level by 2026 and implemented by 2030.
L.11	Fund ongoing R&D for improving existing land CDR approaches, uncovering new approaches, and finding new ways to combine land CDR with other GHGR approaches.	$		R&D efforts are aimed at uncovering novel forms of biomass including through genetic engineering, novel ways of cultivating biomass, and novel ways of processing that biomass for GHGR purposes. Progress in these areas is assessed on five-year increments.
L.12	Field coordination across land CDR stakeholders to engage in iterative target setting and problem solving across policy, regulation, markets, and standard-setting.[1,12]	$		Ongoing field-level collaboration should be used to aligned on priorities and next steps to advance the pathway. This includes disseminating critical information and updates across Initiatives L.1 – L.10. Every five years, funders and field builders should update strategies to drive the most promising technology areas forward.

Source: Author analysis. See figure notes in *Appendix C*.

Land CDR approaches have some of the highest TRLs across all of CDR, and as a result, they are more ready to deploy than air, ocean, or rock CDR. Therefore, they must play a critical role in the near-term deployment of CDR. Initiatives L.2, L.3, L.4, L.5, L.6, and L.7 are all dedicated to deploying land CDR approaches in some way.

Box 16
Research priorities for land CDR

- Improved measurement and monitoring approaches for land-based CDR systems to better quantify, assess, and ensure durability
- Improved life cycle assessments (LCA), technoeconomic assessments (TEAs), resource assessments, and assessments of environmental and health impacts
- Research on synthetic and genetically enhanced cultivars including those that increase plant carbon uptake and storage, survivability through pest and pathogen resistance, and durability
- Improved understanding of sustainable land CDR potential by region, including community impacts, costs, risks, and benefits
- Novel and improved processes for biomass direct storage
- Novel and improved processes for pyrolysis approaches
- Optimization of BECCS equipment and processes
- Breakthrough material cultivation and processing such as non-woody biomass building materials

At the level of field trials, low-TRL land CDR approaches should investigate open questions about the performance and durability of these removals when using different biomass sources (L.2). Many land CDR approaches have been shown to work on a small scale, and field trials can help determine how these approaches work in practice. Several of these approaches should also be deployed at the demonstration scale (L.3). These demonstrations should be sited by 2026 and operational by 2030 in order to contribute to the CDR portfolio and goals outlined in Section 3. Demonstrations should assess commercial viability across removal types and deployment conditions, with demonstration projects utilizing alternative ownership models where possible (L.8). By the mid-2030s, only those approaches that can scale safely should advance to larger scale.

Some land CDR approaches should also be implemented at commercial scale (L.4), and some should be integrated into other industrial processes such as construction or agriculture (L.5). Approaches that are technically viable at commercial scale must be tested for market readiness of the approach and for establishing CDR markets. New commercial operations should advance approaches such as timber buildings, BECCS, and biochar toward providing CDR as the primary product or coproduct (L.4). In parallel, other operations should integrate CDR into existing industrial value chains, such as construction materials and soil amendments, to provide CDR as an additional product or benefit to industry while utilizing existing infrastructure (L.5). Commercial operations should investigate how to optimize removals with colocation for supply chain integration, community co-benefits, and regional suitability.

Deployments at commercial scale should also include the development of best practices for building infrastructure, permitting, and stakeholder coordination across varied operating conditions and constraints (L.6). Other process questions, such as water requirements for biomass cultivation and energy requirements for feedstock processing and transportation, should also be thoroughly investigated at demonstration scale. In general, land CDR projects should be deployed at scales relevant to their current TRLs and as rapidly as safely possible.[xliii] More mature approaches should advance only when they have a proven and sufficiently positive LCA, proven safety record, and positive community benefits plan, which each require continued attention to sustainable biomass sourcing over the duration of the project.

Growing enough sustainable biomass will be a major barrier to scaling land CDR. Without rigorous standards and safe practice for growing and harvesting sustainable biomass, land CDR at scale could have devastating impacts, especially as climate change further affects the availability of arable land. Initiative L.1 is aimed at ensuring that land CDR is done sustainably. Clear standards and enforcement from government, permitting, and crediting organizations that are clearly communicated with all project stakeholders are essential to ensure adequate sustainable biomass while avoiding practices such as crop rotations to actively produce waste biomass or change food production (L.1, L.9). All land CDR projects should assess the best use of available biomass, as well as health and environmental implications, with LCAs that account for cultivation practices to inform MRV (L.3, L.4, L.5, L.6, L.7).

Aligning stakeholders, including community members, researchers, project funders, and NGOs, on the state of land CDR efforts and next steps will also be important for enabling and accelerating deployment. Conversations and collaboration can surface ongoing and shared challenges, successes, and failures across project deployment, permitting, communications, and other common areas of effort. This will also facilitate coordinated advancement across the industry with minimal duplication of effort (L.12).

The potential for land-use change resulting from land CDR approaches requires careful assessment of sustainable biomass production and project deployment. This makes engagement and input from all stakeholders, especially those who have been historically excluded, essential before planning or undertaking any new deployment (L.12). Unintended consequences, such as damage to soil fertility, ecosystem loss, displacement of food production, and other specific local concerns, are a substantial risk that should be accounted for at all technical maturity levels. These risks and interdependencies must be carefully assessed with appropriate safeguards identified and enforced before scaling any project demonstration or deployment (L.1).[xliv] Solutions such as reverse desertification, environmental remediation, and enhanced cultivars can provide increased CO_2 uptake or increased durability of CO_2 storage in soils (L.7) and advance land CDR in parallel with other climate solutions.[48]

The learnings at each level of technical advancement should be applied across relevant approaches to continuously improve sustainable biomass production, land use, LCA implementation, best practices for siting projects, and beyond, to better deploy and scale land CDR. All land CDR projects should also provide due consideration to minimizing new infrastructure and impacts to relevant communities and environments through prioritizing strategic colocation with local efforts and implementation. These projects must have equitable engagement, respecting Indigenous land rights and addressing land-use conflict to avoid a repetition of historical harms. Projects should be incentivized to explore opportunities for alternative (municipal, community, nonprofit, public) ownership models and the associated opportunities to enable community, economic, and environmental co-benefits (L.6).

The quality and certification of land CDR removals depend on LCAs and standards for MRV that enable nuanced consideration of the full life cycle of sustainable biomass production, additionality of removals, storage durability, and long-term monitoring of the environment and soils with transparent, high-quality data from projects (L.8, L.9). Environmental impacts, health, and safety should all be considered, both to address potential risks and to understand the environmental remediation and related co-benefits that are possible. Additionality is critically important, especially for durable products such as timber and building materials, to determine whether net removals have occurred. Supply

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[xliii] See ***Roads to Removal*** (Lawrence Livermore National Lab, 2023) for example deployment scenarios.

[xliv] See ***The Applied Innovation Roadmap for CDR*** (RMI, 2023, pp. 13–20) regarding the critical path and stage-gates for safe scaling and deployment.

chain tracing and establishment of baseline carbon stocks will likely be essential to enable effective implementation. Developing these assessments and protocols is underway, but they must be iteratively improved with knowledge gained from ongoing deployments.

Box 17
Biggest barriers facing land CDR

- **Sustainable biomass:** Gigaton-scale removals will require a tremendous amount of biomass and associated land for cultivation. Optimizing cultivation and use of biomass (including synthetic cultivars) will be essential to ensuring sustainable biomass production.
- **Durability:** Land CDR removals are less stable than many other types of CDR, but the stability over time and under varied environmental conditions is not yet well quantified.
- **Open-system measurements:** Quantifying removals for open systems requires new measurement and modeling capabilities.
- **LCAs:** Full LCAs, including for the cultivation of biomass, are needed for land CDR to ensure that approaches are significantly carbon negative.
- **MRV development:** Better MRV is needed to determine whether removals occur when accounting for additionality, permanence, leakage, and the results of complete LCAs that include the emissions associated with cultivation and durability.

7.4 Initiatives for Rock CDR

Rock CDR includes all technological CDR approaches that remove CO_2 from the atmosphere by reacting it with alkaline minerals. These approaches typically seek to accelerate naturally occurring reactions of certain types of rock, such as basalt or other alkaline materials, to form either solid carbonate minerals or dissolved bicarbonates. In a simplistic way, one type of rock is reacted with CO_2 to form another type of rock or dissolved mineral.

Some rock CDR approaches simply seek to speed up the processes of natural weathering or mineralization under ambient conditions, whereas other approaches may increase the capacity of source materials to react or to accelerate feedstock reactions with CO_2 under controlled settings. For example, in enhanced weathering processes, alkaline materials are ground up and spread on land or along coastlines where they react passively with CO_2 and water.[xlv] In ex-situ processes, the weathering and mineralization steps take place in controlled reactors. In in-situ approaches, the CO_2 is mineralized in subsurface deposits, eliminating the need for mineral or rock extraction.[xlvi] In-situ approaches are often used for storage of concentrated CO_2 streams.

According to *The State of Carbon Dioxide Removal (second edition)*, funding for rock CDR still lags behind other forms of CDR.[49] In 2022, it was only 5% of total grant-funded CDR research. As a result, publications for rock CDR also lag far behind other CDR technology approaches, as do deals for scale-up and total removals.

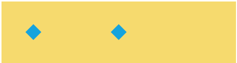
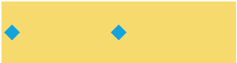
[xlv] Enhanced weathering is sometimes also referred to as enhanced rock weathering (ERW).

[xlvi] These and other rock CDR approaches, including definitions and examples and the innovation needed to advance them, are described in ***The Applied Innovation Roadmap for CDR*** (RMI, 2023).

Figure 11 presents technology roadmap initiatives that are needed to advance rock CDR toward scale, to determine what approaches have the greatest potential, and to enable the field to focus on the most promising approaches by 2035. These initiatives are focused on deployments, the development of standards for quantifying removals, and improved measurement and modeling techniques to inform MRV.

Figure 11 Initiatives for advancing Rock CDR technology to 2035

Costs: $ <$100M $$ $100M-$1B $$$ >$1B **Timeline:** 🟨 Work ongoing 🔷 Checkpoint 🔶 Decision point

INITIATIVE	ACTION	COST	2025 2030 2035	ASSESSMENT OR MILESTONES
R.1	Increase the safety and measurability of rock CDR through targeted R&D. Key areas for research are in measurements of mineralization to confirm that removals are occurring on relevant time scales. Research should be accompanied by environmental modeling to understand impacts of rock CDR interventions.[1,2,3]	$		Key research should be funded in 2025 for measuring mineralization rates for rock CDR approaches under deployment conditions and to fund the building of software models for characterizing rock CDR in open systems. By 2030, the results from this research should inform future deployment decisions. R&D should continue after 2030 on ways to improve rock CDR pathways, but the focus must be on 2025-2030.
R.2	Increase the efficacy of rock CDR through new methods for characterization of cost-efficient materials, improved processing, and feedstock pre-treatment.[3,7]	$		Material efficiency characterization methods should be funded in 2025 and in conjunction with Initiative R.1. By 2030, this funding should lead to significant increases in net removals through cost efficiency measures, process improvements, pre-treatment, ecosystem interactions, or other activities that enhance or accelerate CO_2 uptake.
R.3	Create a global inventory of alkaline feedstocks, including raw materials and industrial wastes, with information on reactivity, kinetics, contaminants, and other factors that inform optimal feedstock utilization.[3]	$$		Global alkaline mineral inventory should be funded by 2025 and active by the late 2020s. Globally, virgin and waste alkaline feedstocks should be identified and characterized to inform decision making on best use for specific materials in specific locations. This should inform resource, siting, and supply chain analyses and future deployments such as those of Initiative R.4.
R.4	Fund and operate 50-100 demonstrations capable of >200 Mt CO_2/y combined removals, distributed across distinct geographies and with a variety of ownership models, to assess performance across varied feedstocks and environmental conditions.[1,2,3,4]	$$$		Demonstrations include co-deployment with other CDR pathways as well as sharing of learning and best practices to identify the safest and most effective approaches. 30-50 demos should be scoped by 2026 and operational by 2030. By 2035, data from demonstrations should be used to determine which approaches should receive additional funding.
R.5	Deploy >10 industrial projects that integrate rock CDR into existing industry. This may include mining, construction, water treatment, and farming.[1]	$$		Pilot projects across at least four industries should be scoped in 2025 and deployed by the late 2020s with a focus on beneficial colocation of industrial activity and CDR. By 2030, safety results and best practices should inform decisions about larger demonstrations in the 2030s. These should be done in conjunction with R.4.
R.6	Develop new health, safety, and environmental measures for rock CDR processes and corresponding MRV protocols. Where possible, develop these processes from other industries, such as mining and farming.[1,5]	$		Draft processes completed by 2026 in conjunction with demonstrations of Initiative R.4 and in all regions where demonstrations are planned. By 2030, these processes should be adopted alongside the first operational demos. Processes and protocols should thereafter be updated regularly as the field evolves, in conjunction with Initiative R.7.
R.7	Establish location-specific community engagement processes with government support and backing for siting and permitting decisions on rock CDR projects; establish community benefit plans as negotiated by communities.[1]	$$		Alongside Initiatives R.4 and R.5, community engagement processes should be in place by 2026 as projects are scoped and implemented as projects are deployed. These processes should evolve based on feedback and project success, with local support, and with community guidance.
R.8	Align and improve on methodologies to quantify net removals, along with health and environmental impacts, to inform MRV and establish equivalencies between distinct projects.[6]	$$		MRV needs should be established in 2025. By 2030, ongoing research in Initiative R.1 should enable greater understanding of rock CDR MRV. By the early 2030s, rock CDR should meet recognized standards and demonstrate net climate and ecosystem benefits, leading to greater inclusion in Initiatives R.4 and R.5.
R.9	Expand supply chain to ensure adequate equipment for processing, transportation, and dispersal for increased feedstock handling and distribution.[7]	$$		By the late 2020s, planning should be initiated for scaling up rock CDR supply chains. By 2035, sufficient supply chains should be built to ensure expansion toward gigaton scale.
R.10	Field coordination across rock CDR stakeholders to engage in iterative target setting and problem solving across all relevant thematic areas.[1,8]	$		Field is aligned on priorities and next steps to positively advance rock CDR with established methods for disseminating critical information and updates, for example, across Initiatives R.1–R.9. Every five years, funders and field builders should update strategies to drive the most promising technology areas forward.

Source: Author analysis. See figure notes in *Appendix C*.

Rock CDR has significant potential as a means of climate change mitigation but has yet to establish a record of environmental safety and community co-benefits, or to overcome the barrier of robust quantification of removals in open systems, such as agricultural fields and waterways flowing to the ocean. The ability to provide trusted removals depends on addressing these challenges through understanding how to quantify net removals and to minimize negative impacts on human health and the environment.

The first initiatives needed to advance rock CDR are therefore in addressing these open questions. Initiative R.1 seeks to better characterize the safety and measurability of rock CDR through targeted R&D. This is necessary for quantifying removals, including the impact of environmental conditions on reaction rates. This work will also require complex software modeling to understand carbon fluxes and other impacts in large, open environments where empirical measurements are not practical or possible.

The research of Initiative R.1 should be accompanied by Initiative R.2, which seeks to increase the efficacy of rock CDR through cost-efficient material characterization methods, improved processing, and feedstock pretreatment. The science and evidence base for rock CDR remains immature, and long-term experiments have not yet been recorded. Priorities for research include long-term trials to evaluate the effects of rock CDR on soil fertility and health, its long-term impacts on productivity and profitability for farmers, and potential unintended health consequences of air, land, and water pollution associated with rock CDR. These open questions will need to be addressed through both R&D (R.1 and R.2) as well as demonstration projects (R.4).

Box 18

Research priorities for rock CDR

- Field testing rates of mineralization and methods to improve understanding of mineralization kinetics
- Siting analysis and mapping of the global distribution of mineral resources most appropriate for carbon mineralization, availability of mineral resources near agricultural areas, and assessment studies on regional rock CDR potential based on siting data and transportation constraints.
- Development of new sensors and hardware for improved in-field measurements
- Novel and improved technologies, including those incorporating existing infrastructure and input resources (e.g., mine tailings, mining or industrial waste, rock flour), materials and process efficiencies, and feedstock pre-treatments
- Development of rock CDR modeling tools for characterizing CDR durability, MRV, LCA, and the final destination of soluble carbonates, especially in varied environmental conditions and areas where direct measurements are not feasible
- Impact assessments to understand indirect effects of enhanced weathering, mining of alkaline minerals, and other rock CDR activities on agriculture, human health, local environments, and communities (impacts, costs, risks, and benefits).
- Hydrological surveys and follow-on studies to understand potential impacts of rock CDR on water (including availability).
- Pilot-scale field tests to research removal effectiveness and environmental and ecosystem impacts.
- Novel processes for integrating mineralization solutions into existing industry (e.g., integration with mining operations, wastewater or water treatment, building materials like concrete).

Besides R&D, one of the critical first steps for understanding the potential of rock CDR is to create a global inventory of alkaline feedstocks, including raw materials and industrial wastes, with information on reactivity, kinetics, contaminants, and other factors that inform optimal feedstock utilization (R.3). The goal of this initiative is to better understand where there is potential for rock CDR and to deploy those approaches in the most favorable locations. Many rock CDR projects do not require significant infrastructure build-out because they are technologically simple or they can be integrated into existing material handling workstreams, such as mining. This increases the geographic potential of rock CDR compared with air, ocean, and land CDR.

Demonstrations across geographies, deployment environments, and feedstocks should begin as soon as they can be safely conducted (R.4). These projects should be conducted across varied geographies and environments to assess performance. This includes determining optimal process conditions, such as water requirements for carbonate formation, and logistical considerations, such as the balance between additional material handling and carbon removals. In parallel, these projects can serve to identify potential improvements through material characterization for best use, process efficiencies, and feedstock pretreatment (R.2). Demonstrations and industrial integration should also inform supply chain requirements for projects to safely scale in the future, including the regional needs for equipment and feedstocks (R.8).

Some rock CDR approaches resemble many existing industrial practices such as agricultural liming. This creates opportunities to take advantage of existing health and safety standards and regulations for the transportation and utilization of minerals (R.6). It also facilitates the integration of rock CDR into existing industries (R.5). For example, integration with agriculture provides the possibility to increase soil productivity and displace carbon-intensive production of agricultural lime. Integration with the mining sector is expected to be significant given the sourcing and processing of large quantities of alkaline feedstock and because of the potential for environmental liability reduction through the carbonation of mining waste.[50] It may also be possible to use new and emerging forms of rock CDR to improve existing mining practices while simultaneously performing CDR.

Local engagement will be key to the success of rock CDR. These projects should establish location-specific community engagement processes with government support, pursue backing for siting and permitting decisions on rock CDR projects, and establish community benefit plans negotiated by communities (R.7). Rock CDR projects should fully engage relevant communities from ideation to end of life and seek to provide local co-benefits, such as improving agricultural production for small farmers.[51]

Accelerating rock CDR deployment should be done through equitable collaboration across the field, including stakeholders from academia, industry, and local communities, in order to create a positive feedback mechanism with regular touchpoints that align the field on progress, needs, and next steps. This is important for all projects, but it is especially critical for larger agricultural deployments and those integrated into industrial settings (R.4 and R.7). These collaborations should inform the development of best practices for community engagement and coordination in each project (R.7), advance standards for MRV development (R.8), and address ambiguity in policy and regulation for implementation, resource allocation, and safety.

Finally, it will be important for the field of rock CDR to align and iterate on methodologies to quantify net removals (R.10). All of the work across the first nine initiatives is intended to develop a greater understanding of what is possible and desirable with rock CDR. As this information is collected, comparative assessments across geographies will be crucial to share learnings and enable coordinated progress, as well as to track overall impact.

Box 19
Biggest barriers facing rock CDR

- **Impacts on human health and the environment:** There is still significant uncertainty about the impacts of rock CDR approaches on human health, other organisms, soil, water, and air from added alkalinity, metal leaching, or other environmental changes.
- **Modeling and measurement:** Sensors and measurement techniques are not yet sufficiently developed to monitor projects, and better models are needed to quantify removals at scale.
- **Mineralization rates:** Measurements of mineralization and weathering are needed to confirm that removals are occurring on relevant timescales.
- **Feedstock inventory:** A global assessment and inventory of alkaline feedstocks is needed to inform best use and strategic deployment of rock CDR projects around the world. Additionally, there are energy requirements for mining, processing, and moving alkaline minerals.

