Summary Report:

Strategy Workshop on Scaling Greenhouse Gas Removal

February 6-7, 2024

BEZOS EARTH FUND

Table of Contents

Introduction: Workshop Objectives

The Strategy Workshop on Scaling Greenhouse Gas Removal ('GHGR') was held on February 6th and 7th, 2024, convened by the Bezos Earth Fund alongside the U.S. Department of Energy (DOE) and Stanford University's Doerr School of Sustainability. This workshop convened a group of over 500 experts, including leading scientists, entrepreneurs, policymakers, and funders, to address the urgent need for global solutions to combat climate change through the removal of greenhouse gases from the atmosphere.

The workshop's primary goal was to identify the greatest barriers, enablers, dependencies, risks, and uncertainties pertaining to scaling GHG removals, with a goal of 10Gt/y of removals by 2050. Throughout the workshop, attendees engaged in a series of interactive, facilitated sessions designed to prioritize key actions, identify relevant stakeholders, and establish milestones towards achieving this goal. On Day 1, the workshop featured breakout sessions focused on specific technologies for greenhouse gas removal (GHGR), including methods such as carbon dioxide removal ('CDR') via air, oceans, rocks, and land, as well as strategies for removing methane and nitrous oxide emissions. Day 2 focused through a different lens of the broader ecosystem required for scale, covering topics such as technological and scientific advancements, socio-behavioral impacts and community engagement, policy and regulatory frameworks, financial and market mechanisms, and measurement, reporting, and verification ('MRV') processes. Given the nascent nature of this field, it also provided an opportunity to approach the important issues of equity and justice more intentionally - not only as standalone themes, but also as cross-cutting ones that were interwoven into the other topic areas.

The workshop's structure was designed to foster active engagement and data collection through a combination of plenary sessions, interactive tools, and breakout discussions. Plenary sessions, including presentations from experts and deep dives into specific topics, were conducted jointly with both in-person and virtual participants. Interactive polling tools were utilized to capture broad input on key questions from every attendee. The breakout sessions were led by both subject matter experts ('SME'), who offered insights and context relevant to each topic while guiding the conversation, and facilitators, who guided the participants through the interactive activities and discussions.

Ultimately, the workshop sought to lay the groundwork for a global roadmap on scaling greenhouse gas removals, identifying funding opportunities and gaps, and creating new collaborations and partnerships, aligned with a strategic vision to achieve the ambitious goal of 10Gt/y of greenhouse gas removal by 2050. The workshop's results are anticipated to inform and catalyze future initiatives in the GHGR sector.

Methodology

This document provides a comprehensive summary of the discussions, insights, and recommendations that emerged during the recent Strategy Workshop on GHGR. The write-up captures the diverse perspectives and ideas shared by participants over the course of the workshop, including those from both in-person and virtual breakout sessions. The content was developed by synthesizing notes, flipcharts, and recordings from the sessions, with the aim of presenting a clear and accurate reflection of the key themes and outcomes. A similar process was used for the virtual group, using data from interactive polling tools and session recordings to provide insight into the discussion.

It is important to note that while this document aims to provide a faithful representation of the workshop proceedings, the views and opinions expressed are those of the participants and do not reflect the official positions or perspectives of the Bezos Earth Fund. These views and opinions are the verbatim inputs of participants and have not been vetted for accuracy. Readers are encouraged to consider the content as a snapshot of the ongoing dialogue within the GHGR community, with the understanding that it reflects a wide range of experiences and expertise.

This document is structured chronologically, following the workshop agenda attached below.

Agenda

Day 1		
Time (ET)	**Agenda Topic**	**Notes**
9:00 - 9:30	**Welcome** *Andrew Steer, Bezos Earth Fund* *Noah Deich, Department of Energy* **Workshop Goals, Agenda, + Logistics** *Noël Bakhtian, Bezos Earth Fund*	Joint Plenary (Empire Ballroom & Zoom)
Getting to Scale		
9:30 - 9:40	**Reflections on Scaling Technology** *Arun Majumdar, Stanford University*	Joint Plenary (Empire Ballroom & Zoom)
9:40 - 9:55	**Workshop Framing: Deep Dive** *Rudy Kahsar, Rocky Mountain Institute*	Joint Plenary (Empire Ballroom & Zoom)
9:55 - 10:30	**Breaking the Ice: Top Priorities to Scale** Individual input & small group discussions	In Person: Table Discussions Virtual: Moderated Inputs
10:30 - 10:45	Break	

Day 1		
Time (ET)	**Agenda Topic**	**Notes**
Day 1 Breakout Discussions		
10:45 - 11:45	**Lightning Talks** ***CDR Air*** *– Rory Jacobson, Department of Energy* ***CDR Oceans*** *– Anya Waite, Ocean Frontier Institute* ***CDR Rock*** *– Colin McCormick, Carbon Direct* ***CDR Land*** *– Dave Hillyard, CTR Foundation* ***Methane Removal*** *– Rob Jackson, Stanford University* ***Nitrous Oxide Removal*** *– Erika Reinhardt, Spark Climate Solutions*	Joint Plenary (Empire Ballroom & Zoom)
11:45 - 12:45	Lunch Break	
12:45 - 1:00	Instructions and Move to Breakout Rooms	Joint Plenary (Empire Ballroom & Zoom)
1:00 - 3:30	**Breakout Session – Day 1** • Identify & prioritize barriers, system dependencies, unintended consequences, enablers, and uncertainties • Deep dive to address barriers and enablers • Identify milestones (action, timeline, type of stakeholder)	In Person: Moderated breakout rooms (assigned day-of) Virtual: Moderated plenary session
3:30 - 3:40	Break / Return to Plenary Room	
3:40 - 4:25	**Breakout Session Report Outs** Day 1 Thematic Facilitators (listed in Appendix p.112)	Joint Plenary (Empire Ballroom & Zoom)
4:25 - 4:55	**Day 1 Insights** Individual input, group discussions, sharing across plenary • What has been overlooked? • Common solutions	Joint Plenary (Empire Ballroom & Zoom)
4:55 - 5:00	**Day 1 Closing Remarks** *Kelly Levin, Bezos Earth Fund*	