7.5 Initiatives for Non-CO_2 GHGR

Non-CO_2 GHGR refers to the removal of greenhouse gases other than carbon dioxide. As described in Section 2, the IPCC identifies four major categories of GHGs, but this roadmap focuses only on the removal of methane and nitrous oxide because of their significant warming impact and increasing atmospheric concentrations. The ways in which they differ from CO_2 significantly impact the technology, funding, and governance implications of their removals.[xlvii] These differences include:

1. **Potency:** Immediately upon release, methane and nitrous oxide have 120x and 273x more warming impact by mass than CO_2, respectively.
2. **Concentrations**: In the atmosphere, methane and nitrous oxide are respectively 200x and 1,200x less concentrated than CO_2.[xlviii] Because of their low atmospheric concentrations, much more air would need to be processed to remove 1 ton of the target gas.
3. **Residence time**: Methane and nitrous oxide have average atmospheric perturbation lifetimes of 12 and 110 years, respectively.[xlix] This means they are shorter lived in the atmosphere than CO_2, which has a perturbation lifetime of up to 5,000 years. Furthermore, the concentrations and resultant warming impacts of methane and nitrous oxide gradually decay as they degrade or exit the atmosphere. This makes their impact less stable over time than CO_2.
4. **Sources:** Anthropogenic emissions of CO_2 are dominated by the combustion of fossil fuels for energy. The breakdown of sources of methane and nitrous oxide is more complex. Direct emissions of these gases include direct leaks from fossil fuel operations, releases from agricultural activities (such as enteric fermentation in livestock and altered microbial activity in soils), and waste management processes (such as anaerobic decomposition in landfills).[l]

[xlvii] Concentrations, lifetimes, and discussion of related values such as global warming potential (GWP) metrics for these gases can be found in the *Sixth Assessment Report* Section 7.6.1.4, p. 1017. Note that GWPs are integrated over limited time horizons, showing lower values over longer timescales as atmospheric concentrations decrease.

[xlviii] Methane is 200x less concentrated in the air than CO_2 (1.9 ppm vs. 418 ppm), but each molecule is ~3x lighter than a molecule of CO_2, so it is 600x less concentrated by mass. Nitrous oxide is 1,200x less concentrated by both number and by mass because it has the same molecular weight as CO_2.

[xlix] Perturbation lifetimes indicate the time after a pulse emission of a gas for the atmospheric concentration to decay to 36% (1/e) of the initial increase.

[l] Enteric fermentation is fermentation that takes place in the digestive systems of animals. This is an especially important process in ruminant animals (cattle, buffalo, sheep, goats, and camels) that have a large forestomach, or rumen where microbial fermentation breaks down food into soluble products ("**14.4 Enteric Fermentation—Greenhouse Gases**," U.S. Environmental Protection Agency, accessed July 2024).

Indirect releases include emissions of methane from natural systems such as wetlands and thawing permafrost caused by warming temperatures.

5. **Complexity:** Unlike CO_2, methane and nitrous oxide are not chemically inert in the atmosphere. Instead, they interact with other gases and pollutants in ways that generate complex feedback loops tied to Earth systems, climate systems, and atmospheric chemistry. For example, methane can react with surface ozone.[52] Similarly, nitrous oxide is intimately connected to food systems and the nitrogen cycle, and increased nitrogen fertilizer applications can result in increased emissions.[53] Furthermore, biological sources and sinks of methane and nitrous oxide are connected, and reducing one of these gases may increase concentrations of the other. These interactions make it difficult to determine the effects of interventions or removals.

6. **Technological maturity:** Whereas CDR includes a range of medium- or high-TRL technologies, atmospheric methane and nitrous oxide removal technologies have not yet advanced past TRL 2, which is defined as "conceptual research applied to practical applications."[li] Some non-CO_2 removal technologies are at slightly higher TRL when deployed as mitigation strategies on sites with higher GHG concentrations, but even these technologies are not yet mature. Continued research in these areas may enable materials or process improvements that allow them to be used for atmospheric removals in the future.

Because of these differences, the removal of non-CO_2 gases from the atmosphere rarely refers to sequestration of the target gas, as is the case in CDR. Instead, non-CO_2 GHGR often involves a chemical conversion of the gas into a molecule with lower warming potential, such as the oxidation of methane to CO_2. Such processes are preferred because they are more energy efficient than atmospheric capture of the target gas. Often, this conversion would have eventually occurred naturally, but deliberately accelerating the process can accelerate the climate benefit by removing the gas more quickly.[lii]

Another important difference between CO_2 and non-CO_2 gases is that non-CO_2 gases are generally less well understood. This includes knowledge about the technological or economic feasibility of atmospheric removals of these gases, as well as modeling of the climate and Earth systems impacts of direct atmospheric removals of these gases. For this reason, it is not yet defensible to set explicit targets for non-CO_2 GHGR deployment. Instead, this roadmap sets a goal in Section 3 to advance the science of non-CO_2 removal by the early 2030s such that decisions can be made about future development and deployment.

Figure 12 presents technology roadmap initiatives that are necessary to achieve this goal. These initiatives are intended to develop a better understanding of which processes are technically feasible and can be deployed safely and what role, if any, removals of these gases should play in the overall portfolio of removal solutions.

[li] For more information on TRLs, see ***The Applied Innovation Roadmap for CDR*** (RMI, 2023, pp. 379, 387–390).

[lii] Throughout this section on non-CO_2 GHGR, atmospheric removals are discussed alongside high-concentration removals located near anthropogenic sources such as fossil fuel operations, dairy barns, feedlots, and landfills. The term "high-concentration removals" as opposed to "atmospheric removals" is used when discussing non-CO_2 GHGR in order to distinguish sources that are localized to human activities but not based on the combustion of fossil fuels for energy, and thus are not being abated through other aspects of the energy transition. This distinguishes them from point source capture approaches for CO_2 and changes the extent to which they pose a moral hazard of affecting emissions reduction efforts. High-concentration removals fall outside the direct scope of this roadmap as mitigation strategies. This is because only atmospheric removals can address legacy emissions and directly counteract the increasing extent of low-concentration releases from natural systems. However, work toward an improved understanding of the impacts of these gases, the sources of their emissions, and the expected extent of unmitigated or residual sectoral emissions will all factor into future scenario assessment and target setting for non-CO_2 GHGR. This will require coordination across the mitigation and removal spaces while being clear that activities to advance GHGR are, like CDR, not a substitute for reduction of emissions. Additionally, R&D on high-concentration removals may result in process improvements that make them feasible to implement at lower concentrations, thus adding them to the atmospheric removals portfolio in the future.

Figure 12 Initiatives for advancing Non-CO_2 GHGR to 2035

Costs: $ <\$100M $$ \$100M-\$1B $$$ >\$1B   **Timeline:** 🟨 Work ongoing 🔷 Checkpoint 🔶 Decision point

INITIATIVE	ACTION	COST	2025 2030 2035	ASSESSMENT OR MILESTONES
N.1	Fund 500 R&D projects[1] in academic and national labs. These projects should include interdisciplinary efforts to develop or improve S&T for the removal of methane and nitrous oxide and understand the basic science of non-CO_2 GHGR.	$$	🔷 🔷 🔷	By 2025 an R&D funding plan should be developed specifically for non-CO_2 GHGR. By the late 2020s, this plan should be funded and by the early 2030s, information for making decisions on the future deployability of these approaches should be possible. Research as part of this initiative should include: • Developing or improving non-CO_2 GHGR approaches, with regular updates and data sharing • Prioritizing approaches that show potential for deployment at atmospheric concentrations • Modeling and measuring unintended consequences including natural systems impacts and off-target GHG effects, for open-system approaches[2] • Determining feasibility and estimating material and energy costs at scale • Building relevant LCAs and including effects on CH_4, N_2O, VOC, and O_3 concentrations • Evaluating potential synergies with CDR approaches or industrial processes • Deploying at pilot scale when supported by TRL and safety assessment • Developing the necessary measurement and modeling capabilities to enable MRV of these approaches *Research priorities should be re-evaluated along with the results of Initiative N.2.*
N.2	Form teams focusing on non-CO_2 GHGR within national/international coordinating bodies to evaluate R&D priorities, fund crosscutting research projects, and create non-academic research structures where appropriate.	$	🔷 🔷	By 2025, international coordinating bodies should be assembled to evaluate R&D priorities for non-CO_2 GHGR and to determine means of collaboration. By the late 2020s, these groups should be assembling regularly. These groups should be engaged in activities such as: • Identifying feasible removal approaches targeting high- and low-concentration GHG sources for mitigation and removals portfolios • Iterating research targets with rapid shared learning based on key barriers (efficiency, safety, systems modeling, etc.) impacting removals approaches deemed relevant in N.5 • Initiating specific research efforts, such as interdisciplinary collaborations or focused research organizations, for specific projects such as improving efficiency, modeling natural systems, or trialing systems integration *Requests for proposals and project updates should occur annually. Successes are used to inform priorities in N.5.*
N.3	Allocate up to \$100M in research funding over 5-10 individual projects to develop coupled Earth systems models[3] to assess climate and pollutant impacts of proposed atmospheric interventions. These models should include atmospheric chemistry studies as well as atmospheric modeling.	$$	🔷 🔷 🔶	By 2026, funding should be allocated for these studies. By 2030, preliminary results should be available, and by the mid-2030s it should be clear how atmospheric interventions will affect atmospheric chemistry. Modeling efforts should include: • Incorporating atmospheric chemistry, kinetics, and capacities of CH_4/N_2O sinks, lifetime changes due to changes in atmospheric composition, and air quality feedbacks into coupled Earth systems models[4] • Using measurements from N.4 and scenario forecasts incorporating emissions reductions as inputs • Predicting warming and Earth systems impacts of emissions reduction/removals of CH_4/N_2O *Developed Earth systems models should provide key input for decision-making process in N.5.*
N.4	Implement spatially explicit monitoring of non-CO_2 GHG and related non-greenhouse gases.	$$	🔷 🔷	By 2025, this work should be scoped and funded. By the late 2020s, first results should be available. Activities should include: • Establishing consistent spatiotemporal records with source attributions of CH_4, N_2O, and H_2 concentrations[5] with constellations of ground, aerial, and satellite systems[6] • Monitoring emissions from natural systems and modeling increased emissions caused by climate feedbacks • Measuring outcomes of mitigation and removal efforts considered in N.5 and changes due to other human activities, such as CO_2 emissions reduction efforts increasing H_2 and CH_4 levels *Data should be made available after validation and quantification and used for modeling in N.3.*
N.5	Identify potential role of atmospheric removals in response to scenario forecasts of CH_4/N_2O emissions from natural system climate feedbacks and direct anthropogenic activity.	$$	🔷 🔶	Funding for these activities must be secured by 2026. By 2035, relevant metrics and achievable targets for atmospheric CH_4 and N_2O removal should be identified. And, based on the results of N.1 and N.3, these should be built into scenario models. To get there, this initiative includes: • Performing sectoral analysis of fossil fuel operations, agriculture, and waste management to predict residual emissions in different mitigation scenario forecasts • Assessing changes in and impact of CH_4/N_2O concentrations from residual anthropogenic emissions and natural systems, including increases from climate feedbacks • Considering best-case energy, material, and cost demands and net environmental impacts of approaches through R&D in N.1 and N.2, and net climate impact based on modelling and scenarios in N.3 and N.4 • Deciding what role atmospheric removals should play and what removals targets should be set

Source: Author analysis. See figure notes in *Appendix C*.

The first initiative that is necessary to help realize the goals for non-CO_2 GHGR is in basic research around removal of these gases (N.1). The goal of this initiative is to develop a better understanding of whether it is possible to remove these gases from the atmosphere, and this will require a significant increase in lab-scale research and modeling efforts (N.1). Specific research activities are included in Figure 12 as well as in Box 20 below.

Box 20

Research priorities for non-CO_2 removal (e.g., methane, nitrous oxide)

- Development of coupled Earth systems models that directly incorporate methane and nitrous oxide removal and assess climate and pollutant impacts of proposed interventions
- Studies on the feasibility, safety, scalability, and potential unintended consequences of removal approaches.
- Novel technological approaches for removing non-CO_2 GHGs from the atmosphere, including those that target multiple GHGs or benefit from synergies with industrial processes (see Section 2 for more information on point source removals being out of scope).
- Improved monitoring, including developing baseline assessments and forecasting models.
- Early studies of the impacts, benefits, risks, and costs of development and deployment of these technologies on communities.

One of the biggest challenges facing the removal of these gases is that they exist in such low concentrations in the atmosphere that removing them is very energy intensive. Even if removal is achieved, LCAs must be used to determine whether these removals are truly climate-beneficial, especially given the significant volumes of air that need to be treated to remove these low-concentration gases.[54,liii]

While always considering human and environmental safety, each approach should be moved to pilot-scale deployment as rapidly as possible to test its feasibility under real-life conditions (N.1). Closed-system approaches, such as catalytic reactors and bioreactors, that prove to be feasible may move to demonstration-scale testing before 2035. Open-system approaches, such as atmospheric oxidation enhancement, perturbations of microbial sinks in natural systems, and passive photooxidation systems, may need small-scale field trials, mesocosm studies, or even closed-system tests to study their impacts on natural systems.[liv] Further tests at the demonstration scale should take place only after approaches are proven to be environmentally safe and unintended consequences on natural and climate systems, including off-target GHG effects, are well understood. Increasing understanding of these open-system impacts is itself a key research priority within this initiative.

Because the field of non-CO_2 GHGR is so new, even if it proves viable, it will require rapid development to play a significant role in climate change mitigation by 2050. This will in turn require high levels of coordination across research efforts, rapid iteration based on early results, and reprioritization based on project successes (N.2). To facilitate this process, teams focusing on non-CO_2 GHGR should be formed within national or international research coordination bodies to evaluate the field and iteratively determine research priorities. This is already being done, for example, by the National Academies of Science, Engineering, and Medicine through a consensus study on atmospheric methane removal.[55]

[liii] A cube of air with side length of 900 m contains 1 t of CH_4 and 0.5 t of N_2O, but over 600 t of CO_2 (calculated at sea level and room temperature).

[liv] See Katrine A. Gorham et al. ("Opinion: A Research Roadmap for Exploring Atmospheric Methane Removal via Iron Salt Aerosol," ***Atmospheric Chemistry and Physics*** 24, no. 9 [2024]: 5659–5670) for examples of R&D objectives for an open-system atmospheric intervention, including research on relevant atmospheric chemistries and potential unintended Earth systems consequences.

Alongside academic research, structures supporting crosscutting and interdisciplinary research may be effective for rapid progress toward specific targets. This could include the development of LCAs of the climate impact of proposed interventions, studies of co-benefits and unintended consequences on natural systems, and impacts of removals on the concentrations of nontarget gases, as well as improvements in process efficiency and reductions in material costs.

While use-inspired basic research should inform what non-CO_2 GHGR is possible, parallel efforts must investigate the effect of these removals. Funding is needed to develop coupled Earth systems models to predict the impact of removal approaches and mitigation of methane and nitrous oxide emissions on climate and Earth systems (N.3). Such models should move beyond a stand-alone treatment of these gases and directly incorporate atmospheric chemistry, kinetics and capacities of sinks, air quality feedback, and changes in methane and nitrous oxide lifetimes due to changes in atmospheric composition. Together with efforts to better measure the sources and concentrations of relevant gases (N.4), models can help predict the Earth systems impacts of removals or mitigation activities against developed counterfactual scenarios, which model the outcome in the absence of a given action.

The first four non-CO_2 GHGR initiatives (N.1 to N.4) will be essential to inform decisions about the future role non-CO_2 GHGR should play in climate solutions (N.5). By 2035, relevant metrics and achievable targets for atmospheric methane and nitrous oxide removal should be identified and informed by the results of N.1 and N.3; these results should be built into scenario models that inform policy decisions. Given the early state of the field, these decisions may need to be iteratively updated based on advances in removal technologies (N.1, N.2) or changes in mitigation scenarios and intervention needs (N.3, N.4).

Initiatives N.1 and N.2 should also be used to determine whether non-CO_2 mitigation activities should count as removals or as reductions, because removals near high-concentration sources could count towards emissions reductions targets rather than the removal targets. This may include non-fossil fuel sources of non-CO_2 gases such as from agriculture and waste management.[56] It may also be necessary to remove a growing volume of indirect emissions that come from natural feedback processes, for example, natural releases of methane as a result of climactic warming. The availability of feasible technologies for non-CO_2 removals (N.1, N.2) and increased understanding of emissions trajectories determined through modeling and monitoring (N.3, N.4) will inform consideration of whether removals of well-mixed, low-concentration GHGs can effectively offset such indirect human emissions.

A key barrier to rapid progress in non-CO_2 GHGR is the lack of public understanding and awareness of non-CO_2 greenhouse gases. This includes knowledge of the existence of these gases, their climate impacts, sources, and mitigation options, as well as the analogies and differences between non-CO_2 GHGR and CDR. Outreach and public engagement, including through evidence-based journalism, can help build awareness and combat mis- and disinformation. Social science research is needed to understand public awareness and opinion of non-CO_2 GHGs and identify community concerns related to different proposed interventions. This understanding needs to be developed alongside the feasibility and impacts of different removal technologies to make it possible to build appropriate governance and funding structures. Projects that are deemed climate-beneficial must be deployed not only quickly but also transparently and safely.

Many of the approaches proposed to date that may be effective for atmospheric removals are open-system interventions, meaning they are enacted in the open environment. Safe deployment of such technologies will require an enhanced understanding of how interventions affect natural systems, in order to allow the prediction of GHG impacts and any unintended consequences or environmental risks. If the deployment of such approaches is deemed part of the climate solutions portfolio, careful and deliberate work will be needed to minimize and monitor environmental impacts, determine the appropriate scale of field testing, establish supportive governance structures, and develop community engagement processes that center on community needs while focusing on safety and equity. Non-CO_2 GHGR approaches should learn from and build on the development of the CDR industry.

As the field of non-CO_2 GHGR matures, it will also be necessary to develop metrics for these gases. This may include target atmospheric concentrations for different gases, emissions reductions relative to a baseline year, or total removals targets. This will require increased awareness and consideration of non-CO_2 gases in policies such as public and private net-zero commitments, as well as careful treatment of the implied fungibility of interventions across different GHGs. Although equivalence metrics such as global warming potentials provide an easy and convenient way to convert mitigated or removed tons of methane or nitrous oxide into tons of CO_2 equivalent, such values approximate the effects of complex time dependencies and Earth systems feedbacks related to changes in concentrations of these GHGs through a single average number. Short-lived GHGs generally demand different treatment when discussing targets for emissions or removals.[57] When attempting to analyze the equivalence between technological interventions targeting different GHGs, policymakers and regulators, informed by scientists, should carefully consider the most appropriate timescale over which any comparisons should be drawn and the impacts caused by climate and other natural system feedbacks.[58] By 2035 if not before, the field needs to have developed a sense of how these technologies can contribute to the overall GHGR scaling strategy. With that information, there will be a need to revisit the roadmap goals and path, taking non-CO_2 GHGRs into account.

Box 21

Biggest barriers facing non-CO_2 GHGR

- **Understanding of atmospheric systems:** The interactions of non-CO_2 GHGs with other molecules and particles in the atmosphere, which affect their residence times and polluting effects, are complex. Improved measurements and modeling are required to understand the impacts of removing these gases.
- **Removal technologies:** It is still unclear whether it is feasible to remove non-CO_2 gases from the atmosphere, and more research is needed to develop and improve possible removal approaches.
- **Unintended consequences:** The complex and interconnected web of sources and sinks of methane and nitrous oxide is not yet well understood. The effect of interventions is therefore uncertain. For example, some interventions could result in a longer atmospheric lifetime for methane.
- **Quantification of different removals:** Because non-CO_2 GHGs have different potencies, residence times, and atmospheric interactions, it may be difficult to quantify, compare, and incentivize removals.

8. GHGR Decadal Initiatives

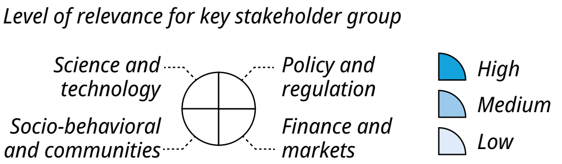
The goals set by this GHGR roadmap are for CDR to reach 10 Gt CO_2/y of durable, technological removals in 2050 and to advance the basic science of non-CO_2 removals such that decisions can be made about future development and deployment by the early 2030s. These goals, described in greater detail in Section 3, will subject the field of GHGR to intense scaling pressures. Achieving them will require setting a clear path of action, setting specific tactical milestones along the way, and then sticking to that path.

This decadal section of the roadmap describes that path and its milestones. It lays out the actions required from 2024 to 2050 to achieve the roadmap goals by uniting the activities of the thematic areas (Section 6) and technology initiatives (Section 7) to define crosscutting initiatives that must be achieved across the GHGR ecosystem. In this way, Section 8 is the main section of the GHGR roadmap because it describes the collective assembly of field-level initiatives that must be accomplished. Stakeholders should use this section to inform contributions, identify upcoming commitment and resource gaps, and accelerate partnering in the broader ecosystem of activities that are in service of the highest-level scaling goals of technological GHGR. This will ensure progress toward these goals and provide the best chance of attaining the needed scale by 2050.

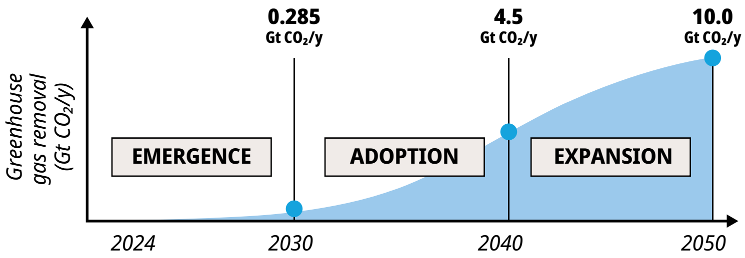
To create this path, the years from 2024 to 2050 are broken into three decadal periods.[lv] The first decadal period, from 2024 to 2030, is characterized by the emergence of GHGR and requires activities that enable the development of a portfolio of technological GHGR approaches. The second decadal period, from 2030 to 2040, is characterized by adoption of GHGR and will require dedicated activities to advance this new industry from a period of technological emergence to a period of widespread global implementation. The final decadal period, from 2040 to 2050, is characterized by expansion of GHGR and requires actions that sustain year-on-year growth rates of 5%–15% and achieve a gigaton-scale industry.

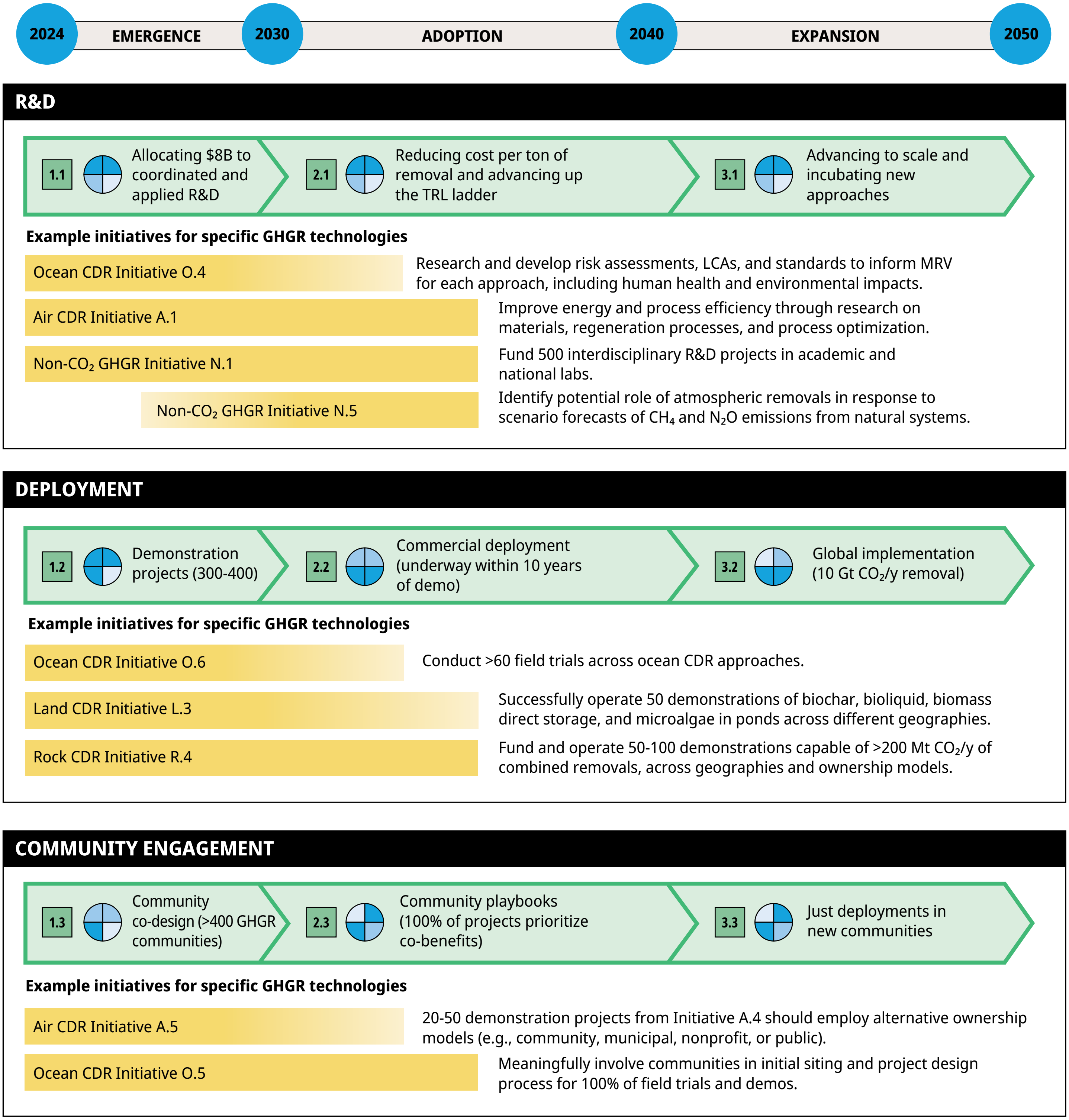
[lv] These three phases follow an S-curve trajectory and are described in greater detail in Section 4.

Figure 13 Roadmap for scaling technological greenhouse gas removal by 2050



Note: This figure combines elements from both the technology initiatives (Figures 8-12) and the decadal initiatives (Figures 14-16). The technology initiatives included here in yellow are examples and are intended to provide a sample of others covered in Section 7.





R&D

1.1 Allocating $8B to coordinated and applied R&D

2.1 Reducing cost per ton of removal and advancing up the TRL ladder

3.1 Advancing to scale and incubating new approaches

Example initiatives for specific GHGR technologies

Ocean CDR Initiative O.4	Research and develop risk assessments, LCAs, and standards to inform MRV for each approach, including human health and environmental impacts.
Air CDR Initiative A.1	Improve energy and process efficiency through research on materials, regeneration processes, and process optimization.
Non-CO_2 GHGR Initiative N.1	Fund 500 interdisciplinary R&D projects in academic and national labs.
Non-CO_2 GHGR Initiative N.5	Identify potential role of atmospheric removals in response to scenario forecasts of CH_4 and N_2O emissions from natural systems.

DEPLOYMENT

1.2 Demonstration projects (300-400)

2.2 Commercial deployment (underway within 10 years of demo)

3.2 Global implementation (10 Gt CO_2/y removal)

Example initiatives for specific GHGR technologies

Ocean CDR Initiative O.6	Conduct >60 field trials across ocean CDR approaches.
Land CDR Initiative L.3	Successfully operate 50 demonstrations of biochar, bioliquid, biomass direct storage, and microalgae in ponds across different geographies.
Rock CDR Initiative R.4	Fund and operate 50-100 demonstrations capable of >200 Mt CO_2/y of combined removals, across geographies and ownership models.

COMMUNITY ENGAGEMENT

1.3 Community co-design (>400 GHGR communities)

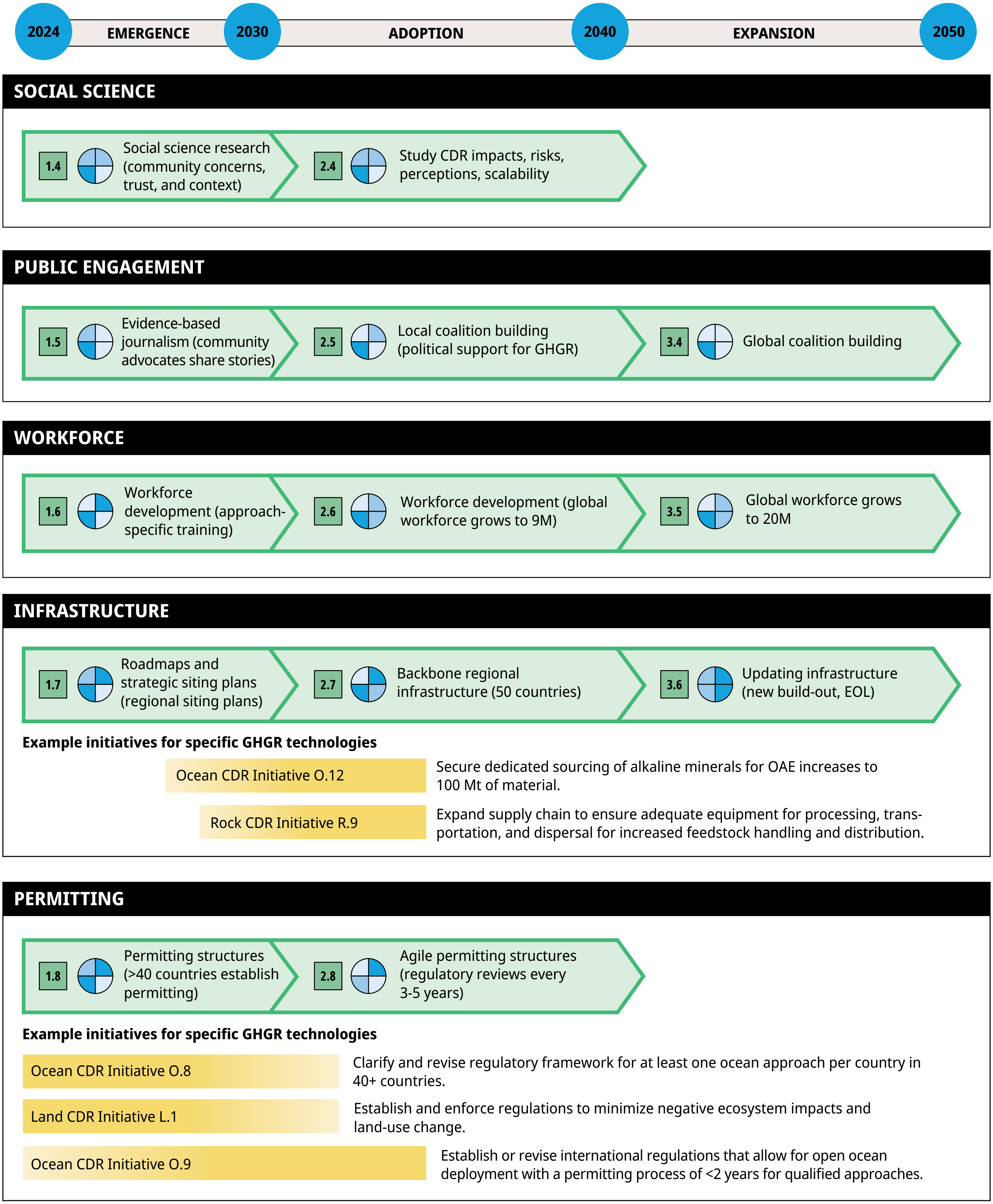
2.3 Community playbooks (100% of projects prioritize co-benefits)

3.3 Just deployments in new communities

Example initiatives for specific GHGR technologies

Air CDR Initiative A.5	20-50 demonstration projects from Initiative A.4 should employ alternative ownership models (e.g., community, municipal, nonprofit, or public).
Ocean CDR Initiative O.5	Meaningfully involve communities in initial siting and project design process for 100% of field trials and demos.

Figure 13 (Continued)



2024 EMERGENCE 2030 ADOPTION 2040 EXPANSION 2050

SOCIAL SCIENCE

1.4 Social science research (community concerns, trust, and context)

2.4 Study CDR impacts, risks, perceptions, scalability

PUBLIC ENGAGEMENT

1.5 Evidence-based journalism (community advocates share stories)

2.5 Local coalition building (political support for GHGR)

3.4 Global coalition building

WORKFORCE

1.6 Workforce development (approach-specific training)

2.6 Workforce development (global workforce grows to 9M)

3.5 Global workforce grows to 20M

INFRASTRUCTURE

1.7 Roadmaps and strategic siting plans (regional siting plans)

2.7 Backbone regional infrastructure (50 countries)

3.6 Updating infrastructure (new build-out, EOL)

Example initiatives for specific GHGR technologies

Ocean CDR Initiative O.12	Secure dedicated sourcing of alkaline minerals for OAE increases to 100 Mt of material.
Rock CDR Initiative R.9	Expand supply chain to ensure adequate equipment for processing, transportation, and dispersal for increased feedstock handling and distribution.

PERMITTING

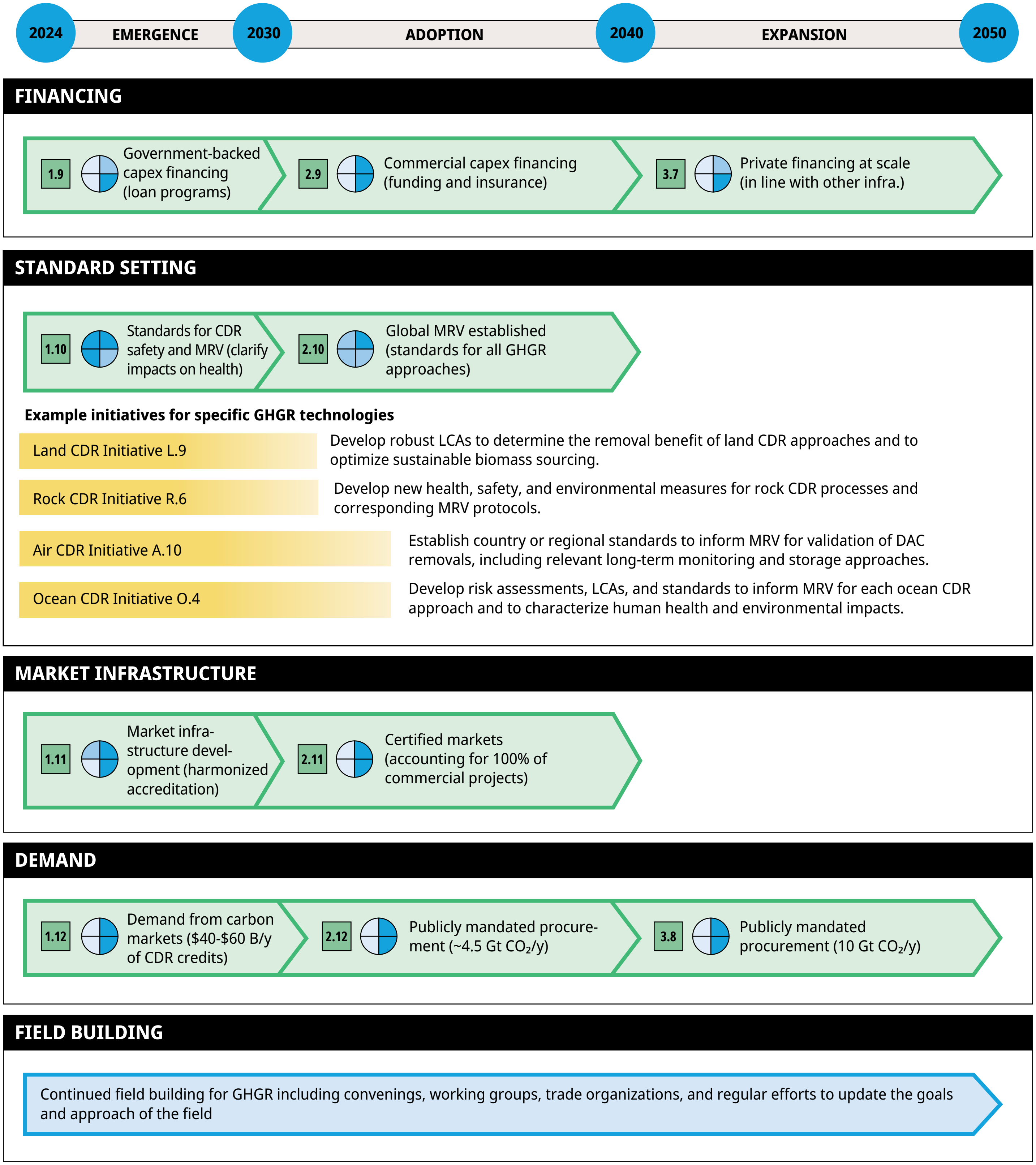
1.8 Permitting structures (>40 countries establish permitting)

2.8 Agile permitting structures (regulatory reviews every 3-5 years)

Example initiatives for specific GHGR technologies

Ocean CDR Initiative O.8	Clarify and revise regulatory framework for at least one ocean approach per country in 40+ countries.
Land CDR Initiative L.1	Establish and enforce regulations to minimize negative ecosystem impacts and land-use change.
Ocean CDR Initiative O.9	Establish or revise international regulations that allow for open ocean deployment with a permitting process of <2 years for qualified approaches.

Figure 13 (Continued)



2024 EMERGENCE 2030 ADOPTION 2040 EXPANSION 2050

FINANCING

1.9 Government-backed capex financing (loan programs)

2.9 Commercial capex financing (funding and insurance)

3.7 Private financing at scale (in line with other infra.)

STANDARD SETTING

1.10 Standards for CDR safety and MRV (clarify impacts on health)

2.10 Global MRV established (standards for all GHGR approaches)

Example initiatives for specific GHGR technologies

Land CDR Initiative L.9	Develop robust LCAs to determine the removal benefit of land CDR approaches and to optimize sustainable biomass sourcing.
Rock CDR Initiative R.6	Develop new health, safety, and environmental measures for rock CDR processes and corresponding MRV protocols.
Air CDR Initiative A.10	Establish country or regional standards to inform MRV for validation of DAC removals, including relevant long-term monitoring and storage approaches.
Ocean CDR Initiative O.4	Develop risk assessments, LCAs, and standards to inform MRV for each ocean CDR approach and to characterize human health and environmental impacts.

MARKET INFRASTRUCTURE

1.11 Market infrastructure development (harmonized accreditation)

2.11 Certified markets (accounting for 100% of commercial projects)

DEMAND

1.12 Demand from carbon markets ($40-$60 B/y of CDR credits)

2.12 Publicly mandated procurement (~4.5 Gt CO_2/y)

3.8 Publicly mandated procurement (10 Gt CO_2/y)

FIELD BUILDING

Continued field building for GHGR including convenings, working groups, trade organizations, and regular efforts to update the goals and approach of the field

Source: Author analysis. See figure notes in *Appendix C*.

The sequencing of initiatives across these three decadal periods is critical to ensure that GHGR can achieve the necessary scale in the time required. As shown in Figure 13, initiative areas extend across all three decadal periods with specific milestones defined at the end of each decade. This does not mean that action can wait until the end of the decade. Timing of the start of each initiative must take into account the length of time needed to meet the milestone by the year provided, to ensure no delays in this complex system of interconnected workstreams and realization of the roadmap goals in 2050.

Furthermore, the vertical ordering of the milestones in Figure 13 is due to grouping of initiative areas based on their primary thematic area (e.g., science and technology) and is not indicative of the level of importance of the initiatives. All initiatives within a decadal period must be addressed simultaneously to keep the field on track to achieve the 2050 scaling goals outlined in Section 3.