Day 2		
Time (ET)	**Agenda Topic**	**Notes**
8:00 - 8:10	**Day 2 Overview** *Kelly Levin, Bezos Earth Fund*	Joint Plenary (Empire Ballroom & Zoom)
Day 2 Breakout Discussions		
8:10 - 9:00	**Lightning Talks** ***S&T*** *– Nikki Batchelor, XPRIZE Foundation* ***SB&C*** *– Holly Buck, University at Buffalo* ***P&R*** *– Jack Andreasen, Breakthrough Energy* ***F&M*** *– Nan Ransohoff, Frontier* ***MRV*** *– Anu Khan, Carbon180*	Joint Plenary (Empire Ballroom & Zoom)
9:00 - 9:15	Instructions and Move to Breakout Rooms	Joint Plenary (Empire Ballroom & Zoom)
9:15 - 11:45	**Breakout Session – Day** • Identify & prioritize barriers, system dependencies, unintended consequences, enablers, and uncertainties • Deep dive to address barriers and enablers • Identify milestones (action, timeline, type of stakeholder)	In Person: Moderated breakout rooms (assigned first day) Virtual: Moderated plenary session
11:45 - 12:00	Return to Plenary Room	
12:00 - 1:00	**Lunch and Team Report Outs** Day 2 Thematic Facilitators (listed in Appendix)	Joint Plenary (Empire Ballroom & Zoom)
1:00 - 1:30	**Day 2 Insights** Individual input, group discussions, sharing across plenary • What has been overlooked? • Common solutions	Joint Plenary (Empire Ballroom & Zoom)
Back to the Big Picture		
1:30 - 2:45	**Small Group Discussions with Notetakers** • Capture the most critical milestones, priorities, gaps, and opportunities across both days	In Person: Moderated discussion tables Virtual: Moderated plenary session
2:45 - 3:00	Break	

Day 2		
Time (ET)	**Agenda Topic**	**Notes**
Mapping Out Short-Term Priorities		
3:00 - 4:15	Small group discussions with notetakers, plenary readout Deep dive on actions and organizations needed to 2030	In Person: Moderated discussion tables Virtual: Moderated plenary session
4:15 - 4:30	**Closing Remarks & Next Steps** *Brad Crabtree, Department of Energy* *Noël Bakhtian, Bezos Earth Fund*	Joint Plenary (Empire Ballroom & Zoom)

Day 1: Morning Plenary Session

Breaking the Ice: Top Priorities to Scale

Objective:

The "*Breaking the Ice: Top Priorities to Scale*" activity served as an initial, unbiased collation of participants' perspectives across the full spectrum of GHGR strategies. Conducted using an interactive polling tool at the start of the conference, this exercise was designed to capture a broad range of ideas and priorities before participants engaged in group discussions. Participants were asked to respond to five key questions:

- What are the top 1-3 barriers or roadblocks through 2050, and by when do they need to be overcome?
- What are the top 1-3 systems dependencies through 2050, and by when do they need to be addressed?
- What are the top 1-3 risks or unintended consequences through 2050, and by when do they need to be mitigated?
- What are the top 1-3 enablers or game-changers through 2050, and by when do they need to come into play?
- What are the top 1-3 largest open questions or uncertainties through 2050, and by when do they need to be answered or addressed?

By focusing on the key questions that would later guide breakout sessions, the activity provided a snapshot of participants' views, laying the groundwork for deeper exploration during the workshop. The following insights reflect a set of collated responses that have been refined and edited for clarity, but not validated for accuracy.

Key Insights:

Question 1: Barriers and Roadblocks through 2050:

- High costs associated with deploying carbon removal technologies
- Market uncertainty regarding long-term demand and sustained financing
- Insufficient policy support, unclear and slow permitting processes, and a lack of political will and commitment from governments to implement and enforce supportive regulations
- Technological challenges, including the readiness and development of scalable carbon removal solutions
- The creation and development of markets for carbon removal credits, along with the establishment of strong demand and incentives for corporate buyers
- Social license and public acceptance
- The availability and management of resources such as energy, land, and water, along with the development of necessary infrastructure
- Effective and accurate MRV systems
- Establishing robust market mechanisms, including carbon pricing and secure revenue streams
- Global collaboration and coordination among policymakers, as well as a robust supply chain
- Investing in workforce development
- Building trust and transparency

- Addressing time constraints and engineering challenges of large projects

Question 2: System Dependencies through 2050:

- Energy requirements, use, and supporting infrastructure, including clean energy systems and grids
- Clean energy availability and low carbon energy sourcing
- Energy inputs, development financing, and the management of excess renewable energy production
- Sustainable biomass supply and scaling nuclear energy
- Excess energy management, energy efficiency, and parallel dependencies with energy efficiency
- Policy support, enabling policies, and policy frameworks
- Movement to compliance markets and political support with policy predictability
- Regulatory frameworks and international cooperation
- Institutional interplay and the creation of compliance mechanisms to recognize the CDR pathway
- Robust supply chains, transport infrastructure, and accessible pilot facilities
- Decarbonized infrastructure for CDR and effective CO2 pipelines and transport systems
- The availability and management of land and ocean resources
- Scaling technologies responsibly and addressing CO2 infrastructure requirements
- Effective CO2 storage and transport/utilization systems
- Storage sites and securing Class VI permits for large-scale deployment
- Social acceptance, public perception, and engagement
- Addressing “Not-In-My-Backyard" (‘NIMBY’) sentiments
- Clear articulation of science and sustained social and political will
- Human capital and a skilled workforce
- High integrity and trustworthy MRV standards
- Recognition and mitigation of side effects and avoiding negative impacts on current systems are essential
- Environmental impacts and feedback loops, and the ecological consequences must be addressed
- Development of markets for trading and retiring credits and creating early successful projects to build support
- Market mechanisms, demand for removals, and clear unit economics
- Capital, finance, and sustainable funding and investment for research and development
- First-of-a-kind (FOAK) financing and responsible innovation should be prioritized
- Financial efficiency
- Integration of GHGR in industrial and climate policy
- Addressing voters' understanding, climate change feedback, and feedstock availability
- Ensuring public perception, verifiable value, and trust about permanence of approaches
- Scaling technologies responsibly and addressing environmental and social impacts
- Communication within the industry to track growth and recognizing climate and biodiversity crises

Question 3: Risks or Unintended Consequences through 2050:

- Potential environmental and health externalities, including ecological collapse, negative impacts on ecosystems, unintended ecological consequences, and biodiversity loss
- Poor MRV could lead to solutions that do not have the intended impacts, and mechanization of the natural environment could cause additional harm
- Feedback loops from existing tipping points, robbing funding from intact nature, and unintended pollutants mobilized by the CDR process
- Public opposition, including NIMBY syndrome, social resistance, and a lack of public acceptance
- Winning hearts and minds, addressing community harm, and preventing public backlash (e.g., similar to genetically modified organisms 'GMOs') are essential for social license
- Greenwashing and not understanding the negative impacts on life can undermine public support and trust
- High costs, financial instability, and economic feasibility issues, with market volatility and carbon price collapse
- The concentration of financial benefits among the already wealthy, and the potential for market manipulation
- The opportunity costs of investing in GHGR versus alternative markets
- Reduced corporate incentives to reduce emissions and the willingness of capital markets to undertake risks and carbon removal efforts
- Corporate greed, confusion, and poor project execution undermining the carbon market
- Policy changes, regulatory uncertainty, and policy instability create an unpredictable environment for scaling efforts
- Moral hazard, where carbon removal delays reducing emissions and keeps fossil fuels in business longer
- Technological failure and the premature commercialization of technologies could lock in suboptimal solutions and harm ecosystems
- Risk of non-delivery, high profile early failures, and the impact of technological failures on sector credibility
- The burden on the Global South, exacerbating environmental justice issues, and entrenching injustices in disadvantaged communities
- Fossil fuel industry influence, geopolitical instability based on resource distribution, and perpetuating global north benefits
- Ensuring equitable distribution of benefits
- Lack of permanence, non-delivery, and failure to achieve significant yearly growth by 2030
- Mitigation deterrence, resource prioritization, and clean power cannibalization undermining broader sustainability goals
- Social destabilization due to climate disruption and the impact on emissions mitigation efforts
- Hubris, unanticipated consequences, and rapid cooling associated with large-scale deployment
- Public backlash, conspiracy theories, and short attention spans shifting to other issues
- The opportunity cost of using renewables for CDR instead of grid greening and the need for continued government support and regulatory environments

Question 4: Enablers and Game Changers through 2050:

- Programs that support early CDR companies with FOAK/demonstration plant financing and engineering support, along with significant funding from project financing, non-dilutive capital, and long-term commitments
- Philanthropic support, large off-take agreements from bankable buyers, and efforts such as funding numerous startups and pilot plants during the adoption phase
- Efforts should include contributions from influential individuals like Bezos and Gates, capital willing to take risks and weather losses, and private sector funding
- Effective policy governance, including compliance policies, strong environmental and social safeguards, and robust government support
- Legal frameworks, policy incentives, and demand support from public procurement and compliance markets
- Coordinated efforts between funding, policy, and research and development ('R&D'), alongside clear government indications of success metrics
- Carbon pricing, a robust and standardized MRV system, and market-driven innovation
- Direct government procurement and a respected, fungible carbon market
- Compliance markets, high carbon prices, and alignment of commercial incentives with social benefits are essential for market development
- Innovations such as nuclear fusion, gene-edited crops, Direct Air Capture ('DAC') chemical catalysts, and enhanced rock weathering
- Development of energy-efficient carbon removal technologies and rapid decarbonization.
- Technological accelerators and agnostic approaches to technology development
- Robust and trustworthy MRV systems, with high confidence in carbon removal accuracy.
- Standardized MRV and independent validation
- Significant investment in science-based MRV
- Abundant clean energy sources, including limitless carbon-free energy and renewable resources
- Cost-effective and selective processes, along with energy-star certifications for CDR.
- Marine CDR, which uses no land, and innovations in clean energy availability and management
- Effective public outreach, communication, and building social acceptance, especially in the global south
- Strong public and political will, broad public recognition of the need and urgency, and trained professionals
- Inclusivity and political commitment to mitigation before using CDR
- International collaboration, government partnerships, and regional and community buy-in
- Utilization of ocean resources, scientific research, and bankable solutions
- Breaking away from the ton-for-ton financing assumption and focusing on value propositions, such as improved crop production
- Moving forward with subscale projects and developing a high price on carbon, while prioritizing methane removal
- Articulating co-benefits, growing small teams into larger entities, and ensuring demand and price certainty
- Independent evidence, better onramps to tax credits, and avoiding circular firing squads