Finally, Figure 13 includes one additional initiative for field building that stretches across all three decadal periods. This initiative area is meant to capture the continued need for convenings, working groups, and other activities in service of building the supporting ecosystem of GHGR, including efforts to update the goals and initiatives of this roadmap as more information becomes available and the field develops.[lvi]

Initiatives across the three decadal phases are a blend of forward-looking assessments of what is most needed to advance the field and a backward-looking view from 2050 of what will be needed to achieve the long-term goals of this roadmap. As a result, the 2024–2030 initiatives contain greater detail on the specifics of what is needed in the near term, whereas the 2040–2050 initiatives are written more broadly and are meant to communicate where the field is aimed in the future. The differences between these two types of initiatives also signal the intended use of the roadmap. Near-term initiatives should be implemented immediately in service of 2030 milestones. They should also be seen as enablers for the success of the second and third decadal periods. However, by the time those periods arrive, the field of GHGR will have changed and will require new goals and new initiatives to guide near-term actions. With this in mind, all of the goals and initiatives of this roadmap should be updated regularly (every one to four years) to take into account the latest learnings, developments, and progress of the field.

8.1 Initiatives for 2024–2030

The first decadal period, from 2024 to 2030, is critical for laying the groundwork for GHGR, and the roadmap goals described in Section 3 will be achieved only if this first decadal period is a success. Therefore, action toward the initiatives described in this decadal period must be considered of high urgency and must begin immediately.

In line with the goals of the roadmap, this first decadal period must focus on scaling durable, technological CDR to ~285 Mt CO_2/y by 2030 and advancing the basic science of non-CO_2 GHGR so that decisions can be made by the early 2030s about future deployment. For the field to achieve these goals, several foundational elements must be established as soon as possible. The field must develop the technical elements of GHGR, codesign deployment alongside communities, clarify standards for MRV across different approaches, build political support, and establish sufficient demand at scale.

Figure 14 presents the initiatives that are necessary to advance GHGR during this decade. Note that the ordering of initiatives is not indicative of importance; many of the initiatives interact with and are dependent on each other, and all of them must be pursued simultaneously to keep the field on track to achieve its 2030 milestones. Scaling of GHGR, especially in the second and third decadal periods, will depend on success during the first decadal period; thus, it is imperative that the initiatives in this decade are rapidly planned, funded, and executed.

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lvi This initiative is included on its own because it does not apply to any of the thematic areas described in Section 6 but instead sits outside this framework and is meant to guide the field itself.

Figure 14 Roadmap initiatives for scaling GHGR removals from 2024 to 2030

Relevance of actors: ■ High ▨ Medium □ Low **Milestones:** 🔷 Checkpoint 🔶 Decision point

INITIATIVE CATEGORY	INITIATIVE	ACTION	ASSESSMENT OR MILESTONE BY 2030	THEMATIC AREAS S&T	SB&C	F&M	P&R
R&D	1.1 Technology search, incubation, and testing	Allocate $8 billion from a diverse set of funding sources to coordinated, use-inspired basic and applied R&D on GHGR between 2024 and 2030 with the goal of advancing scalable GHGR up the TRL ladder. Place particular focus on advancing non-DAC CDR and jump-starting non-CO_2 GHGR.[1,2,3]	🔷 At least 10 unique technological GHGR approaches have achieved first commercial deployment. Focus is placed on those approaches that have potential to achieve gigaton scale.	■	▨	□	■
Deployment	1.2 Successful first projects	Deploy 300-400 demonstration-scale projects across varied geographies and a range of CDR technologies. Integrate these facilities into existing industry and supply chains whenever beneficial and utilize innovative financing methods.[4,5,6]	🔶 Develop a situational awareness of global GHGR resources and capacities, to inform siting potential and other decisions. Proceed with future funding only for those technologies that demonstrate safe, durable, measurable, and cost-effective scale.	■	■	□	■
Community engagement	1.3 Frameworks for community codesign	Involve >400 GHGR communities in GHGR demonstration or deployment co-design from an early stage. Some deployments should be community-led and owned.[7,8]	🔶 Proceed only with future projects and GHGR approaches that are desired and approved by communities (e.g., community benefit agreements, feedback in public settings, surveys).	▨	■	□	▨
Social science	1.4 Community concerns, trust, and context	Conduct social science research to shed light on community concerns, trust, and social/cultural contexts, risks, costs, benefits, opportunities, and unintended consequences of GHGR technologies and their impacts on people and the environment.[9]	🔶 Community codesign practices are shaped by social science research.	▨	■	□	▨
Public engagement	1.5 Evidence-based journalism	Support a well-resourced comms strategy including funding local news outlets as well as community advocates to share stories about successful GHGR demonstrations. These stories should lead to ongoing dialogue and deliberation in the public eye.[9,10]	🔷 News stories have reached those not well-acquainted with GHGR and have led to increased interest. CDR and GHGR become part of vernacular, similar to "solar PV."	▨	■	□	□
Workforce	1.6 Approach-specific training	Establish approach-specific training and educational programs alongside workforce development organizations for all GHGR above TRL 6 and informed by the geographic and strategic planning activities of Initiative 1.7.[11]	🔷 Programs have been developed focused on both early-career (e.g., degrees, internships) and mid-career (e.g., reskilling, job transition) opportunities.	□	■	□	■
Infrastructure	1.7 Strategic siting	Publish global as well as country-wide and regional GHGR roadmaps and siting plans in collaboration with governments and NGOs in >40 globally distributed countries.[12,13] These plans should be developed alongside Initiatives 1.3 and 1.4 and should inform Initiative 1.6.	🔶 Countries commit additional resources to areas scoped for GHGR and have included GHGR targets in climate strategies (e.g., NDCs, climate action plans).	▨	■	□	■
Permitting	1.8 Established and clear permitting structures	Clarify and establish project permitting for at least one CDR approach in >40 globally distributed countries.[14] Permitting should include stringent community engagement guidance.	🔷 CDR activities are established globally so that there is sufficient traction for GHGR expansion from 2030-2040.	▨	■	□	■
Financing	1.9 Government-backed capex financing	Establish sufficient government-backed financing to ensure that access to capital for capex construction does not limit GHGR deployment.	🔷 Ensure financial support for up to ~285 Mt CO_2/y of cumulative early stage GHGR capacity deployment.	□	□	■	▨
Standard setting	1.10 Setting standards for CDR safety and MRV	Assess and quantify potential impacts of CDR deployment on environmental and public health, including through peer-reviewed research, to inform government-backed safety standards and MRV.[15]	🔷 MRV is informed by government-backed standards on environmental and public health impacts.	■	■	▨	■
Market infrastucture	1.11 Market systems, standards, intermediaries	Build commitments among existing markets and CDR actors to build out harmonized CDR accreditation, certification, fungibility, and risk management standards.[16]	🔷 Harmonized standards for CDR markets are developed.	▨	□	■	■
Demand	1.12 Increased purchasing from carbon markets	Facilitate purchases of $40-$60 billion per year of CDR credits from governments, voluntary buyers, companies, and others in voluntary and compliance markets. Develop framework and build support for publicly mandated procurement plans that have a collective, global purchase requirement of >4.5 Gt CO_2/y in 2040 and can be adopted in the first half of the 2030s.[17]	🔷 CDR procurement reaches ~285 Mt CO_2/y and is on track for integration into publicly mandated procurement in the early 2030s.	□	□	■	■

Source: Author analysis. See figure notes in *Appendix C*.

As discussed at the start of Section 7, achieving the overall goals of this roadmap will require a portfolio of technological GHGR approaches to reach commercial success. For this reason, one of the top goals of this decadal period is to advance GHGR up the TRL ladder to a point where at least 10 technological GHGR approaches have achieved first commercial deployment by 2030 (1.1). This will require use-inspired basic and applied R&D to incubate novel approaches, ensure public and environmental safety of technologies, and drive performance improvements in existing approaches. Particular focus should also be placed on advancing the technical readiness of non-DAC CDR (Sections 7.2, 7.3, and 7.4) and jump-starting the basic science behind non-CO_2 GHGR (Section 7.5) to determine its feasibility and potential role in lowering overall atmospheric GHG concentrations. The goal for this decadal period should be to complete the R&D necessary to determine which technological GHGR approaches have potential to achieve safe, durable, measurable, and cost-effective scale so that they can be maximally resourced in the second decadal period of 2030–2040.

Demonstration facilities across geographically diverse areas are also critical to enable deployment-led learning (1.2). Because of the financial risk of FOAK projects, GHGR stakeholders need to develop innovative financing interventions, including blended finance models, innovative insurance mechanisms, and large pools of equity and offtake. It will also be necessary for government-backed financing to be made available to ensure that access to capital is not limiting to early-stage GHGR capacity deployment (1.9). While most deployments are currently in North America and Europe, there is a need to test deployments under different geographies and operating conditions, including in the global south.

Where possible, demonstrations should be integrated into existing industry and supply chains to reduce the need for new infrastructure and to leverage existing waste streams (1.2, 1.7). For example, mining sites and wastewater treatment facilities both provide potential feedstocks (e.g., alkaline minerals and process water) for CDR processes and colocating with these activities can reduce the overall impact of deployment, reduce the overall costs, and potentially mitigate or neutralize existing waste streams.

Technology development, planning, and site selection for GHGR deployments must start with those who will be most directly affected by these activities: GHGR communities. As discussed in Section 6.2, deployment should seek to reduce potential harms, provide co-benefits, and be shaped by communities to create safe, equitable GHGR (1.3). To this end, funding should be allocated to local capacity building so GHGR communities, especially vulnerable populations, are able to design and influence deployment.[lvii] Governments can also incentivize community-led deployment by promoting communities as the driving force of GHGR and exploring alternative ownership models (e.g., cooperative, community, municipal, nonprofit, or public ownership models).

In instances when a developer enters a community seeking to deploy CDR, two-way engagement with community members must begin as early as possible and should continue through the entire timeline of a project. Alongside decision-making power, communities should reap tangible benefits, outlined by negotiated agreements with developers. Further, because CDR is a global solution and deployment needs to occur across a variety of social, cultural, economic, and political backdrops, social science research on community concerns, power dynamics, trust, and social contexts should explore place-based models of community codesign, ownership, and engagement (1.4). Deployments during this decadal period should seek to create a model framework of best practices that can be continuously improved upon and that can serve as a guide for deployments in future decades.

Different GHGR approaches vary widely in their TRLs and ARLs, and because of this, they will have different needs for R&D or demonstration-type support.[lviii] Some approaches, such as non-CO_2 GHGR, are very low TRL and ARL and require early-

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[lvii] For more information on local capacity building, see ***Removing Forward*** (Carbon180, 2021).

[lviii] For more information on project scope and TRLs as defined in this roadmap, see ***The Applied Innovation Roadmap for CDR*** (RMI, 2023, pp. 379, 387–390).

stage research. Other approaches, such as BECCS and timber building materials, are already being commercially deployed and simply need to demonstrate their viability under different operating conditions.[lix] Regardless of the readiness levels, researchers and companies of all approaches should be incentivized to share data, best practices, and lessons learned from their efforts to speed development, establish standards for MRV, and streamline permitting processes. Additional details on specific needs by technology approach can be found in the technology initiatives in Section 7.

During this first decadal period, it will also be critical to establish permitting standards and to develop protocols for MRV (1.10). MRV is a key enabler across all four thematic areas described in Section 6 because it enables buyers and sellers to confidently exchange removal credits, which in turn enables policymakers and financiers to confidently support the deployment ecosystem. Permitting standards also ensure that these activities properly quantify and regulate the impacts of GHGR deployment on environmental and public health. Clear standards for safety and MRV go hand in hand with the establishment of market infrastructure for supply chain traceability, accreditation, certification, fungibility, and risk management (1.11). Market infrastructure includes the companies and stakeholders that create the enabling environment for GHGR. Standard-setting and market infrastructure bodies must work toward harmonization of standards by 2030 because this will be critical for enabling the scale of absolute growth required from 2030 to 2040.

As discussed in Sections 6.3 and 6.4, government actors will serve an important role during this decade by developing strategic deployment plans and clarifying permitting pathways (1.7, 1.8). Subnational and national governments should work with NGOs to outline which areas are best suited for different types of GHGR, set removal targets that are separate from decarbonization targets, and identify actions necessary to meet these targets.[lx] Furthermore, government agencies should clarify permitting pathways within subnational and national jurisdictions and should model these permitting regimes based on FOAK demonstration projects. By 2030, there should exist a clear permitting pathway for at least one approach in at least 40 different countries (1.8). The goal of this initiative is to begin establishing CDR activities globally because this will be an important factor for enabling success in subsequent decadal periods.

The same applies to workforce development. Efforts (e.g., mapping labor and skills requirements, educational curriculum and programming development, university partnerships, accelerator and incubator programs, apprenticeship programs, retraining and job placement services) that prepare a GHGR workforce must be made available by 2030 so that these programs are ready to scale in the decade from 2030 to 2040 (1.6). These workforce development programs should place emphasis on creating safe, well-paying jobs for local community members.

[lix] Although these approaches are being deployed, they are not always being used for the primary purpose of CDR.

[lx] For more on the roles different levels of government should play in GHGR development, see Section 6.4.

Achieving all of these activities will require positive and sustained political support. This can be achieved through well-resourced, independent communications and journalism as well as evidence-based efforts to counter mis- and disinformation (1.5). Journalists and community advocates should publicize ongoing GHGR efforts, encourage dialogue, and help counteract mis- and disinformation surrounding GHGR. Moving into the 2030s, these efforts should also lead to local coalition building led by community advocates that advance equitable GHGR deployment.

In general, success in the first decadal period will be uniquely dependent on government involvement. It will be necessary to develop sufficient and scaled demonstration projects, standards and regulations, and workforce. However, the greatest need for political support and government involvement will be in establishing stable, scaled, long-term demand for CDR. As of April 2024, *cumulative* sales of CDR were around \$2.4 billion.[59] This must rise to \$40–\$60 billion *per year* if the field is to reach its intermediate scaling goal of ~285 Mt CO_2/y in 2030 in line with 10 Gt CO_2/y in 2050 (1.12). In the near term, this demand is expected to be driven by voluntary markets, advanced market commitments, purchases from major donors, models for massively aggregating the purchasing power of other actors such as buyers' coalitions, and other voluntary means.[lxi] These voluntary means of procurement will be important for advancing GHGR purchases to 2030, and they must remain a priority in the first decadal period. But, by the period from 2030 to 2040, in order to achieve the levels of purchases required of scaling goals, demand must move toward publicly mandated procurement (2.12). For this reason, the decadal period from 2024 to 2030 is important for demonstrating the effectiveness of CDR and generating the political support necessary for scaling CDR in future decades. Governments can also begin working toward this future by increasing incentive programs such as 45Q, the U.S. federal tax credit for carbon capture activities; building new programs for procurement, for example through compliance markets, federal procurement, or historical removal markets; and establishing stand-alone GHGR targets that are specified independently of reductions targets, as discussed in Section 6.4.

Putting all of this together, the period from 2024 to 2030 will be critical for laying the groundwork for the field of GHGR. By the end of this decadal period, it will be necessary to have deployed 300–400 demonstration projects and additional commercial facilities; established standards for safety, MRV, and community-led deployment; and mobilized \$40–\$60 billion/y of CDR demand in order to achieve the interim milestone of ~285 Mt CO_2/y of removals in 2030. The successes and failures of these initiatives will set precedents for how the field evolves in future decades. Moreover, fast-tracking progress on CDR in this first decade through policy, market development, and MRV should lay a path for potential non-CO_2 GHGR deployment in future decades. Achieving the goals of this roadmap will require stakeholder action in the first decadal period, from 2024 to 2030, to launch GHGR on an exponential growth trajectory to set the field up for success in future decades. This will only be achieved if significant action is taken immediately.

8.2 Initiatives for 2030–2040

To be on track to achieve the deployment goal of 10 Gt CO_2/y of removals by 2050, the decadal period from 2030 to 2040 must enable a 15-fold growth in CDR deployment from ~285 Mt CO_2/y in 2030 to ~4.5 Gt CO_2/y of capacity in 2040. This period will be especially challenging because it will require GHGR to emerge as a global, gigaton-scale industry.

Achieving the goals of this decade will require mobilization of supply chains, a build-out of workforce and critical infrastructure, evolving and expanding permitting structures, scaled financing, and the establishment of publicly mandated procurement. Community codesign and the development of a political-economic framework to support scaled demand will also remain essential during this period. Figure 15 presents initiatives aimed at advancing each of these areas during this decade. Note that the ordering of initiatives is not indicative of importance; many of the initiatives interact with and are dependent on each other, and all of them must be pursued simultaneously to keep the field on track to achieve its 2040 milestones.

[lxi] **Frontier** is an advance market commitment that has dedicated to buying > \$1 billion of removals from 2022 to 2030. It has >\$150 million in offtake contracts and almost \$70 million in prepurchases as of April 2024.

Figure 15 Roadmap initiatives for scaling GHGR removals from 2030 to 2040

Relevance of actors: ■ High ▨ Medium □ Low **Milestones:** 🔷 Checkpoint 🔶 Decision point

INITIATIVE CATEGORY	INITIATIVE	ACTION	ASSESSMENT OR MILESTONE IN 2040	THEMATIC AREAS S&T	SB&C	F&M	P&R
R&D	2.1 Technology adoption and emergence	Reduce the cost per ton of promising CDR and advance GHGR up the TRL ladder by allocating 0.5% of all climate spending to use-inspired and applied R&D.[1,2,3]	🔶 At least 10 unique CDR approaches with a combined scaling potential of >10 Gt CO_2/y have achieved commercial deployment. Decisions made on whether and how non-CO_2 GHGR should be deployed.	■	▨	□	■
Deployment	2.2 Commercial deployment	Initiate commercial deployment of successful FOAK demonstration-scale projects from Initiative 1.2 such that deployment targets must reach ~4.5 Gt CO_2/y removals by 2040.[4,5,6,7]	🔶 Deprioritize technologies that have not demonstrated safe, durable, measurable, and cost-effective scale.	▨	■	■	▨
Community engagement	2.3 Community playbooks based on successful deployments	Continue to co-develop CDR projects with communities based on past project successes and high community demand. Create customizable guides based on successful deployments that include siting, business, infrastructure, and community plans. Prioritize high-quality employment and ecosystem services.[8]	🔷 Each CDR approach that has reached commercial deployment has developed a set of customizable guides for future deployments.[4]	□	■	▨	■
Social science	2.4 Study CDR impacts, risks, perceptions, scalability	Conduct social science research on all CDR approaches that have reached commercial deployment as defined in Initiative 2.1 and with a focus on perceptions, risks, costs, benefits, and unintended consequences of scaling these approaches to a collective 10 Gt CO_2/y by 2050. Conduct similar social science research on non-CO_2 GHGR as appropriate and based on the results of Initiative 2.1.[9]	🔷 Engagement practices and future deployment decisions for CDR and non-CO_2 GHGR are shaped by ongoing social science research.	▨	■	□	▨
Public engagement	2.5 Local coalition building	Continue activities for public communication from Initiative 1.5. Form coalitions with community-based organizations and community advocates in new countries and new communities to sustain broad political support. Combined local support for GHGR projects globally must lead to ~4.5 Gt CO_2/y.[8]	🔷 Public support for CDR is high, and cities and regions compete for CDR projects.	□	■	□	▨
Workforce	2.6 Workforce development	Work with companies, governments, and workforce development organizations to develop adequate workforce training for GHGR regions and communities. ~4.5 Gt CO_2/y of deployment would require 9 million workers globally.[10]	🔷 Well-paid, high-quality, local jobs with worker safety standards and reskilling resources provide sufficient workforce to staff CDR deployment efforts.	□	■	▨	▨
Infrastructure	2.7 Backbone regional infrastructure	Build out of infrastructure and supply chains relevant to strategic roadmaps and siting plans for GHGR in at least 50 globally distributed countries to ensure global coverage and buy-in.[11]	🔷 GHGR infrastructure capacity sufficient to enable a >10 Gt CO_2/y global industry is in some stage of planning, development, or operation.	□	■	▨	■
Permitting	2.8 Agile and clear permitting structures	In all countries with planned GHGR activities, create a regulatory review process that cycles every 3-5 years. This will be necessary to reflect changes in GHGR landscape and knowledge base and to enable the field to grow.	🔶 Regulations and standards that inform deployment are updated to address new information on GHGR approach viability and best practices.	□	▨	□	■
Financing	2.9 Commercial capex financing at scale	Implement varied financing structures to provide up-front funding and insurance for GHGR projects with varying risks and capex.[12]	🔷 Mechanisms are in place to ensure financing for >10 Gt CO_2/y of GHGR projects to be financed in the 2040s.	□	□	■	■
Standard setting	2.10 Global MRV established	Develop robust standards for all commercial and scaled CDR approaches that are continually approved, and globally adhered to. This could include global MRV frameworks or organizational bodies.[13]	🔷 Sufficient verification bodies exist to validate 100% of ongoing CDR projects >10 kt CO_2/y and ensure the public and environmental safety of projects, with transparent LCAs and supply chain tracing.	▨	▨	▨	■
Market infrastructure	2.11 Certification markets for GHGR	Standardize GHGR markets so they are traceable and serve an accepted role within carbon accounting frameworks. Include regular updates to standards that reflect updated learnings across GHGR.	🔷 Subnational and national markets have linked and harmonized their standards; removals certification provides accounting standards for 100% of commercial-scale projects.	□	□	■	■
Demand	2.12 Publicly mandated procurement	Launch publicly mandated procurement plans developed in Initiative 1.11. Continue to build support for CDR purchases by means of regulation, including compliance markets, tax incentives, procurement, pay for practice, and/or regulatory measures that build support for 10 Gt CO_2/y by 2050.[14,15]	🔷 Purchases through publicly mandated procurement grow to >4.5 Gt CO_2/y in 2040. Support is created to expand this to >10 Gt CO_2/y in 2050.	□	□	■	■

Source: Author analysis. See figure notes in *Appendix C*.

Technical progress through R&D will continue to be important in the decade from 2030 to 2040. A primary goal of the first decadal period is to advance the TRL of GHGR to a point where at least 10 technological GHGR approaches achieve first commercial deployment. The second decadal period must build on that work by doubling down on the GHGR technology approaches that show the most promise. This means funding research that continues to reduce the cost per ton of removals while maintaining or improving safety, durability, measurability, and scalability.[lxii] Applied research will take on a more prominent role and will include activities such as process efficiency improvements, LCA practice updates, Earth systems modeling, and impact assessments. Measurement and modeling will be particularly important for open-system approaches because they will be necessary to enable MRV and to identify both positive and negative impacts on communities and ecosystems. By the end of the decade, the 2050 portfolio of approaches must be established and ready to scale. As a result, this decadal period will require approximately 10 unique CDR approaches with a combined scaling potential of >10 Gt CO_2/y (an average of 1 Gt CO_2/y per approach) that achieve commercial deployment by 2040 (2.1).[lxiii]

Reaching gigaton scale for the first time and growing beyond in this decade will require incubating a portfolio of GHGR technologies. No single technology approach will be able to scale quickly enough on its own, and nearly all approaches will run into unique scaling constraints such as insufficient supply of sustainable biomass, alkaline minerals, or low-carbon energy. In order to ensure a variety of approaches, it will be necessary to push a portfolio — not just a single approach — of viable CDR technologies toward commercial deployment as quickly as possible (2.2). This can be accomplished by initiating commercial deployment of successful FOAK demonstration-scale projects from Initiative 1.2. Likewise, it will be necessary during this period to deprioritize technologies that have not demonstrated safe, durable, measurable, and cost-effective scale.

In this decadal period, it will also be necessary to determine whether and to what degree non-CO_2 GHGR must play a role in climate solutions (2.1). Building on work from the first decadal period, this decade must deliver sufficient understanding of the technical potential of removal technologies, their impacts, and the climate context of future emissions from human activities and natural systems. If deployment of non-CO_2 GHGR is deemed feasible, safe, and climate-beneficial, it may be desirable to rapidly build out non-CO_2 GHGR during this decadal period, incorporate it into IPCC models and planning, and fast-track demonstration projects, all leveraging lessons learned from the path CDR will have taken. This may be especially true for methane due to its relatively high atmospheric concentration among the non-CO_2 GHGs. R&D priorities for non-CO_2 GHGR are discussed in greater detail in Section 7.5.

For the field to stay on track with the deployment goal outlined in Section 3, it will be important to ensure that the massive build-out of GHGR capacity in this decadal period is done in a way that is just and equitable. Early-mover communities can assume roles as codesigners of projects and community advocates. Developers must involve communities early and consistently in project planning and implementation (2.3). To this end, it may also prove valuable during this period to deploy projects under alternative ownership models (e.g., community, municipal, nonprofit, or public) rather than conventional developer-led GHGR. Continued social science research during this period will shed additional light on community concerns and inform engagement practices (2.4).

All of this will be important to ensure that GHGR deployment is done correctly and that it builds and maintains a positive reputation that in turn leads new cities and regions to desire and commission GHGR projects (2.5). This can be enabled through coalitions with community-based organizations and community advocates who can help sustain political support and ensure equitable GHGR deployment (2.5).

[lxii] For more information on project scope and TRLs as defined in this roadmap, see ***The Applied Innovation Roadmap for CDR*** (RMI, 2023, pp. 379, 387–390).

[lxiii] Note also that the technology roadmap initiatives in Section 7 reach only to 2035. The reason for this is that it will be critical in the decadal period from 2030 to 2040 to focus funding on only the most successful GHGR approaches.

The same approaches should also be applied to the build-out of infrastructure and supply chains because these will be critical to achieving long-term scaling goals. By the end of this decadal period, infrastructure and supply chains relevant to strategic roadmaps and siting plans for GHGR should be in place for at least 50 globally distributed countries. Infrastructure sufficient to enable a >10 Gt CO_2/y industry must be in some stage of planning, development, or operation so that CDR projects can be commissioned quickly and on time in the final decadal period, from 2040 to 2050 (2.7).

Rapid deployment of GHGR during this decadal period will also require concerted action to overcome key scaling challenges. First, CDR projects will go from requiring thousands to millions of workers. For this to be accomplished, it will be important to ensure that these jobs are local, well paid, high quality, and safe, and that they will help GHGR have a positive impact on communities (2.6). Second, as approaches scale up, they will compete with other industries, including other climate change mitigation projects, for land use, energy, and materials. For scale to be achieved, it will be important to deploy GHGR approaches within a context of careful resource allocation across climate solutions and other human activities (2.7). Achieving this will require coordinated planning and deployment and reducing demand for these inputs, where possible (2.1). Third, scale-up will require the maturation of capital markets for financing GHGR with large-scale participation by banks, standardization in contracting — analogous to the proliferation of power purchase agreements in renewable energy — and falling costs of capital. This can be accomplished by implementing varied financing structures to provide up-front funding and insurance for GHGR projects with varying risks (2.9).

This build-out of removal capacity will be possible only if regulatory and permitting structures that inform deployments are well established, clear, and supportive of GHGR deployment. But above all, they will need to be agile (2.8). The rapid scaling, cost reductions, and consolidation of viable approaches will require permitting structures to be updated regularly to keep pace with the industry. CDR markets will need to simultaneously mature toward a system that is standardized and traceable (2.11). They may find an accepted role within existing carbon accounting frameworks or in new frameworks.

It is also during this decadal period that the challenge of scaled demand must be solved. Voluntary private carbon markets may be able to buoy the field in the period to 2030, but they will not be able to generate sufficient demand for the ~4.5 Gt CO_2/y of deployment required by 2040 or 10 Gt CO_2/y by 2050. In this decade, it will be necessary to establish a significant, scaled, and stable demand-pull mechanism through a variety of devices, including some form of mandated procurement (2.12). And for this to achieve the scale required, it will also likely need to be global. Furthermore, this is not an initiative that can wait. It will take many years to lay the groundwork of sufficient standards, market infrastructure, and MRV to ensure transparent and high-quality data on removals (2.10). Work in this direction must begin during the first decadal period and extend into the 2030s (1.10, 1.11, 1.12). Further discussion of what is required to scale demand can be found in Sections 6.3 and 6.4.

The decadal period from 2030 to 2040 will be characterized by the challenges that come with rapid growth and the attainment of gigaton scale. During this decade, it will be necessary to determine whether non-CO_2 GHGR can and should be deployed and to down select CDR approaches toward those that are most effective at achieving safe, durable, measurable, and cost-effective scale. And finally, all of this will be possible only if stable, scaled demand for CDR is established. If these initiatives can be fulfilled, then the field will be on track for success in the final decadal period, when it will seek to grow toward 10 Gt CO_2/y of CDR in 2050.

8.3 Initiatives for 2040–2050

The final decadal period, from 2040 to 2050, will be characterized by the challenges of sustaining year-on-year deployment growth rates of 5%–15% that will be required to reach 10 Gt CO_2/y by the end of the decade. This will require the amount of CDR deployed globally to more than double over the course of this final decade, making it one of the world's largest commodities by mass. Achieving this will require the GHGR footprint to become truly global, which will require engagement with new communities across the global north and global south, expanded manufacturing and supply chains, global coalition building, workforce scaling, expanded international standards and infrastructure, development of new markets, and continued policy support for procurement.

Figure 16 presents initiatives required to achieve these outcomes. Note that the ordering of initiatives is not indicative of importance; many of the initiatives interact with and are dependent on each other, and all of them must be pursued simultaneously to keep the field on track to achieve its 2050 milestones.

Figure 16 Roadmap initiatives for scaling GHGR removals from 2040 to 2050

Relevance of actors: ■ High ▨ Medium □ Low **Milestones:** 🔷 Checkpoint 🔶 Decision point

INITIATIVE CATEGORY	INITIATIVE	ACTION	ASSESSMENT OR MILESTONE IN 2050	THEMATIC AREAS S&T ▼	SB&C ▼	F&M ▼	P&R ▼
R&D	3.1 Technology scaling	Allocate 0.5% of all climate spending to basic and applied R&D on GHGR in line with R&D spending in other industries. The goals of this R&D are primarily focused on advancing the technology of current GHGR approaches and secondarily focused on incubating new GHGR approaches so the field can continue to grow through 2050 and beyond.[1,2,3]	🔷 Deployment of at least 10 Gt CO_2/y of technological GHGR. At least 5 new GHGR approaches with potential of >100 Mt CO_2/y are developed during this decade.	■	▨	□	■
Deployment	3.2 Global implementation	Enable global deployment of CDR to reach 10 Gt CO_2/y while meeting internationally accepted standards for quantification, quality, accounting, and MRV. Depending on outcomes in previous decades, it may also be necessary to deploy non-CO_2 GHGR.[4,5,6]	🔷 At least 10 Gt CO_2/y is in some phase of planning, development, or deployment by the first half of the decade. Support for removals are distributed across at least 60 countries representing 80% of global emissions.[7]	□	■	■	▨
Community engagement	3.3 Just deployments in new communities	CDR projects prioritize co-benefits relevant to GHGR communities. Playbooks from previous decades should be revisited to ensure that they are capable of reaching a broader range of more diverse communities and their needs. These guides are used to direct the activities of Initiative 3.2.[8] Community benefits are considered an essential component of all GHGR deployment.[4]	🔶 Community engagement enables 10 Gt CO_2/y of technological GHGR globally. These projects are sought and commissioned by community-led development.	□	■	▨	■
Public engagement	3.4 Global coalition building	Facilitate global coordination among community-based organizations and advocates to expand political and resource support and advance equitable GHGR deployment.[8]	🔷 Cities and regions continue to compete for GHGR projects. Public perception of GHGR is net positive. GHGR is seen as a critical waste management service.	□	■	□	□
Workforce	3.5 Workforce scaling	Governments, companies, communities, workforce development organizations, unions, industries, and new workers must work together to ensure sufficient workforce (20 million) for staffing all active GHGR deployment. These activities must be pursued globally and should not hurt other needed industries including cleantech.[9]	🔷 Well-paid, high-quality, local jobs with worker safety standards and reskilling resources provide sufficient workforce to staff GHGR deployment efforts. Workforce training precedes GHGR buildout.	□	■	▨	▨
Infrastructure	3.6 Updating infrastructure	Ensure the continued expansion of necessary supply chains, manufacturing, natural resources, and other enabling infrastructure. Develop end-of-life and recycling plans for first-generation GHGR equipment.	🔷 GHGR infrastructure capacity sufficient to enable a >10 Gt CO_2/y global industry is operational by the first half of the decade.	▨	▨	■	■
Financing	3.7 Competitive global market for financing	Ensure that financial institutions can accurately assess project risks. Ensure that the most cost-effective, safe, and scalable GHGR projects are commissioned globally, and that cross-border flows of capital enable global projects.[10]	🔷 Private financing costs reach parity with comparable infrastructure projects.	□	□	■	▨
Demand	3.8 International standards, markets, and procurement	Implement publicly mandated procurement plans of Initiative 1.12 so that demand for >10 Gt CO_2/y by 2050 is established in the first half of this decade. Demand should incorporate international standards that consolidate activities of the previous decadal period, including clear, global MRV (2.10) and certified market standards (2.11).[5]	🔷 Purchases of GHGR are >10 Gt CO_2/y in 2050. There is a clear, stable purchasing regime that stretches at least 15 years into the future to ensure continued GHGR deployment.	□	□	■	■

Source: Author analysis. See figure notes in *Appendix C*.

In the decadal period from 2040 to 2050, the role of R&D will be primarily to continue to advance the technology of existing GHGR and secondarily to incubate new GHGR approaches so the field can continue to grow to 2050 and beyond (3.1). This may occur through breakthroughs that, for example, improve DAC energy efficiency, streamline integration with existing industry, or use synthetic biology to increase biomass yields. Technology can evolve significantly in 25 years, and novel breakthroughs are an important part of this process. Use-inspired basic research can help unlock new GHGR approaches and pathways, and although new approaches will not scale this decade, they may be important in the second half of the century.

Building on Initiative 2.2 of the previous decadal period, the period from 2040 to 2050 will need to continue to deploy new projects at a rapid rate in order to meet its scaling goals. At least 10 Gt CO_2/y needs to be in some phase of planning, development, or deployment by the first half of the decade for it to be operational by 2050. This will require adding 500–800 Mt CO_2/y of additional removal capacity *each year*, which is more than the cumulative target for the entire first decade. Projects will have to move beyond the low-hanging fruit of early projects and toward the deployment of GHGR in new, less favorable conditions (3.2, 3.3). Achieving this will require projects to continue to meet internationally accepted standards for quantification, quality, accounting, and MRV while also prioritizing co-benefits relevant to GHGR communities where they are located. This will also provide an opportunity for new communities to invest in GHGR deployment, including across the global south.

To ensure this trust continues to be well deserved as deployment more than doubles, coalition building and community-led deployment will need to increase (3.3, 3.4). Projects should continue to focus on co-benefits such as income, high-quality employment, and ecosystem services, as negotiated with communities. One way of aiding this process is by developing GHGR projects that are rightsized to their locations and climates. By centering around community codesign, GHGR projects can become highly desirable to communities, providing ecosystem services and environmental improvements, new industry, economic and health benefits, and other co-benefits to local stakeholders while pushing project developers to leverage local expertise and insight to identify the best match between project type and host locations (3.3).[lxiv] Global coalition building can help this process by ensuring equitable advancement of GHGR projects and by advocating for supportive policies that maximize co-benefits (3.4). Furthermore, depending on outcomes in previous decades, it may also be desirable to deploy non-CO_2 GHGR during this decade. If so, non-CO_2 GHGR will need to be held to the same standards. After years of community co-design, exploration of alternative ownership models (see initiatives across Section 7), social science research, and coalition building, GHGR should be a beneficial and trusted industry.

Like the previous decadal period, the decade from 2040 to 2050 will encounter scaling challenges. But, whereas the previous decade encountered challenges at the emergence of scale, the decade to 2050 will encounter challenges of maintaining high growth at scale. By 2050, the GHGR industry will have surpassed the size of the current oil and gas industry and will require a workforce on the order of 20 million people.[lxv] Governments, companies, communities, workforce development organizations, unions, transition adjacent industries, and new workers must work together to ensure sufficient workforce. This can be achieved with vocational on-ramps and clear career transition pathways into stable, safe, good-paying jobs (3.5).

The challenges of sustained growth at scale may also lead to externalities and secondary effects. For example, land-use change and biomass production for land CDR, mining for rock CDR, and the build-out of energy infrastructure for air and ocean CDR may each put stress on ecosystems and communities that will need to be understood and managed (3.1, 3.2). Wherever possible, GHGR projects should integrate with existing industry and infrastructure (3.2, 3.3) to minimize

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lxiv Morgan Stanley reports more than $820 billion lost each year due to medical needs and lost wages associated with air pollution and climate change (“**Investing at the Intersection of Climate and Health**,” Institute for Sustainable Investing, 2024).

lxv Per Statista (“**Number of Employees in the Oil and Natural Gas Industry Worldwide in 2022, by Commodity Type**,” accessed July 2024), the worldwide oil and natural gas industry recorded more than 11.5 million jobs in 2022.

impacts on natural habitats and ecosystems. Old infrastructure will also need to be modernized and refreshed to ensure the continued expansion of supply chains, manufacturing facilities, and other enabling infrastructure. For example, it will be necessary to ensure that manufacturing capacity is keeping up with the growth of the GHGR industry, and to develop plans and protocols for handling GHGR equipment at the end of its life cycle (3.6). MRV, standards, and procurement must consider these impacts, and account for them accordingly when assessing and valuing CDR projects (3.2, 3.7, 3.8).

Adherence to these quality standards, along with best practices and codes of conduct for safety and environmental impacts, should be well codified and widely applied on a global basis. These standards should be agile and able to incorporate new learnings as the industry evolves. It will be important during this decade to ensure that financial institutions can accurately assess project risks and bring financing costs in line with comparably sized infrastructure projects (3.7). And finally, as with the previous decadal period, publicly mandated procurement, including compliance markets, tax incentives, pay for practice, regulatory measures, and other means, will remain essential if CDR is to reach 10 Gt CO_2/y in 2050 (3.8). Decreasing project risks, growing public enthusiasm, and building a global coalition will help enable this outcome (3.4).

The goal of this decadal period and of this roadmap is to scale CDR toward 10 Gt CO_2/y by 2050 and to potentially deploy non-CO_2 GHGR as well. However, it would be a mistake to develop GHGR into another hard-to-abate sector. By midcentury, GHGR should not be a pervasive presence with large facilities on every horizon, but rather a quiet background function of our lives, like a well-run utility, that serves to protect individual health and community well-being while stabilizing and, eventually, repairing our climate.

9. Uncertainties Facing GHGR and How To Address Them

The primary purpose of this roadmap is to identify goals for the field of GHGR (Section 3) and then articulate a path to realize these goals (Sections 6–8). However, as with any field, there are also high-level and crosscutting uncertainties and risks that have the potential to disrupt this planned course of action and to derail this path to scale. Ensuring success requires anticipating and preemptively planning for how to address these challenges.

This section discusses four areas of uncertainty and risk that face GHGR in the path to scale:

1. The amount of GHGR needed to hit climate targets

2. Cost and willingness to pay for GHGR

3. The amount of GHGR that can be practically and responsibly deployed by 2050

4. What happens when GHGR projects or technology approaches fail

This list is not meant to be exhaustive of all potential uncertainties and risks, but instead to highlight indeterminate outcomes that could alter the course of GHGR. For each of the uncertainties discussed, this section identifies a series of actions that should be taken to mitigate associated risks.

Uncertainty #1: The amount of GHGR needed to hit climate targets

Section 3 of this roadmap sets a CDR target of 10 Gt CO_2/y of removals by 2050 while noting that climate scenarios report total CDR requirements ranging from zero to more than 30 Gt CO_2/y of removals. This wide range of removal requirements is due to several major sources of uncertainty:

- **Climate modeling:** Integrated assessment models are the best available tools for understanding the future of the climate and the need for GHGR. However, because GHGR is such a new field, climate models still have wide variability in their outputs for how much GHGR will be needed and what types of GHGR will supply those removals.