- Encouraging public and economic acceptance, fostering regenerative capitalism, and ensuring inclusivity in the conversation
- Integration of carbon removal strategies into mainstream business models and driving innovation through investment

Question 5: Open Questions and Uncertainties through 2050:

- Will there be sufficient political will and support to drive CDR initiatives?
- How will global political cooperation and resilience against populism affect CDR efforts?
- What will be the impact of escalating global conflict and short-term crises on long-term CDR projects?
- How can public acceptance and support for CDR be secured, especially in the face of potential pushback and fickle public perception?
- What is the impact of social license to operate and fear mongering by certain stakeholders on political will and voluntary demand?
- How will MRV protocols be developed and standardized, and can their trustworthiness be ensured?
- How can we prove the effectiveness of carbon removal and understand the true performance of CDR technologies?
- Who will buy carbon credits, and how can revenue uncertainty be mitigated?
- Will private capital be willing to tolerate losses, and how will financial risk aversion be managed?
- What are the cost and performance improvements needed for CDR options, and what is the business case for large-scale deployment?
- How can permitting, manufacturing, and infrastructure capabilities be addressed to enable rapid scaling?
- What is the potential for locked-in suboptimal technologies, and is achieving 50% year-over-year growth feasible?
- How can reliable supply chains and logistics be ensured?
- How will human behavior, including greed and mistrust, impact CDR efforts?
- How can public support for a price on carbon be motivated, and how can engagement be expanded beyond traditional stakeholders?
- What are the impacts of other societal priorities and the risk of famine on CDR initiatives?
- How durable and permanent is carbon removal, and what are the risks of CO_2 leakage?
- What are the true environmental impacts of CDR options, and how will slow-emerging ecological harm be assessed?
- How will interactions with renewable energy and climate tipping points affect CDR efforts, and can large-scale ecological monitoring be effectively implemented?
- How will global conflict, war, and unilateral geoengineering by rogue states or individuals impact CDR initiatives?
- What will be the influence of rising global fascism and strongman politics on CDR efforts?
- What is the current policy environment, and how do the absence of regulation and policy barriers affect CDR deployment?
- How will regulatory frameworks that may slow deployment and permitting issues be addressed?
- Who will buy carbon credits, and what is the business case for CDR?

- What are the true costs of CDR options, and how will the market growth rate affect CDR companies?
- What is the risk of a venture capital funding bubble, and how can it be mitigated?
- How can the process of scaling durable CDR be clarified, and what is the impact of climate change feedbacks?
- What are the risks of early market failures, and how can they be addressed?
- How will NIMBYism, runaway emissions from permafrost, and cheaper solar radiation modification impact CDR efforts

Day 1: Breakout Session

Objective:

The breakout sessions held on Day 1 were structured to facilitate an in-depth exploration of key topics related to GHG removal, encompassing the major carbon removal pathways (rock, ocean, land, and air), alongside the emerging pathways of methane and nitrous oxide removal.

Subject matter experts first presented a "lightning talk" in the plenary session, providing an overview of the current landscape and state of play for each field. Following this, participants gathered in two breakout rooms per topic, and individually shared responses to the following five questions through a post-it note exercise:

- What are the top 1-3 barriers or roadblocks through 2050, and by when do they need to be overcome?
- What are the top 1-3 systems dependencies through 2050, and by when do they need to be addressed?
- What are the top 1-3 risks or unintended consequences through 2050, and by when do they need to be mitigated?
- What are the top 1-3 enablers or game-changers through 2050, and by when do they need to come into play?
- What are the top 1-3 largest open questions or uncertainties through 2050, and by when do they need to be answered or addressed?

These responses were subsequently voted on by each breakout group to highlight the top issues in each category. Following the voting process, the top voted answers to two of the questions - the barriers/roadblocks and open questions/uncertainties - were further explored in a deep dive discussion session, which aimed to outline pathways and milestones (action, timeline, type of stakeholder) to mitigating these to identify GHG removal goals by 2030, 2040, and ultimately, by 2050. The following insights were synthesized from the collective input and discussions recorded during the breakout sessions.

CDR Oceans

State of Play:

During the intro lightning talk at the workshop, Anya Waite from the Ocean Frontier Institute discussed the potential of marine carbon dioxide removal ('mCDR') as a significant opportunity for addressing global carbon emissions. The speaker emphasized that oceans present a multi-gigaton opportunity for carbon sequestration, capable of capturing and storing substantial amounts of CO_2, which has not yet been fully harnessed. mCDR involves

enhancing ocean systems to absorb CO_2 or employing specific technologies to extract CO_2 from seawater.

The speaker differentiated between coastal blue carbon, which includes small-scale ecological interventions like mangroves and seagrasses, and deep blue carbon, which focuses on the vast water bodies and deep-sea sediments. The latter holds the real potential for significant carbon sequestration. The speaker illustrated the massive scale of oceanic carbon capture by comparing it to terrestrial and DAC methods, demonstrating that even a 1% increase in the ocean's natural carbon uptake could offset a full day's worth of global emissions.

Key mCDR technologies highlighted include nutrient fertilization (e.g., iron fertilization), artificial downwelling and upwelling, microalgae and macroalgae cultivation, and ocean alkalinity enhancement. Each method aims to increase the ocean's capacity to absorb CO_2, either by promoting algae growth through nutrient delivery or by chemically enhancing the water's ability to sequester carbon. The unique challenge of MRV in the ocean was also emphasized, as the captured carbon moves through marine ecosystems and must be meticulously tracked to ensure effective sequestration.