- **Natural feedback loops:** Climate warming is generally assumed to scale in direct response to GHG emissions. However, Earth systems contain several natural feedback loops that, if triggered, could accelerate warming. For example, warming of arctic regions could release large amounts of methane, thus accelerating climate warming. If this occurs, the world may need to deploy even more GHGR at an even greater speed than is currently estimated.

- **Emissions reduction outcomes:** The amount of GHGR required is to some degree dependent on the rate at which the world manages to mitigate emissions. In other words, if the world rapidly decarbonizes, then there will be fewer emissions to remove. However, if the world misses its reduction goals, then GHGR will have to remove even more than current models suggest.

If the world decarbonizes slowly, if climate models underestimate how much GHGR is needed, or if natural feedback loops begin to accelerate warming, then it may become necessary to scale GHGR even faster than this roadmap describes. Alternatively, a lack of demand for GHGR may leave the field underdeveloped and unable to scale.

Because GHGR is starting from such a low baseline, the best way to mitigate risk is the same in either case: to ramp the field as quickly as possible in the next 10 years. To be on track for 10 Gt CO_2/y of removals in 2050, the world should follow the scaling goals of this roadmap and seek to remove ~285 Mt CO_2/y in 2030. This may seem small, but it will already test the limits of scaling. Achieving it will give policymakers more options to consider as it becomes clearer in the coming decade how much CDR is required to hit specific climate targets.

Uncertainty #2: Cost and willingness to pay for GHGR

Society's willingness to pay for GHGR will be an important factor for determining how much and how quickly these technologies are able to scale. If costs do not come down sufficiently and for a sufficient supply of CDR, then society might not be willing to bear the cost of removals.

- **Cost per ton:** Different GHGR approaches have a wide range of costs. Some approaches, such as biomass direct storage, already cost less than \$150/t CO_2, whereas others, such as various forms of DAC, currently cost more than \$600/t CO_2.[60]

- **Sensitivity of demand:** As the cost of GHGR comes down, conventional economics suggests that more of it will be purchased. The demand curve for GHGR will in large part be set by policy. The U.S. Department of Energy, for example, uses a target of \$100/t CO_2 by 2030 as a pricing benchmark of what will be required for GHGR to be bought and sold at scale.[61] However, this is not a magic number, and it is possible that costs may need to fall even lower to enable scaled procurement.

- **Political and governance challenges**: As discussed in Section 6.4, large-scale procurement will necessarily be driven by policy. Determining who will pay and how much they will be required to buy will need to be resolved politically. This will also include questions of who will govern and regulate payment and procurement.

The most effective and immediate actions are for governments to set clear policy structures and targets for how GHGR will be procured at scale. This is captured in several initiatives across the roadmap, especially in the initiative categories of standard setting, market infrastructure, and demand.

Uncertainty #3: The amount of GHGR that can be practically and responsibly deployed by 2050

As described in Section 4, reaching 10 Gt CO_2/y will make GHGR the largest commodity on Earth by mass. This will in turn require engagement from a wide variety of industries and geographies and naturally raises the question of how much GHGR can be practically and responsibly deployed.

- **Safety of GHGR approaches:** Many GHGR approaches require deployment in open systems such as open oceans, rivers, farmlands, open-air installations, or along coastlines. While these approaches are promising for the potential scale they may achieve, they may also pose risks to the environment and local communities that are difficult to monitor. The bar for safety should be especially high for open-system approaches. Robust monitoring techniques, baseline data sources, and acceptability standards must be developed to scientifically verify safety before these approaches can be deployed at scale.

- **Community acceptance of GHGR:** While every effort should be made to mitigate any negative impacts of GHGR, there may still be externalities, and communities may still determine that they do not want to host GHGR projects. Local resistance to projects has slowed the adoption of a variety of energy transition technologies, and it is possible that communities could be slow to adopt GHGR or not adopt it ever, even if a GHGR approach is demonstrated to be safe and beneficial.

- **Resource limits:** Many GHGR approaches have significant resource requirements, including land, water, rocks, and energy, which may constrain the scalability of certain approaches. RMI's *Applied Innovation Roadmap for CDR* identifies three critical inputs that are expected to affect the upper scaling limits of CDR.[62]
    - **Sustainable biomass:** Biomass is a key input for all durable CDR approaches that use photosynthesis to remove CO_2 from the atmosphere. By some measures, the world is already pushing up against the global limit of sustainable biomass. The IEA estimates that global supply of sustainable biomass will grow more than 50% from 2024 to 2050, but that this biomass will be allocated to other energy transition activities. Even if all sustainable biomass were allocated to CDR, it would only be able to achieve ~10 Gt CO_2/y of removals.
    - **Alkaline minerals:** Rock CDR processes react alkaline minerals with water and CO_2 to form either solid carbonate minerals or bicarbonate dissolved in water. Theoretical global capacity of these minerals is far greater than the amount of CO_2 removal that is ever expected to be needed because much of the Earth is covered in rock types suitable for CDR. However, in order to create reactions that are *additional* to those that would occur naturally, these feedstocks need to be mined, crushed, and transported, which is an energy-intensive process. Furthermore, these materials may not be located in areas where they are easily mined and used. By 2050 it is estimated that growth in energy transition metal mining, dedicated mining, and other increases in alkaline mineral production could allow for up to 9 Gt CO_2/y of rock CDR removals.[63]
    - **Low-carbon energy:** Energy is critical for many CDR activities, including DAC and direct ocean capture facilities, and it may be critical to running non-CO_2 removal facilities as well. For these facilities to have net negative emissions, they must run on low-carbon energy. However, many of the mitigation activities that are critical to the energy transition also require low-carbon energy. If an adequate supply of low-carbon energy is not secured, the deployment of some forms of GHGR could be delayed or other aspects of the energy transition could be derailed.
- **Speed of deployment:** Beyond the scale of GHGR required is the speed at which this scale is needed. Even if it is physically possible to achieve scale, doing so on a shortened timeline will put pressure on existing infrastructure, required inputs, markets, governments, and communities.
- **Scale of deployment:** Humans have not yet scaled any major international commodity to the 10-Gt level. As a result, there may be unknown constraints that are not yet visible. These could include both technical and nontechnical limitations in manufacturing, supply chains, economic policy, and global trade.
- **Measurability of deployment:** Although many GHGR approaches may be technically viable, there are still significant open questions about how reliably their removals can be measured. Especially for open-system approaches such as many of the ocean CDR and rock CDR approaches, the ability to reliably measure and credit removals may be critical to unlocking funding and scale.
- **Effectiveness of non-CO_2 GHGR:** Methane, nitrous oxide, and other non-CO_2 gases can have significant warming effects. Many efforts are currently underway to mitigate the emissions of these gases, but it is still unclear whether these gases can be removed from the atmosphere in a way that is effective and environmentally beneficial.

It is easy to talk about deploying GHGR at the gigaton scale, but actually achieving it will require a monumental effort across a portfolio of approaches. Furthermore, this work must be done in a way that is responsible and effective. The best way to mitigate risks around long-term scaling is to de-risk GHGR approaches as quickly as possible in the near term. Projects and deployments should focus on validating safety and scalability, collecting and sharing data, and learning from mistakes as a field. To this end, this roadmap has identified critical initiatives in each of five technical areas to ensure that GHGR is incubated and scaled in accordance with safety and community concerns. This roadmap has also laid out initiatives that look ahead at potential scaling bottlenecks in supply chains and deployment. Best practices in the near term will be critical for setting the field up for future success.

Uncertainty #4: What happens when GHGR projects or technology approaches fail

The field of GHGR is new and unproven, and as a result it will inevitably encounter failures and setbacks. It will be critical to manage both so that the field learns from them quickly and does not allow them to derail the progress of the entire field.

- **Failed projects:** As in every other sector, some GHGR companies, approaches, and projects will fail, which is normal for innovative technologies, startup companies, and new business models. This can include failure at any technical level, including basic R&D, pilots, demonstrations, and commercial projects. Though it is to be expected that not every new technology successfully commercializes, high-level failures, for whatever reason, can put a bad mark on a field or negatively affect the future ability of a specific approach to raise capital or to maintain political or social support. Especially early on, failures can destabilize a GHGR technology approach or the entire GHGR field.
    - **Failure for commercial reasons:** Many times, companies fail for reasons that have little to do with the technology itself. Inadequate leadership, project management, logistical planning, or supply chains can cause a company to fail on its own terms. Insufficient financing, poor operating conditions, or even poor timing with financial markets can also cause a company to fail.
    - **Failure for technical reasons:** It is possible that many GHGR approaches will not work or scale as expected. Many technologies are still in early TRL stages and are little more than ideas or pilot-scale deployments. As these technologies are developed and scaled, it may become clear that some simply do not work as intended or that their costs are not competitive.
    - **Failure for environmental, human, or ecosystem harms:** All GHGR approaches interact with the environment and inherently modify the environment. The goal is that their impact on the environment is beneficial, not harmful. However, there is uncertainty surrounding environmental and human health impacts of some technologies. Technologies may fail because of this, and impacts should be understood as early as possible to avoid failure and harm at large scale.
- **Reversals:** Projects may also fail through a reversal of removals. For some CDR approaches, the captured CO_2 may be rereleased either through system changes (such as unexpected conditions that lead to decomposition of stored biomass or biochar) or unintended use of CDR products (such as the burning of plastics made from captured CO_2). Reversals reflect poorly on the field and also invalidate previous removals.
- **Mis- and disinformation:** As GHGR is deployed, it will draw more attention and will be vulnerable to mis- and disinformation. The field should be thoughtful and transparent when communicating about unsuccessful or underdelivered deployments. Early GHGR deployments will not be perfect, and the field should be resilient and learn from setbacks when striving toward long-term approaches. It is also important to share when projects are successful to counteract mis- and disinformation.

No field has ever been completely devoid of failures, and GHGR will almost certainly have its own. The key is to prepare for them and to get ahead of them, rather than simply wait for them to happen. For example, the risk of reversals occurring due to failures in storage projects will require legal frameworks and appropriate insurance, liability, and ownership frameworks. Risks related to project failure require constant attention to public disclosure and the establishment of best practices, along with transparency on failure mechanisms that are established in advance. Risks related to mis- and disinformation can be countered by evidence-based journalism, community engagement, and public engagement. Failures can also be managed by properly setting expectations, ensuring transparency, and learning from failures so that the wider endeavor of GHGR can advance. Finally, it will be necessary to enable constructive public dialogues that assess the risks of deploying GHGR against the climate risks of not deploying enough of it.

The goals set out in this roadmap (Section 3) and the path described to get there (Sections 6–8) are daunting and will require GHGR to achieve massive scale in a short timeline. However, in addition to these challenges, it is also necessary to avoid the downside risks of uncertainties that face GHGR deployment. Addressing and mitigating the uncertainties identified in this section will increase the probability of achieving the goals of this roadmap.

10. Conclusions

The data is clear: greenhouse gas removal will be critical for meeting long-term climate targets. In the context of these IPCC targets, this roadmap establishes two goals. First, to grow CDR to 10 Gt CO_2/y of durable technological removals in 2050. Second, to advance the science of non-CO_2 removal such that decisions can be made by the early 2030s about future development and deployment.

These goals represent one of the most ambitious technological scaling challenges taken on by humanity. Reaching the 10 Gt CO_2/y CDR goal will require scaling deployment by 10,000x over 25 years, rivaling the scale of the largest industries on the planet. Similarly, the field of non-CO_2 GHGR barely exists, and yet within 10 years it will be necessary to have advanced the science to a point where decisions can be made about whether and how it should be deployed at scale.

Given these challenges, work toward these goals is urgent and must begin immediately. It will require a step change in the speed and scale of technological advancement as well as focused, coordinated efforts by stakeholders across thematic areas, including science and technology, socio-behavioral and communities, finance and markets, and policy and regulation. To that end, this roadmap identifies 83 initiatives to guide GHGR actors toward meaningful near-term goals aligned with long-term outcomes.

One of the most important takeaways from the roadmap is that near-term deployment initiatives must put communities first. Because GHGR is a global solution, deployment needs to occur across a variety of social, cultural, economic, and political backdrops across a wide range of settings. This will mean that deployments and approaches will need to be tailored by approach and by setting. Early deployments will set precedents for the future of the field, and if done well, deployments in the decadal period to 2030 will serve as models and touchstones to guide deployments in future decades. Given the speed and scale at which deployments must be made in future decades, the success of the field will depend on the establishment of positive near-term precedents.

Such an ambitious, global undertaking cannot be achieved unilaterally. Coordination and collaboration will be critical. All GHGR stakeholders should pursue communication, coordination, and cooperation across initiatives and interdependencies. Furthermore, the initiatives in this roadmap build on a wide body of previous work, and readers should also look to other topic-specific roadmaps (see Appendix A) for more details on what is needed in particular thematic or technical areas. Where there are still gaps for different technology and thematic areas, more roadmaps should be written to help guide the specifics of those areas. Finally, this roadmap itself should be updated on a regular basis (every one to four years) as more information comes to light and to ensure that the field continues to move forward.

The goals of this roadmap are ambitious, and they will subject the field to intense deployment and scaling challenges. But, as the impacts of global warming become increasingly evident, they are what is needed to ensure that sufficient GHGR is available to serve its essential role in the portfolio of climate solutions. Humanity must come together swiftly to resource and execute one of the most pressing technological scale-ups in history. If GHGR stakeholders unite to drive the field forward in a deliberately coordinated way, then the goals of this roadmap are well within reach.

Appendix A: Other Relevant Roadmaps

This roadmap builds on the work of many previous efforts for mapping and accelerating the GHGR ecosystem. The following is a non-exhaustive list of GHGR-related publications from the past several years. The list is organized by publication date.

- *National Marine Carbon Dioxide Removal Strategy,* National Science and Technology Council, 2024, **https://www.whitehouse.gov/wp-content/uploads/2024/11/U.S.-Marine-Carbon-Dioxide-Removal-Research-Strategy.pdf**

- *A Research Agenda Toward Atmospheric Methane Removal,* National Academies of Science, Engineering, and Medicine, 2024, **https://nap.nationalacademies.org/catalog/27157/a-research-agenda-toward-atmospheric-methane-removal**

- *The State of Carbon Dioxide Removal*, 2nd edition, Oxford University, 2024, **https://www.stateofcdr.org**

- *Opinion: A Research Roadmap for Exploring Atmospheric Methane Removal via Iron Salt Aerosol,* Spark Climate, 2024, **https://acp.copernicus.org/articles/24/5659/2024**

- *The Landscape of Carbon Dioxide Removal and US Policies to Scale Solutions,* Rhodium Group, 2024, **https://rhg.com/research/carbon-dioxide-removal-us-policy**

- *Agenda for a Progressive Political Economy of Carbon Removal*, Institute for Responsible Carbon Removal, American University, 2024, **https://aura.american.edu/articles/report/Agenda_for_a_Progressive_Political_Economy_of_Carbon_Removal/24985833**

- *Proposed Roadmap to Build on Key Milestones of the International Agenda as a Follow-up to the Summit on a New Global Financing Pact*, Les Présidents de la République, 2023, **https://pactedeparis.org/pdf/proposed-roadmap.pdf**

- *Carbon Dioxide Removal Innovation Workshop Pre-Read Document*, SRI & SLAC National Accelerator Laboratory, 2023, **https://www.sri.com/wp-content/uploads/2023/10/CDR-Innovation-Workshop-Pre-Read-Doc_FINAL.pdf**

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

- *Roads to Removal: Options for Carbon Dioxide Removal in the United States*, Lawrence Livermore National Laboratory, 2023, **https://roads2removal.org/resources**

- *Applied Innovation Roadmap for Carbon Dioxide Removal*, RMI, 2023, **https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr**

- *UN Emissions Gap Report*, United Nations Environment Programme, 2023, **https://www.unep.org/resources/emissions-gap-report-2023**

- *Breaking Ground: Guidance for Carbon Removal Companies and Funders on Responsible Project Deployment*, XPRIZE, 2023, **https://www.xprize.org/prizes/carbonremoval/articles/breaking-ground-guidance-for-carbon-removal-companies-and-funders-on-responsible-project-deployment**

- *How to Avoid Carbon Removal Delaying Emissions Reductions*, Carbon Gap, 2023, **https://carbongap.org/avoid-carbon-removal-delaying-emissions-cuts**
- *The Time for Carbon Removal has Come*, BCG, 2023, **https://web-assets.bcg.com/67/f7/0f41cd074a66b49cdb8baf5e59c0/bcg-the-time-for-carbon-removal-has-come-sep-2023-r.pdf**
- *CDR Innovation Landscape and 2024 Outlook*, XPRIZE, 2023, **https://www.xprize.org/prizes/carbonremoval/articles/cdr-innovation-landscape-and-2024-outlook**
- *Microsoft Carbon Removal: Observations from Our Third Year*, Microsoft, 2023, **https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RW16V26**
- *Depending on the Ocean: Research and Policy Proposals for Responsible Ocean Carbon Removal*, Carbon180, 2023, **https://carbon180.org/wp-content/uploads/2023/08/Carbon180-DependingOnTheOcean.pdf**
- *Strategy for NOAA Carbon Dioxide Removal Research*, National Oceanic and Atmospherica Administration, 2023, **https://sciencecouncil.noaa.gov/wp-content/uploads/2023/06/mCDR-glossy-final.pdf**
- *A Roadmap for Achieving Scalable, Safe, and Low-cost Direct Air Carbon Capture and Storage*, RMI et al., 2023, **https://chemrxiv.org/engage/chemrxiv/article-details/642d530c736114c963f3f382**
- *Pathways to Commercial Liftoff: Carbon Management*, U.S. Department of Energy, 2023, **https://liftoff.energy.gov/wp-content/uploads/2023/04/20230424-Liftoff-Carbon-Management-vPUB_update.pdf**
- *From the Ground Up: Recommendations for Building an Environmentally Just Carbon Removal Industry,* XPRIZE and Carbon180, 2023, **https://www.xprize.org/prizes/carbonremoval/articles/from-the-ground-up**
- *The State of Carbon Dioxide Removal*, 1st edition, Oxford University, 2023, **https://www.stateofcdr.org/**
- *Paths Forward for Exploring Ocean Iron Fertilization*, Exois, 2023, **https://oceaniron.org/wp-content/uploads/sites/54/2023/10/PathsForward-ExOIS-Full.pdf**
- *Carbon Removal Knowledge Gaps,* Frontier, 2022, **https://gaps.frontierclimate.com**
- *Geochemical Negative Emissions Technologies: Part II. Roadmap*, The Climate Map, Heriot-Watt University, et al., 2022, **https://www.frontiersin.org/articles/10.3389/fclim.2022.945332/full**
- *Carbon Dioxide Removal Technology Roadmap: Innovation Gaps and Landscape Analysis*, Mission Innovation, 2022, **https://mission-innovation.net/wp-content/uploads/2022/09/Attachment-1-CDR-Mission-Roadmap-Sept-22.pdf**
- *Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited*, Energy Transitions Commission, 2022, **https://www.energy-transitions.org/wp-content/uploads/2022/07/ETC-CCUS_Executive-Summary_final.pdf**
- *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*, Energy Transitions Commission, 2022, **https://www.energy-transitions.org/publications/mind-the-gap-cdr**
- *Initial Considerations for Large-Scale Carbon Removal in the United States*, Office of Science and Technical Information, 2022, **https://www.osti.gov/biblio/1867535**

- *A Research Strategy for Ocean-Based Carbon Removal and Sequestration*, National Academies of Sciences, 2022, **https://nap.nationalacademies.org/catalog/26278/a-research-strategy-for-ocean-based-carbon-dioxide-removal-and-sequestration**
- *Guidance for Ocean-Based Carbon Dioxide Removal Projects Report*, Aspen Institute, 2021, **https://www.aspeninstitute.org/publications/ocean-carbon-dioxide-removal**
- *Ocean-Based Carbon Dioxide Removal: Road Maps*, Ocean Visions, 2021, **https://www2.oceanvisions.org/roadmaps**
- *ICEF 2020 Roadmap: Biomass Carbon Removal and Storage (BiCRS)*, Innovation for Cool Earth Forum, 2021, **https://www.icef.go.jp/roadmap**
- *DAC Climate Mobilization Report*, Elk Coast Institute, 2020, **https://static1.squarespace.com/static/5f87568f1d6c5b6fd770af0b/t/5fb31d807f660d78bad6b346/1605574022092/DAC-Climate-Mobilization-Report-20201116.pdf**
- *Uncharted Water*s, Energy Futures Initiative, 2020, **https://efifoundation.org/reports/uncharted-waters**
- *Biomass Carbon Removal and Storage (BiCRS) Roadmap*, Lawrence Livermore National Laboratory, 2020, **https://www.osti.gov/biblio/1763937**
- *Getting to Neutral: Options for Negative Carbon Emissions in California*, Lawrence Livermore National Laboratory, 2020, **https://livermorelabfoundation.org/2019/12/19/getting-to-neutral**
- *Negative Emissions Technologies and Reliable Sequestration, a Research Agenda*, National Academies of Sciences, 2019, **https://nap.nationalacademies.org/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda**
- *Clearing the Air*, Energy Futures Initiative, 2019, **https://efifoundation.org/wp-content/uploads/sites/3/2022/03/ClearingTheAir_Report_compressed.pdf**
- *Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology,* Rhodium Group, 2019, **https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/**

Appendix B: Acronyms and Abbreviations

- **AR5:** The IPCC's *Fifth Assessment Report* (2014)
- **AR6:** The IPCC's *Sixth Assessment Report* (2022)
- **ARL:** Adoption readiness level
- **BECCS:** Bioenergy with carbon capture and storage
- **BiCRS:** Biomass Carbon Removal and Storage
- **Capex:** Capital expenditure
- **CBO:** Community-based organization
- **CCS:** Carbon capture and sequestration
- **CDR:** Carbon dioxide removal
- **CH_4:** Methane
- **CO_2:** Carbon dioxide
- **DAC:** Direct air capture
- **DACS or DACCS:** Direct air capture with carbon storage
- **DOE:** U.S. Department of Energy
- **ERW:** Enhanced rock weathering
- **F&M:** Finance and markets
- **FOAK:** First of a kind
- **GHG:** Greenhouse gas
- **GHGR:** Greenhouse gas removal
- **Gt:** Gigaton (metric)
- **GWP:** Global warming potential
- **IEA:** International Energy Agency
- **IPCC:** Intergovernmental Panel on Climate Change
- **IWC:** Indirect water capture
- **kt:** Kiloton (metric)
- **LCA:** Life-cycle assessment
- **MRV:** Measurement, reporting, and verification
- **Mt:** Megaton (metric)
- **N_2O:** Nitrous oxide
- **NDCs:** Nationally determined contributions
- **NGO:** Nongovernmental organization
- **OAE:** Ocean alkalinity enhancement
- **P&R:** Policy and regulation
- **R&D:** Research and development
- **RD&D:** Research, development, and demonstration
- **RDD&D:** Research, development, demonstration, and deployment
- **S&T:** Science and technology
- **SB&C:** Socio-behavioral and communities
- **SRM:** Solar radiation management
- **TEA:** Technoeconomic assessment
- **TRL:** Technology readiness level
- **VCM:** Voluntary carbon market
- **y:** Year

Appendix C: Figure Notes

Figure 1 Roadmap for scaling technological greenhouse gas removal by 2050 (abridged)

This summary roadmap is a timeline of initiatives that must be accomplished to achieve the long-term goals of the GHGR roadmap. The summary roadmap contains 13 initiative categories that capture major areas of activity. Each initiative category contains specific decadal initiatives that describe the activities that must be undertaken in that decadal period. The initiatives shown here are highly interdependent, and within each decadal period they should be enacted in parallel because they enable and reinforce one another toward the same urgent goal of deploying and scaling GHGR. The initiatives are described in greater detail in Section 8.

Figure 3 Removal of greenhouse gases is critical to achieving long-term climate goals

The curve of emissions and removals shown here is based on an average of all C2 scenarios in the Intergovernmental Panel on Climate Change (IPCC) *Sixth Assessment Report*. C2 scenarios are scenarios that limit warming to 1.5°C by 2100 but do so with a midcentury overshoot in emissions. IPCC models only consider carbon dioxide removal, not other forms of GHG removal such as methane or nitrous oxide removal.

Figure 4 Scope of GHGR technology approaches included in this roadmap

[1] Using chemical reactions or filters to capture CO_2 from ambient air.

[2] Some ocean CDR pathways leverage biological systems to capture and sequester CO_2 whereas others leverage technologies to extract CO_2 from seawater.

[3] Processes that leverage photosynthesis to capture CO_2 from the air.

[4] Rock-based methods can be divided into two broad categories: those that happen underground (where CO_2 is injected into a subsurface formation) and those that happen above ground (by exposing crushed rocks to CO_2).

[5] These are CO_2 storage approaches rather than direct removal approaches but are included in scope because of relevant scaling needs and resource requirements.

[6] Biomass direct storage includes terrestrial biomass storage, as well as other techniques such as biomass sinking or injection.

[7] Approaches are in scope contingent on life-cycle assessment (LCA) results pointing toward positive removals and their implementation being driven by technical breakthroughs such as the use of enhanced cultivars (including genetic modification and crossbreeding), drones, or artificial intelligence.

[8] Timber building products are in scope contingent on positive LCA results.

[9] Living biomass approaches without technical breakthroughs, such as conventional land or agricultural management, conservation, or restoration practices (e.g., afforestation and reforestation), are not in scope.

[10] Electrochemical CO_2 removal is included in all four CDR technology areas because there are some forms of this approach that use elements of air, rock, ocean, and land CDR.

Figure 5 Putting the scale of the global removal challenge into perspective

The notation Gt means a gigaton or a billion tons. Under current waste production, the most recent estimate for global anthropogenic CO_2 emissions is ~41 Gt CO_2/y, which is inclusive of fossil fuel consumption, land use, land-use change, and forestry, and the cement carbonation sink. The future removal requirements data shown here is based on an S-curve that reaches 10 Gt CO_2/y in 2050.

Figure 6 Hypothetical CDR deployment trajectory that takes the shape of an S-curve

This hypothetical deployment curve was built as a logistic function or a logistic growth curve that produces an S-curve. The curve shown here starts at 25 Mt CO_2/y in 2025 and was scaled to reach 10 Gt CO_2/y of removals in 2050. Note that the curve continues to grow in the second half of the century. The S-curve is an aspirational deployment curve, and as such, the waypoints cited in this report at 2030 (~285 Mt CO_2/y) and 2040 (~4.5 Gt CO_2/y) are representative waypoints of the scale needed on the path to 10 Gt CO_2/y in 2050.

Figure 7 Critical roles for GHGR stakeholder groups across four thematic areas

The category of government actors does not include public funding agencies.

Figure 8 Initiatives for advancing Air CDR technology to 2035

Initiatives are collections of actions with targets and milestones (see Section 5 for more details). Initiatives within a technology area are highly interdependent and do not represent a sequenced set of actions or a priority order. Rather, they should be seen as a collective set of actions focused on the same, urgent goal, where collaboration and coordination are imperative.

[1] Safe and climate-beneficial deployment of air CDR requires careful consideration of potential impacts and unintended consequences, such as resource strain on local communities and energy systems and the risk of CO_2 leaks in transportation or storage. This requires early engagement with all stakeholders, especially those who have been historically underrepresented in decision-making, to identify concerns and risks. Monitoring and rigorous safeguards must also be in place for all demonstrations and deployments. Improved energy efficiency and integration with waste heat or other energy sources is essential for climate-beneficial deployment of air CDR to reduce the demand on low-carbon electricity. See *The Applied Innovation Roadmap for CDR* (pp. 15–20, RMI, 2023, **https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr**) regarding stage gates for safe scaling and deployment.

[2] As of 2024, many DAC approaches operate between 5 and 10 gigajoules (GJ)/t CO_2, with some already pushing toward energy intensities below 2.5 GJ/t CO_2. In *The Applied Innovation Roadmap for CDR* (pp. 198–202, 224–325), all DAC approaches have a high or very high risk assessment for energy requirements.

[3] See *The Applied Innovation Roadmap for CDR* (pp. 224–325) for a breakdown of expected costs associated with pre-demonstration and demonstration projects and other path-boosting activities for DAC scale-up. Across synthetic CDR approaches, expected demonstration project costs total to >$2 billion (*The Applied Innovation Roadmap for CDR,* p. 232).

[4] See *The Applied Innovation Roadmap for CDR* (e.g., p. 271, blue boxes) for a success story describing an ambitious but achievable deployment trajectory of DAC from 2024 to 2050, with 60 Mt CO_2/y of deployments by 2030 and 180 Mt CO_2/y by 2035.

[5] Carbon180, **https://carbon180.medium.com/in-the-central-valley-exploring-community-led-dac-4b2565b7eec4**. Some organizations and partnerships are already exploring alternative ownership models. Beginnings of community input structures are codified in the U.S. Department of Energy Project Cypress (**https://www.energy.gov/oced/regional-direct-air-capture-hubs-selected-and-awarded-projects**).

[6] Safe transportation and storage of CO_2 is key for scaled DAC deployment. CO_2 pipeline standards are already being established and updated by ISO (27913:2016). Alternative methods such as trucks and tankers are less well established.

[7] Standardized MRV is less challenging for DAC than other CDR approaches. Protocols are being developed and should be consistently implemented over the next decade for any technologies deployed at demonstration scale.

[8] Based on discussion at the GHGR workshop on the need for targeted coordination efforts such as organization building or tactical convenings. Examples of such efforts underway include the Global Direct Air Conference, Breakthrough Energy projects, and collaborative conversations hosted through Columbia University.

Figure 9 Initiatives for advancing Ocean CDR technology to 2035

Initiatives are collections of actions with targets and milestones (see Section 5 for more details). Initiatives within a technology area are highly interdependent and do not represent a sequenced set of actions or a priority order. Rather, they should be seen as a collective set of actions focused on the same, urgent goal, where collaboration and coordination is imperative.

[1] Safe deployment of ocean CDR requires careful consideration of potential impacts and unintended consequences, such as ocean ecosystem damage and release of contaminants in rock feedstocks for OAE, and requires early engagement with all stakeholders, especially those who have been historically underrepresented in decision-making, to identify concerns and risks. Monitoring and rigorous safeguards must also be in place for all demonstrations and deployments. See *The Applied Innovation Roadmap for CDR* (p. 15–20, RMI, 2023, https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/) regarding stage gates for safe scaling and deployment.

[2] See *The Applied Innovation Roadmap for CDR* for a breakdown of expected costs associated with pre-demonstration and demonstration projects and other path-boosting activities for scale-up (Sections 2.6, 2.7, 2.8, 5.2, 5.3, 6.1, and 6.2) as well as success stories describing ambitious but achievable deployment trajectories for individual approaches. Across ocean CDR approaches, expected pre-demonstration and demonstration project costs total to \$5–\$50 million and \$50–\$400 million, respectively.

[3] LCA and MRV development were a priority focus in discussions during the GHGR workshop. Workstreams described in *The Applied Innovation Roadmap for CDR* are centered around building out LCAs and MRV for different approaches (see note 2). Recent reports and funding calls describing this focus have been published by ClearPath (**https://clearpath.org/wp-content/uploads/sites/44/2024/03/ocean-cdr-report-4-24.pdf**), Carbon180 (**https://carbon180.org/wp-content/uploads/2023/08/Carbon180-DependingOnTheOcean.pdf**), and the U.S. Department of Energy (**https://carbon180.org/wp-content/uploads/2023/08/Carbon180-DependingOnTheOcean.pdf**).

[4] Localized governance structures are vital for ocean CDR approaches (H. Hilser et al., "Localized Governance of Carbon Dioxide Removal in Small Island Developing States," *Environmental Development* 49 [March 2024]: 100942, **https://doi.org/10.1016/j.envdev.2023.100942**).

[5] The cost of community engagement processes will vary across projects based on the nature of the approach and the geographic range and population of relevant communities. Proposed costs for comparable supercritical CO_2 injection research agenda is \$1 million/y for 10 years (National Academies, **https://nap.nationalacademies.org/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda**, Table 7.5).

[6] ClearPath (**https://clearpath.org/wp-content/uploads/sites/44/2024/03/ocean-cdr-report-4-24.pdf**). Field trials are essential for ocean CDR development. The number of proposed field trials is aligned with success stories in *The Applied Innovation Roadmap for CDR* (see note 2).

[7] Global siting methods are mentioned as requirements for CO_2 stripping, electrochemical alkalinity production, mineral/OAE, and macroalgae sinking in *The Applied Innovation Roadmap for CDR*. The outlined cost of these activities is \$40–\$90 million but overlap in these efforts across approaches may reduce the total.

[8] Target number of countries based on an approximate doubling of the number of countries with ongoing marine CDR field trials in 2023 (Ocean Visions, **https://oceanvisions.org/mcdr-field-trials/mcdr-field-trial-map**). The number of projects per country will vary.

[9] The suggested international working group was previously described by Carbon180 (**https://carbon180.org/wp-content/uploads/2023/08/Carbon180-DependingOnTheOcean.pdf**).

[10] Some but not all ocean CDR approaches are immediately ready to be integrated into industrial processes, thus distributing the projects initiated in O.6 across stand-alone and industrial integration projects (see note 2).

[11] *The Applied Innovation Roadmap for CDR* (p. 188).

[12] Based on discussion at the GHGR workshop on the need for targeted coordination efforts such as organization building or tactical convenings.

Figure 10 Initiatives for advancing Land CDR technology to 2035

Initiatives are collections of actions with targets and milestones (see Section 5 for more details). Initiatives within a technology area are highly interdependent and do not represent a sequenced set of actions or a priority order. Rather, they should be seen as a collective set of actions focused on the same, urgent goal, where collaboration and coordination are imperative.

[1] A focus on unintended consequences and environmental impacts of open-system approaches was a key discussion focus in the GHGR workshop. Safe deployment of land CDR requires careful consideration of potential impacts and unintended consequences, such as land or ecosystem damage and land-use changes, and requires early engagement with all stakeholders to identify risks along with monitoring and rigorous safeguards in place for all demonstrations and deployments. See *The Applied Innovation Roadmap for CDR* (p. 15–20, RMI, 2023, **https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr**) regarding stage gates for safe scaling and deployment.

[2] Per *The Applied Innovation Roadmap for CDR* scalability risk assessments, approaches should not lead to water stress, land-use conversion, or negative environmental impacts, or decrease on-site productivity with biomass removal. See *Biomass Carbon Removal and Storage (BiRCS) Roadmap* (Lawrence Livermore National Lab, 2021, **https://www.osti.gov/biblio/1763937**) for discussion of concerns related to loss of biodiversity, natural resource damage, unsustainable practices, and so on.

[3] Approaches may leverage synthetic biology for enhanced biomass production and storage, and land-use efficiency.

[4] See *The Applied Innovation Roadmap for CDR* for a breakdown of expected costs associated with pre-demonstration and demonstration projects and other path-boosting activities for scale-up (Sections 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 3.1, and 3.2) as well as success stories describing ambitious but achievable deployment trajectories for individual approaches. Across land CDR approaches, expected pre-demonstration and demonstration project costs total to $950 million–$1.3 billion and $1.9–$4.4 billion, respectively.

[5] Per *The Applied Innovation Roadmap for CDR* success stories and critical path workstreams, projects should consist of three to four commercial operations each for timber building products, biochar, and BECCS to fuels or electricity; removals are based on 2035 success stories.

[6] Industrial integration should investigate opportunities within land management practices in agriculture, forestry, integration with building materials, and so on, to add CDR to existing projects and practices. See, for example, "Mass Timber Building Life Cycle Assessment Methodology for the U.S. Regional Case Studies" (Gu, et al., 2021, **https://www.fpl.fs.usda.gov/documnts/pdf2021/fpl_2021_gu001.pdf**).

[7] Some organizations and partnerships are already exploring alternative ownership models (Carbon180, **https://carbon180.medium.com/in-the-central-valley-exploring-community-led-dac-4b2565b7eec4**). The beginnings of community input structures are codified in the U.S. Department of Energy Project Cypress (**https://www.energy.gov/oced/regional-direct-air-capture-hubs-selected-and-awarded-projects**).

[8] See *The Applied Innovation Roadmap for CDR* (p. 46, Section 1.1–1.3) for costs and activities of ecosystem-scale grand challenge projects.

[9] MRV for land CDR is challenging to establish with high confidence, especially given the risks of reversals, extent of land area being considered, short- vs. long-term carbon flux, and so on. See (Carbon)Plan (**https://carbonplan.org/research/cdr-verification-explainer**), *Forest Carbon Primer* (**https://crsreports.congress.gov/product/pdf/R/R46312**), and *Biomass Carbon Removal and Storage (BiRCS) Roadmap*.

[10] LCA and MRV development were a priority focus in discussions during the GHGR workshop. Workstreams described in *The Applied Innovation Roadmap for CDR* are centered around building out LCAs and MRV for different approaches (see note 4). Recent reports and funding calls describing this focus have been published by Clear Path (**https://clearpath.org/wp-content/uploads/sites/44/2024/03/ocean-cdr-report-4-24.pdf**), Carbon180 (**https://carbon180.org/wp-content/uploads/2023/08/Carbon180-DependingOnTheOcean.pdf**), and the U.S. Department of Energy (**https://carbon180.org/wp-content/uploads/2023/08/Carbon180-DependingOnTheOcean.pdf**).

[11] Project standards and permitting include requirements for the utilization or storage of biomass materials as a product beyond CDR. The needs vary with the maturity of the approach, for example established building materials and codes adding carbon considerations (RMI, **https://rmi.org/insight/driving-action-on-embodied-carbon-in-buildings**), special permits needed for direct biomass storage (Frontier, **https://github.com/frontierclimate/carbon-removal-source-materials/blob/main/Project%20Applications/2022%20Fall/%5BKodama%20Systems%5D%20Frontier%20Carbon%20Removal%20Purchase%20Application.pdf**), and an extensive permitting environment for BECCS facilities (Energy Futures Initiative, **https://efifoundation.org/wp-content/uploads/sites/3/2022/03/Survey-the-BECCS-Landscape_Report-v2.pdf**).

[12] Based on discussion at the GHGR Workshop on the need for targeted coordination efforts such as organization building or tactical convenings.

Figure 11 Initiatives for advancing Rock CDR technology to 2035

Initiatives are collections of actions with targets and milestones (see Section 5 for more details). Initiatives within a technology area are highly interdependent and do not represent a sequenced set of actions or a priority order. Rather, they should be seen as a collective set of actions focused on the same, urgent goal, where collaboration and coordination are imperative.

[1] A focus on unintended consequences and environmental impacts of open-system approaches was a key discussion focus in the GHGR workshop. Safe deployment of rock CDR requires careful consideration of potential impacts and unintended consequences, such as water or air quality impacts, and requires early engagement with all stakeholders, especially those who have been historically underrepresented in decision-making, to identify concerns and risks. Monitoring and rigorous safeguards must also be in place for all demonstrations and deployments. See *The Applied Innovation Roadmap for CDR* (pp. 15–20, RMI, 2023, **https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr**) regarding stage gates for safe scaling and deployment.

[2] Per *The Applied Innovation Roadmap for CDR* scalability risk assessments, projects should not lead to land-use conversion or negative environmental impacts, or decrease on-site productivity through mineral or soil treatment.

[3] See *The Applied Innovation Roadmap for CDR* for a breakdown of expected costs associated with pre-demonstration and demonstration projects and other path-boosting activities for scale-up (Sections 4.1, 5.1, 5.2, 5.3, 8.2, 8.3) as well as success stories describing ambitious but achievable deployment trajectories for individual approaches. Across rock CDR approaches, expected pre-demonstration and demonstration project costs total to $450–$800 million and $930 million–$2.3 billion, respectively.

[4] Some organizations and partnerships are already exploring alternative ownership models (Carbon180, **https://carbon180.medium.com/in-the-central-valley-exploring-community-led-dac-4b2565b7eec4**). The beginnings of community input structures are codified in the U.S. Department of Energy Project Cypress (**https://www.energy.gov/oced/regional-direct-air-capture-hubs-selected-and-awarded-projects**).