Waite outlined the current state of mCDR technologies, noting that they are in the early stages of development, with small-scale field pilots showing promising results. The speaker mentioned several pioneering projects, such as Running Tide in Iceland and Planetary Technologies in Nova Scotia, which are exploring different mCDR approaches. However, significant regulatory challenges were highlighted, including restrictions under the London Convention and Protocol, which limit large-scale deployment of artificial materials in the ocean for carbon sequestration purposes. This regulatory environment necessitates further research and policy development to enable broader implementation.

In terms of funding and community engagement, Waite pointed out that while philanthropic and government funding is available, much of it is still research-focused. The need for substantial investment was stressed to support commercial pilots and develop international facilities like the proposed North Atlantic Carbon Observatory, which would facilitate global cooperation in mCDR research and deployment. Open questions remain regarding the energy requirements, carbon footprint, and long-term ecological impacts of these technologies. Addressing these uncertainties is crucial to leveraging the ocean's potential for large-scale carbon dioxide removal and contributing to global climate mitigation efforts.

Key Insights:[1]

Top-Voted Response from Breakout Group 1

Top-Voted Response from Breakout Group 2

Question 1: Barriers and Roadblocks through 2050:

- Intergovernmental collaboration and data sharing
- Developing large-scale baseline observations and well-designed observation systems
- Aligning policy jurisdictions (state, national, international)
- Securing funding without strings by 2030 and addressing the valley of death funding gap immediately

Question 2: System Dependencies through 2050:

- Access to clean coastal energy and efficient resource reallocation
- Establishing a legal regime

[1] *For the full list of key insights, please see the Appendix - here*

Question 3: Risks or Unintended Consequences through 2050:

- Ecological and environmental impacts (ocean pollution, green ocean, nitrous oxide ('N_2O'), ecosystem disruptions)
- Disruption of existing ecosystems

Question 4: Enablers and Game Changers through 2050:

- Developing robust MRV systems, including ecological and environmental MRV ('eMRV')
- Securing R&D funding

Question 5: Open Questions and Uncertainties through 2050:

- Ocean circulation changes and tipping points, and the impact on MRV and ocean measurement (keeping track of ocean baselines by 2035)
- Addressing social and environmental impacts

Deep Dive - Top Barrier/Roadblock:

Breakout Group 1: Collaboration and Data Sharing

- Data availability varies greatly between private and public entities, often described as comparing a "teacup" of private data to a "Niagara Falls" of public data. Effective collaboration is essential to combine these resources, making data usable and shareable among all stakeholders. This integration is crucial for overcoming barriers to data access and utilization.
- Establishing a reliable baseline for carbon tracking requires significant international investment in data infrastructure. Proposals like a $100 million contribution from philanthropic donors could encourage other nations to invest similarly. Funding must support system design, data collection, and data sharing. Coordinated efforts are necessary to create an effective data sharing ecosystem.
- Designing a smart MRV system is key, even if it doesn't directly remove CO_2. Such a system would enhance understanding of carbon dynamics in the ocean. Addressing the technological aspects of CDR through focused research is also critical for progress.

Breakout Group 2: Funding

- There is a significant funding gap for mCDR, with $2 billion needed for pilot projects by 2030. Immediate R&D funding requires $20 million, and substantial investment is necessary for MRV systems.
- A coordinated approach involving both government and private sector stakeholders is necessary to address the funding gap for pilot projects by 2030.
- Government funding, being discretionary, presents a challenge as it often competes with other priorities, while private sector investment is limited due to perceived risks and low initial returns.
- The primary economic market for mCDR is currently the voluntary carbon market, which lacks sufficient scale to drive substantial demand. Establishing a robust and sustainable market for mCDR is essential to attract investment. This includes identifying potential off-takers who are willing to invest in and support mCDR projects
- Emphasizing the long-term economic benefits of ocean CDR, including job creation, future cost savings related to climate change mitigation, community development, and benefits in reducing ocean acidification, is essential.

Deep Dive - Top Open Question/Uncertainty:

Breakout Group 1: Demand

- Current barriers include the reliance on public grants and voluntary corporate commitments, along with philanthropic funding. These sources are critical for deploying commercial projects. However, as we approach the 2030s, demand is expected to become the main barrier, requiring significant efforts to sustain market demand for mCDR technologies.
- Science and policy must intersect early on to secure necessary agreements for scientific research, especially in international waters. Policies must support scientific advancements, and vice versa, to promote effective mCDR efforts.
- The lack of demand could render mCDR efforts moot and purely academic. Ensuring there is demand is fundamental to making these efforts practical and scalable.
- Tracking carbon is essential to assess the durability and effectiveness of mCDR methods. Some sequestration methods, like sediment burial, may not need extensive tracking. All efforts must be measured against established baselines to validate their impact. Differentiating between mCDR technologies and pathways is necessary to ensure each is properly integrated and implemented.

Breakout Group 2: Public Concern

- Community engagement must begin immediately to build support for mCDR projects. However, this process should not be rushed. Engaging communities thoughtfully and addressing their concerns thoroughly is critical to avoiding backlash and building long-term support for mCDR initiatives. Effective communication strategies could use examples like Cornwall to illustrate potential benefits and ensure local relevance.
- Building a social license involves gaining support from the community, involving local thought leaders and trusted figures, and ensuring transparency through robust MRV systems.
- Public concerns about the environmental impact of mCDR projects, such as potential harm to marine ecosystems, need to be addressed through transparent MRV and reporting systems.
- Effective public communication should focus on both the positive and negative impacts of mCDR, demonstrating accountability and commitment to environmental stewardship.
- Developing community demand for mCDR ensures that projects are perceived as valuable and necessary. This includes educating the public on the importance of addressing greenhouse gas emissions and the role of mCDR in achieving climate targets.
- Communication strategies should be tailored to local communities and delivered by trusted messengers. It is important to make the case for mCDR in a way that resonates with local values and concerns.
- Challenges specific to open ocean versus coastal installations, including public concerns, permitting issues, and job creation, need to be addressed through clear regulatory frameworks and stakeholder engagement.