[5] Rock CDR can leverage and build on substantial existing best practice (for example, the Federal Mine Safety and Health Act of 1977, **https://arlweb.msha.gov/REGS/ACT/MinerAct2006home.asp**), with regular updates as best practice evolves, based on timelines for rulemaking and standards updates from OSHA (**https://www.osha.gov/sites/default/files/OSHA_FlowChart.pdf**) and ISO (**https://www.iso.org/developing-standards.html**).

[6] LCA and MRV development were a priority focus in discussions during the GHGR workshop. Workstreams described in *The Applied Innovation Roadmap for CDR* are centered around building out LCAs and MRV for different approaches (see note 4). Recent reports and funding calls describing this focus have been published by ClearPath (**https://clearpath.org/wp-content/uploads/sites/44/2024/03/ocean-cdr-report-4-24.pdf**), Carbon180 (**https://carbon180.org/wp-content/uploads/2023/08/Carbon180-DependingOnTheOcean.pdf**), and the U.S. Department of Energy (**https://carbon180.org/wp-content/uploads/2023/08/Carbon180-DependingOnTheOcean.pdf**).

[7] Per analysis in "Mining: Crushing, Grinding, and Comminution Costs?" (Thunder Said Energy, **https://thundersaidenergy.com/downloads/mining-crushing-grinding-and-communition-costs**), a 40% increase in handling needed for feedstock with an uptake of 0.5 t CO_2/t of feedstock would cost ~$40 million per Mt CO_2.

[8] Based on discussion at the GHGR workshop on the need for targeted coordination efforts such as organization building or tactical convenings.

Figure 12 Initiatives for advancing Non-CO_2 GHGR to 2035

Initiatives are collections of actions with targets and milestones (see Section 5 for more details). Initiatives within a technology area are highly interdependent and do not represent a sequenced set of actions or a priority order. Rather, they should be seen as a collective set of actions focused on the same, urgent goal, where collaboration and coordination are imperative. Note that whereas all of the other CDR initiative tables in Section 7 are about how to scale that technology approach, the initiative table for Section 7.5 is about how to decide whether these approaches should scale at all.

[1] A wide range of R&D projects across approaches, covering different technologies and applications, is needed to increase the knowledge base across the non-CO_2 GHGR field. Ocean CDR — another field involving several different proposed approaches, including many open-system interventions requiring complex natural and climate system modeling — provides a reference for the needed scale. In the United States alone, in 2023, 36 projects were allocated a total of $60 million of federal funding. New projects should be funded annually over the next 10 years as the field develops. At this rate, 360 projects would be funded in the United States by 2035, though the number of projects needed is likely higher for non-CO_2 GHGR due to the large number of distinct technologies proposed that are at low TRL. Forty percent of global R&D spending occurs in the United States (Economic Strategy Group, **https://www.economicstrategygroup.org/publication/seven-recent-developments**), suggesting that ~2.5x of this proposed project/funding total is achievable globally.

[2] Research focus on unintended consequences and environmental impacts of open-system approaches was a key discussion focus in the GHGR workshop.

[3] Funding allocations for other large-scale Earth systems modeling projects (Federal Grants, **https://www.federalgrants.com/Earth-System-Modeling-54866.html**; EESM, **https://climatemodeling.science.energy.gov/news/doe-announces-funding-earth-system-model-development-and-analysis**; Climate Program Office, **https://cpo.noaa.gov/earth-system-science-and-modeling-research-in-support-of-the-disaster-relief-supplemental-act-essm-2023-funding-opportunity**; European Commission, **https://cordis.europa.eu/project/id/101003536**) ranged from $2 to $16 million/y. More funding than the amount indicated here may be needed for related experimental research to determine parameter values to feed into atmospheric chemistry models.

[4] For one example of the type of research needed, see the methane removal model intercomparison project described in Robert B. Jackson et al. ("Atmospheric Methane Removal: A Research Agenda," *Philosophical Transactions of the Royal Society A* 379 [November 2021]: **https://doi.org/10.1098/rsta.2020.0454**)

[5] Though H_2 is not itself a GHG, its atmospheric concentrations are relevant for accurate modeling of the climate impacts of CH_4. Because H_2 competes with CH_4 for oxidants, increases in H_2 concentrations increase the lifetime and thus integrated warming impact of CH_4. H_2 concentrations may increase in the future due to the use of H_2 as a replacement for fossil fuels in order to reduce CO_2 emissions.

[6] Efforts are underway in this space but need to be continued and expanded upon. MethaneSAT (**https://www.methanesat.org**), launched in 2024, will measure CH_4 emissions from high-concentration sources such as oil and gas facilities. Ground-based sensor networks are needed for ongoing monitoring of CH_4 and N_2O emissions from diffuse, low-concentration sources, such as wetlands and thawing permafrost.

Figure 13 Roadmap for scaling technological greenhouse gas removal by 2050

The initiatives shown here are highly interdependent and should be enacted in parallel because they enable and reinforce one another. They should be seen as a collective set of actions focused on the same urgent goal. Furthermore, this figure is a roll up of Figures 14–16 with select insertions of initiatives from Figures 8–12. More details on these initiatives can be found in those figures and their accompanying sections.

Figure 14 Roadmap initiatives for scaling GHGR removals from 2024 to 2030

Initiatives are collections of actions with targets and milestones (see Section 5 for more details). The initiatives in this decadal section are highly interdependent and do not represent a sequenced set of actions or a priority order. Rather, they must be enacted in parallel, continually reinforcing each other. Furthermore, collaboration and coordination across the various stakeholders is imperative. Thematic abbreviations include science and technology (S&T), socio-behavioral and communities (SB&C), policy and regulation (P&R), and finance and markets (F&M). Note also that the initiatives in this table are built in the context of this roadmap, which includes complementary and cross-linking initiatives in thematic areas, technology, and decadal periods. All milestones are defined at the end of the decadal period, but achieving them requires significant, sustained action across the decadal period.

[1] *The Applied Innovation Roadmap for CDR* (pp. 16–18, RMI, 2023, **https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr**) estimates that over $5 billion will be needed in pre-demonstration R&D funding in the near term across all CDR pathways. When accounting for necessary R&D needed for non-CO_2 removal and other crosscutting R&D, this estimate increases by a few billion. Note that more details on specific R&D needs can be found in *The Applied Innovation Roadmap for CDR*.

[2] Rhodium Group published a report estimating $6 billion over the next 10 years for U.S. R&D funding. The United States has 40% of the world's R&D budget, which indicates $15 billion for R&D worldwide in the next decade. Divided by half, this means around $7.5 billion is needed in the next 10 years (Rhodium Group, **https://rhg.com/wp-content/uploads/2024/04/The-Landscape-of-Carbon-Dioxide-Removal-and-US-Policies-to-Scale-Solutions.pdf**).

[3] Some estimates may show more R&D funding is necessary in the near term. Representative Paul Tonko proposes $12 billion in the Carbon Dioxide Removal Research and Development Act of 2023 over the next decade (**https://www.congress.gov/bill/118th-congress/senate-bill/2812/text**). The United States has 40% of the world's R&D budget, which indicates $30 billion for R&D worldwide in the next 10 years. Dividing this in half would mean $15 billion in the next 5 years, which is a higher estimate of R&D funding needed than what is indicated by the Rhodium Group report (S.2812 — Carbon Dioxide Removal Research and Development Act of 2023, **https://www.congress.gov/bill/118th-congress/senate-bill/2812/text**).

[4] Safe deployment of any CDR requires careful consideration of potential impacts and unintended consequences and requires early engagement with all stakeholders, especially those who have been historically underrepresented in decision-making, to identify concerns and risks. Monitoring and rigorous safeguards must also be in place for all demonstrations and deployments.

[5] See *The Applied Innovation Roadmap for CDR* for a breakdown of expected costs associated with pre-demonstration and demonstration projects and other path-boosting activities for scale-up as well as success stories describing ambitious but achievable deployment trajectories for individual approaches. The 300–400 metric for demonstration projects is estimated by rolling up demonstration project needs for individual technology roadmaps shown in Section 6. *The Applied Innovation Roadmap for CDR* estimates approximately $15 billion will be needed to fund demonstrations. This initiative does not include field trials or pilots. Furthermore, this does not explicitly include non-CO_2 GHGR, where target numbers for demonstration projects have not yet been determined.

[6] These demonstrations will shed light on successful practices related to data transparency, MRV, community engagement, industrial integration, and innovative financing interventions. Potential funders include governments, industry partners, voluntary credit purchasers, and venture capital.

[7] See key terms for how this roadmap defines communities and co-benefits.

[8] The metric of 400 communities is estimated based on the number of demonstrations needed as outlined in 1.2. This number assumes that, on average, at least one community will be engaged per project. Though rare, some CDR demonstration projects might not have potential impacts on any communities, and some will need to engage with several communities before and during deployment. Community engagement should also occur as early and thoroughly as possible for field trials and pilots, not just demonstrations. More detailed initiatives for field trial, pilot, and demonstration engagement are included in the technical roadmaps in Section 7, and principles that all engagement should adhere to are mentioned in Section 6.2.

[9] The need for social science research and local journalism was raised by several experts during the GHGR workshop and was further emphasized during review of this roadmap. Social science research is intended to shape engagement practices with regard for social and cultural contexts and to explore community design and ownership models. Local journalism is intended to combat mis- and disinformation surrounding CDR and to increase transparency around projects.

[10] Assuming 50% of demonstrations receive media coverage from local news outlets provides an estimate of 200 projects being covered. Multiple local news outlets may cover the same project.

[11] See key terms for more information on TRLs. TRLs above 6 indicate when a technology has had a successful pilot and is moving toward demonstration scale. Workforce development organizations should focus on training, apprenticeship, and other programs that prepare workers for approaches that are likely to scale after successful pilots. NDC stands for nationally determined contributions.

[12] Over 40 countries have mentioned CDR in their long-term strategies (LTSs), which are formal plans submitted by countries to the United Nations Framework Convention on Climate Change (World Resources Institute, **https://www.wri.org/insights/carbon-removal-countries-climate-goals**). These countries provide a rough estimate for the number of countries that should develop roadmaps and strategic siting plans in the next five years. This initiative does not aim to exclude countries that do not currently have CDR mentioned in their LTS but rather to provide a reasonable estimate for number of countries that can begin roadmapping based on work already being done.

[13] An example of these country roadmaps and how NGOs play a role can be found in the work Carbon Gap has done on its country readiness project (**https://carbongap.org/country-readiness-project**).

[14] Approximately 40 countries are already deploying CDR projects (CDR.fyi, **https://www.cdr.fyi/carbon-removal-map**). These countries provide a rough estimate for the number of countries that should, by 2030, have established clear permitting pathways given ongoing project development. This initiative does not aim to exclude countries that do not currently have CDR projects but rather to provide a reasonable estimate for the number of countries that can begin clarifying permitting given the projects already under development.

[15] Government-backed standards related to environmental and public health are vital to inform MRV and to provide proof that a project is mitigating harms and risks. A central standard body for MRV will likely not exist by 2030 given the R&D, technology development, and methodology development still needed. See discussion of 2030–2040 initiatives for more information on standard bodies for MRV.

[16] As mentioned in Section 5, this roadmap is based on results from collective brainstorming during the GHGR workshop in February 2024. The need for standard-setting bodies to work on market infrastructure (as mentioned) was raised by several experts. Harmonized markets will likely not yet exist by 2030 because of necessary MRV and standards development; however, see 2030–2040 for more initiatives on this.

[17] BCG modeling estimates that by 2030, CDR demand will be between $10 and $40 billion. This analysis used BCG's $/ton assumption in the high scenario ($200/t) and the 2030 roadmap goal of ~285 Mt of deployment outlined in Section 4 to estimate the range of $40–$60 billion/y by 2030 (BCG, **https://web-assets.bcg.com/44/75/58c3126c4050b74ae75b037e9434/bcg-the-time-for-carbon-removal-has-come- sep-2023.pdf**). As of April 2024, at least $2.4 billion in total CDR sales have occurred (CDR.fyi, accessed July 2024).

Figure 15 Roadmap initiatives for scaling GHGR removals from 2030 to 2040

Initiatives are collections of actions with targets and milestones (see Section 5 for more details). The initiatives in this decadal section are highly interdependent and do not represent a sequenced set of actions or a priority order. Rather, they must be enacted in parallel, continually reinforcing each other. Furthermore, collaboration and coordination across the various stakeholders is imperative. Thematic abbreviations include science and technology (S&T), socio-behavioral and communities (SB&C), policy and regulation (P&R), and finance and markets (F&M). Note also that these decadal initiatives are built in the context of the 2024 Bezos Earth Fund GHGR Roadmap, which includes complementary and cross-linking initiatives in thematic areas, technology, and decadal periods. All milestones are defined at the end of the decadal period, but achieving them requires significant, sustained action across the decadal period.

[1] The IEA *Net Zero by 2050* scenario models require climate RD&D spend to increase to $90 billion annually, representing 2% of total climate spending targets of $4–$5 trillion/y (IEA, **https://www.iea.org/reports/net-zero-by-2050**). As outlined in Section 1, to limit total warming to 1.5°C, between a quarter and a third of net emissions reductions will have to stem from negative emissions technologies. Applying this ratio to the fraction of allocated research budgets suggests that ~0.5% of total climate spending should go toward CDR R&D.

[2] The Institute for Energy Economics and Financial Analysis extracted information from the IEA *Net Zero by 2050* scenario on RD&D investment needs (Institute for Energy Economics and Financial Analysis, **https://ieefa.org/resources/ieas-net-zero-emissions-2050-maps-huge-increase-global-ambition**).

[3] For context, annual R&D spending by businesses in the United States in 2020 was $538 billion, with 79%, 14%, and 7% on development, applied, and basic research, respectively (National Center for Science and Engineering Statistics, **https://ncses.nsf.gov/pubs/nsf22343**).

[4] Safe deployment of any CDR requires careful consideration of potential impacts and unintended consequences and requires early engagement with all stakeholders, especially those who have been historically underrepresented in decision-making, to identify concerns and risks. Monitoring and rigorous safeguards must also be in place for all demonstrations and deployments.

[5] Not all CDR approaches will scale to be part of the climate solution portfolio in 2050; the most viable, implementable, and climate-beneficial approaches should be selected. One metric to determine viability of rapid scaled deployment is the initiation of a commercial-scale project within 10 years of the first successful demonstration of the technology, which includes standards for community engagement processes, evaluation of the human health, and environmental safety impacts that inform MRV.

[6] Approaches that are already well established by 2030 will need many more than one commercial project underway by 2040 in order to reach overall deployment targets.

[7] Demonstration- and commercial-scale projects will continue to shed light on successful practices related to data transparency, standards and tools for MRV, community engagement, industrial integration, and innovative financing interventions. Potential funders include governments, industry partners, voluntary credit purchasers, and venture capital.

[8] See key terms for how this roadmap defines communities and co-benefits.

[9] The need for social science research to shape engagement practices to social and cultural contexts and to explore community design and ownership models was raised by several experts during the GHGR workshop and further emphasized during review of this roadmap.

[10] For reference on workforce scaling, the global oil, coal, and gas industries produce approximately 15 Gt/y of fossil fuels and require a total global workforce of 32 million individuals (IEA, **https://www.iea.org/reports/world-energy-employment/executive-summary**). This ratio of 2 workers per 1,000 t of material production and processing is in approximate accordance with workforce intensities per kt CO_2/y deployment of current CDR projects based on RMI interviews and is scaled here to match the 2040 deployment target of target of ~4.5 Gt CO_2/y.

[11] Target metric based on an increase of the number of countries engaged in strategic siting for CDR in Initiative 1.7.

[12] As technologies, markets, and governance systems mature, standards for project deployment, MRV, and removal certification, combined with a track record of successful project deployment, should reduce the additional financial risks associated with early CDR projects.

[13] By 2040, projects at commercial scale should utilize MRV with transparent and high-quality data, and deployment impacts should be well understood before significant scale-up. While this goal is not restated in the following decade, successful processes should continue, with systems, data sharing, and protocols being iteratively updated to reflect changes in the CDR landscape.

[14] Aligned with S-curve deployment described in Section 4.

[15] Deployment at the scale of several Gt CO_2/y will require demand-generating mechanisms beyond traditional market structures, potentially including tax incentives, procurement, pay for practice, regulatory measures, and compliance markets, as described in Section 6.4.

Figure 16 Roadmap initiatives for scaling GHGR removals from 2040 to 2050

Initiatives are collections of actions with targets and milestones (see Section 5 for more details). The initiatives in this decadal section are highly interdependent and do not represent a sequenced set of actions or a priority order. Rather, they must be enacted in parallel, continually reinforcing each other. Furthermore, collaboration and coordination across the various stakeholders is imperative. Thematic abbreviations include science and technology (S&T), socio-behavioral and communities (SB&C), policy and regulation (P&R), and finance and markets (F&M). Note also that these decadal initiatives are built in the context of the 2024 Bezos Earth Fund GHGR Roadmap, which includes complementary and cross-linking initiatives in thematic areas, technology, and decadal periods. All milestones are defined at the end of the decadal period, but achieving them requires significant, sustained action across the decadal period.

[1] The IEA *Net Zero by 2050* scenario models require climate RD&D spend to increase to $90 billion annually, representing 2% of total climate spending targets of $4–$5 trillion/y (IEA, **https://www.iea.org/reports/net-zero-by-2050**). As outlined in Section 1, to limit total warming to 1.5°C, between a quarter and a third of net emissions reductions will have to stem from negative emissions technologies. Applying this ratio to the fraction of allocated research budgets suggests that ~0.5% of total climate spending should go toward CDR R&D.

[2] The Institute for Energy Economics and Financial Analysis extracted information from the IEA *Net Zero by 2050* scenario on RD&D investment needs (Institute for Energy Economics and Financial Analysis, **https://ieefa.org/resources/ieas-net-zero-emissions-2050-maps-huge-increase-global-ambition**).

[3] For context, annual R&D spending by businesses in the United States in 2020 was $538 billion, with 79%, 14%, and 7% on development, applied, and basic research, respectively (National Center for Science and Engineering Statistics, **https://ncses.nsf.gov/pubs/nsf22343**).

[4] Safe deployment of any CDR requires careful consideration of potential impacts and unintended consequences and requires early engagement with all stakeholders, especially those who have been historically underrepresented in decision-making, to identify concerns and risks. Monitoring and rigorous safeguards must also be in place for all demonstrations and deployments.

[5] Aligned with S-curve deployment described in Section 4.

[6] Deployment at the scale of several Gt CO_2/y will require demand-generating mechanisms beyond traditional market structures, potentially including tax incentives, procurement, pay for practice, regulatory measures, and compliance markets, as described in Section 6.4.

[7] Target number of countries based on an increase of the number of countries engaged in strategic siting for CDR in Initiative 1.7.

[8] See key terms for how this roadmap defines communities and co-benefits.

[9] For reference on workforce scaling, the global oil, coal, and gas industries produce approximately 15 Gt/y of fossil fuels and require a total global workforce of 32 million individuals (IEA, **https://www.iea.org/reports/world-energy-employment/executive-summary**). This ratio of 2 workers per 1,000 t of deployment is in approximate accordance with workforce intensities per kt CO_2/y deployment of current CDR projects based on RMI interviews and scaled here to match the 10 Gt CO_2/y deployment target by 2050.

[10] As technologies, markets, and governance systems mature, standards for project deployment, MRV, and removal certification combined with a track record of successful project deployment should reduce any additional financial risks associated with CDR projects.

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About the Bezos Earth Fund

The Bezos Earth Fund is helping transform the fight against climate change with the largest ever philanthropic commitment to climate and nature protection. Jeff Bezos has committed $10 billion in this decisive decade to protect nature and address climate change. By providing funding and expertise, we partner with organizations to accelerate innovation, break down barriers to success, and create a more equitable and sustainable world. Join us in our mission to create a world where people prosper in harmony with nature.
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About RMI

RMI is an independent nonprofit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut climate pollution at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; Abuja, Nigeria; and Beijing.
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