Report Out:

Group 1

During the report out session, Anya Waite summarized the group's discussions on key barriers and strategic needs for advancing ocean-based CDR. The group emphasized that while funding and investment were critical, they realized that focusing solely on financial aspects

oversimplified the challenges. They identified the need for significant investment in ocean baseline measurements as crucial to underpin credible MRV. However, they noted that this alone wouldn't suffice; a comprehensive global monitoring system must be developed in parallel to track carbon across various ocean systems and reduce uncertainties in MRV.

The discussion also addressed the complexities of scaling ocean CDR, particularly the potential policy challenges associated with large-scale implementation in open ocean areas. The group raised concerns about potential conflicts with UN protocols and the necessity of resolving these issues to move forward. Additionally, they underscored the importance of understanding the environmental impacts of oceanic carbon removal, which requires global cooperation in data sharing and building observation networks. The facilitator highlighted that some policy experts were surprised by the low TRLs of existing technologies, leading to a conversation about the need to rethink strategies to develop a global system capable of supporting ocean CDR efforts effectively by 2050.

Group 2

David Ho, the SME for group 2, highlighted several critical barriers to the deployment of mCDR technologies, particularly emphasizing the challenges related to public engagement and the need for comprehensive MRV. The group underscored that public understanding of mCDR is currently insufficient, which could lead to resistance if communities are not adequately informed about the potential benefits or at least the minimal risks of these technologies. Ho stressed the importance of early and effective communication, involving trusted local figures and the media, to build the necessary social license for conducting field trials and eventually scaling up these efforts.

The group also addressed the fundamental question of whether mCDR even works, noting that rigorous MRV is essential not only for assessing ecosystem impacts but also for quantifying carbon uptake. They emphasized the need for a combination of modeling, laboratory work, and sufficiently large field trials to determine the efficacy of these technologies. Additionally, Ho pointed out the urgency of engaging communities from the outset and conducting LCAs to evaluate the overall environmental impact, with the consensus being that these efforts must begin immediately to inform future deployment strategies.

CDR Air

State of Play:

During a lightning talk at the workshop, Rory Jacobson from the U.S. DOE's Office of Fossil Energy and Carbon Management provided an overview of CDR from air, focusing primarily on DAC. Jacobson emphasized that DAC involves capturing CO_2 directly from ambient air using a medium that is continuously regenerated, distinguishing it from point source carbon capture and photosynthetic processes. The speaker outlined the two main types of DAC technologies: sorbent-based and solvent-based systems, both of which bind CO_2 to a chemical medium that is later regenerated for repeated use.

Jacobson highlighted the need for DAC systems to achieve net negative emissions by carefully managing energy inputs, typically from electricity and heat, to ensure that the total carbon removal outweighs the emissions produced by the system's operation. The speaker emphasized the importance of durable sequestration, focusing on technologies that can permanently isolate CO_2 from the atmosphere, such as geological storage and incorporation into durable products like concrete. Innovative approaches, such as magnesium oxide looping cycles, were also mentioned as emerging technologies in the DAC space.

The current state of DAC, according to Jacobson, includes a few pilot projects capable of capturing thousands of tons of CO_2 annually, though significant advancements in techno-economic and LCAs are still needed. Jacobson noted that while there is growing investment in DAC, with compliance markets and tax credits like 45Q supporting its development, the scale of funding and infrastructure required is immense, likely necessitating hundreds of billions of dollars to achieve meaningful climate impact.

Jacobson also discussed key challenges and considerations for scaling DAC technologies, including securing reliable, clean energy resources, managing potential unintended consequences like displacement of clean energy from the grid, and addressing community acceptance and willingness to support local DAC facilities. The speaker concluded by highlighting the need for further research into the degradation of capture materials, the co-benefits and risks of various technologies, and the necessity of community engagement to facilitate the deployment of DAC systems at scale.

Key Insights[2]:

Top-Voted Response from Breakout Group 1

Top-Voted Response from Breakout Group 2**Question 1: Barriers and Roadblocks through 2050:**

- Securing public acceptance and social license urgently to avoid derailing efforts
- Developing demand markets and policy frameworks to create compliance markets and enable government procurement

Question 2: System Dependencies through 2050:

- Securing large-scale access to clean energy or waste heat
- Providing clean electricity with attention to land use and competition for resources

Question 3: Risks or Unintended Consequences through 2050:[3]

- Political will and opposition could significantly hinder DAC projects

Question 4: Enablers and Game Changers through 2050:

- Realistic and up-to-date evaluation of DAC relative to other CDR options, with specific metrics and a comprehensive policy framework that follows.
- Technological breakthroughs in new sorbents that significantly reduce energy requirements for DAC

Question 5: Open Questions and Uncertainties through 2050:

- How politically feasible is large-scale government procurement of DAC, and how to ensure policy resilience
- Long-term demand signals and the need for clear policy indicators to support DAC

Deep Dive - Top Barrier/Roadblock[4]:

Breakout Group 1:

- The group emphasized addressing deep-rooted historical and political deficits in communities beyond promising value through new projects and highlighted the importance of defining decision-making processes that consider diverse community views.

---

[2] For the full list of key insights, please see the Appendix - here

[3] Responses from Group 1 regarding Question 3 (Risks or Unintended Consequences through 2050) were not collected during the workshop.

[4] Both CDR Air breakout groups expanded their focus to cover a wider range of topics during the deep dive session.

- Integrating new projects into existing infrastructure was seen as one way to reduce their footprint, but addressing pre-existing systemic injustices and immediate community needs such as housing, financial stability, and education was deemed crucial.
- Ensuring local communities have the resources and power to influence decisions about projects was seen as crucial for genuine engagement, with an emphasis on recognizing the varied priorities and needs of vulnerable communities.
- Authentic community engagement was noted to lack a clear roadmap, with suggestions that educating the communities and learning from them about their needs are essential steps.
- Discussions highlighted the importance of understanding both global and US contexts in environmental justice conversations, noting different regional challenges and the need for knowledge exchange between the West and the Global South.
- The need for diverse metrics to evaluate CDR projects was stressed, moving beyond a one-size-fits-all approach to accurately reflect varied impacts and benefits. Discussions also considered the potential value-added elements and opportunity costs for vulnerable communities.
- Establishing clear milestones for progress in environmental justice projects was deemed important. The costs associated with environmental projects need clearer understanding and communication.
- The group discussed the need to build a global discourse on issues like storage capacity and broader environmental impacts.

Breakout Group 2:

- High initial capital costs and insufficient risk capital deter investment in CDR projects, especially in early-stage technologies.
- Demand uncertainty and market instability hinder the financial viability of CDR, with public and investor skepticism further exacerbating these issues.
- Lack of public understanding and acceptance necessitates effective education and awareness campaigns to increase political will and consumer demand.
- Establishing compliance markets in major economies and integrating CDR into non-CO2 policies, like building codes, is essential.
- Development and rigorous implementation of MRV standards are necessary for credibility and effectiveness.

Deep Dive - Top Open Question/Uncertainty:

Breakout Group 1:

- Innovative policies like pre-permitted storage and community opt-in programs were proposed to ensure communities benefit directly from hosting DAC projects, with discussions on the potential for job creation and economic opportunities in developing countries.
- Integrating national level policies with international policies was seen as crucial for alignment and efficiency, with the municipality's role globally emphasized as particularly important.
- Aside from tax credits, the group discussed other federal-level incentives that could be considered to promote DAC projects.
- The need for incentivizing people on the ground to build interest and support for policies was discussed.

- Criticism of countries giving themselves carbon tax breaks or credits for cleaning up environmental messes they contributed to highlighted the need to stop blame-shifting and take collective responsibility for environmental issues.
- Distrust towards companies was noted, but their role in the system was acknowledged, calling for genuine engagement with communities and addressing their concerns. The potential for policy development in the new industry of environmental justice and carbon removal was highlighted, suggesting new frameworks and regulations could be beneficial.

Breakout Group 2:

- Significant risk-taking is necessary to drive innovation and large-scale deployment, balanced with short-term actions and long-term goals.
- Funding bipartisan demand policies, using creative financial instruments, and defining roles for government and private sector entities are crucial for collaboration.
- Government procurement can stimulate market demand, while non-policy initiatives can drive supportive policy changes.
  Effective scaling requires strong market development and stability, addressing the need for diverse and resilient markets for long-term success in the CDR sector.

Report Out:

Group 1

Rory Jacobson, the SME for group 1, emphasized the critical importance of social license in the deployment of DAC technologies. The group recognized that successful implementation requires addressing community-specific needs and building capacity at the local level, both in terms of technological literacy and dynamic engagement. They discussed the necessity of avoiding "sacrifice zones" and emphasized the principle of "do no harm," ensuring that DAC projects do not negatively impact host communities. Additionally, the group identified opportunities for philanthropic investment and policy incentives to better support community involvement, suggesting that tax credits could be extended to benefit communities directly. They also raised concerns about the durability of policy frameworks over time, particularly in relation to global commitments like the Paris Agreement, and stressed the importance of enforcing regulations to build trust and ensure effective policy implementation at the local level.

Group 2

Noah Deich (U.S Department of Energy), the SME for group 2, emphasized the interplay between political will, policy, and technological innovation in advancing DAC technologies. The group focused on the necessity of creating stable and resilient demand drivers for DAC, which can withstand political fluctuations. The group highlighted that successful technology demonstrations are crucial to convincing communities, investors, and policymakers of the viability of DAC, thereby fostering the political will needed for scaling efforts. However, the group also acknowledged the risks associated with early project failures, which could hinder future scalability by creating resistance.

- In addition to these points, this group explored the potential of integrating DAC into non-traditional markets and policies, such as building codes, to ensure revenue certainty beyond carbon markets. They viewed voluntary markets as a temporary bridge to more robust compliance mechanisms in the near future. Another critical aspect discussed was the importance of MRV as a key enabler for quantifying the benefits of DAC technologies. Ultimately, the group underscored the need for a positively

reinforcing cycle of technology innovation and policy advancement to drive the growth of DAC technologies.

CDR Rock

State of Play:

During a lightning talk at the workshop, Colin McCormick from Carbon Direct provided an overview of CDR using rocks. The speaker emphasized the natural ability of certain minerals in rocks to react with CO_2 and form stable carbonates, effectively removing CO_2 from the atmosphere and storing it in a durable, solid form. This process, illustrated by a piece of mineral with visible CO_2-reacted material, naturally occurs on a massive scale, removing hundreds of millions of tons of CO_2 annually. However, to significantly impact global carbon levels, these natural processes need to be accelerated by factors of 100 to 1,000 through engineered methods such as crushing, grinding, and drilling to increase the surface area of rocks exposed to air.

The speaker outlined various strategies to enhance these processes, including in situ mineralization, which involves injecting CO_2 directly into geological formations, and ex situ approaches where mined rocks or industrial byproducts are brought to the surface to react with CO_2. One particularly promising avenue is the utilization of mine tailings, which are the byproducts of mining operations and already have favorable characteristics for CO_2 reactivity. These materials could offer early-stage revenue opportunities through the production of valuable byproducts like concrete, although the overall scale of such applications would be limited.

A key takeaway from McCormick's presentation was the vast potential of rock resources for CDR, as depicted in a map showing large, globally distributed reserves of suitable rocks like basalts and peridotites. The speaker highlighted that while there are significant technical and economic challenges, such as the need for large-scale crushing and transport of materials, the global abundance and distribution of reactive rocks make CDR rock a feasible approach for large-scale carbon sequestration.

Finally, McCormick discussed the current state of play in the field, noting that while there are several early-stage companies and pilot projects, large-scale deployment is still a work in progress. Increased policy support, market incentives, and robust MRV methods were called for to overcome existing barriers and support the transition from small-scale pilots to large-scale implementations. The session concluded with a call to action for further research and investment to harness the potential of CDR rock technologies.

Key Insights[5]:

Top-Voted Response from Breakout Group 1

Top-Voted Response from Breakout Group 2

Question 1: Barriers and Roadblocks through 2050:

- Lack of standardized MRV, including the need for a framework for open system approaches by 2030, addressing variability in data, and ensuring statistical rigor at field scale
- Policy and market demand, including the need for policymakers to understand the value of rocks by 2025, the urgency due to the lack of a compliance market, and nonexistent policy support for pricing tax credits, procurement revenue streams, and standards

[5] *For the full list of key insights, please see the Appendix - here*

Question 2: System Dependencies through 2050:

- Commodities traders and regulators
- Partnerships between DAC and storage companies/locations
- Rail networks and general infrastructure, including the decarbonization and conversion of transportation systems by 2040

Question 3: Risks or Unintended Consequences through 2050:

- Non-delivery risks and difficulty in reversing processes once distributed
- Over-crediting or miscrediting of carbon removal, leading to backlash against non-transparent carbon credits

Question 4: Enablers and Game Changers through 2050:

- Banning or requiring cement recarbonation after building demolition
- Economic benefits for farmers and political motivations to increase farm subsidies
- Establishing a sufficient carbon price and social license to operate, recognizing CDR as a public good through mass public procurement
- Federal procurement through carbon realization credits

Question 5: Open Questions and Uncertainties through 2050:

- Ecological impacts, including unintended soil interactions, general environmental impacts and community acceptance
- Cost implications at scale
- Long-term fate of carbon removals

Deep Dive - Top Barrier/Roadblock:

Breakout Group 1: Measurement, Reporting, and Verification

Potential Milestones and Relevant Stakeholders:

- Procedure for verifying MRV by 2025 (Academics, Industry Partners, Communities)
- Buyers using the standard by 2026 (Private Industry, Civil Society)
- Financing support by 2025 (Government, Industry Partners)
- The group observed that governments need to invest to develop models and sites, but there is a basic unwillingness to confront the issue directly.
- Framework for collecting by 2025 (Researchers, Philanthropy, Investors)
- Establish a global repository to ensure transparency and public good.
- A participant noted the importance of ensuring that the collected data is not hidden behind intellectual property restrictions.
- Large scale government certification by 2026 (Government, UN)
- Global adaptation of certification by 2028
- Broadly accepted MRV verification protocols and standards established in the community by 2027
- Aim for relatively large-scale purchases using these standards by 2028

Breakout Group 2: Demand

Potential Milestones and Relevant Stakeholders:

- Implement compliance markets starting in 2024 (Legislative Champions, Non-Governmental Organizations ('NGOs'), Experts, Industry Partners)
- Carbon Offsetting and Reduction Scheme for International Aviation ('CORSIA')
- The group questioned if CORSIA could be amended to accept certain classes of mineralization this year as a compliance option for the 2027 ruling
- Zero Carbon Electricity Standards

- It was noted that none of the proposed or active zero carbon electricity standards include CDR as a compliance option, though some could do so quickly
- Low Carbon Fuel Standard ('LCFS')
- Amend to include mineralization as a compliance measure
- Develop specific compliance markets for other industrial sectors
- Formation of collective advocacy groups by 2024 (Companies, Scholars, NGOs)
- The OpenAir Collective was highlighted as a good example, being a collaboration of companies, scholars and experts, and NGOs.
- Successful implementation of compliance and voluntary market initiatives led by collective efforts by 2025
- Launch educational initiatives to build buyer sophistication by 2024
- Encourage major voluntary market leaders to advocate for immediate purchasing of carbon credits
- Increase voluntary market purchases driven by rule setters like the major philanthropies and think tanks by 2025
- Implement financial regulatory changes by 2025
- Leverage social and investor pressures to drive demand
- Initial government procurement policies in place by 2025 (Organization for Economic Co-operation and Development Governments 'OECD', Legislative Champions, NGOs, Experts, Companies)
- Establish federal procurement policies that enable carbon removal practices
- Achieve $30 billion in procurement by OECD governments by 2030

Deep Dive - Top Open Question/Uncertainty:

Breakout Group 1: Ecological Impacts and Social Acceptance

Potential Milestones and Relevant Stakeholders:

- Establish Multi-Stakeholder Coalition by 2025 (Communities, Researchers, Government, Industry)
- Build from existing coalitions in the mining industry
- The group emphasized that building trust is essential, and bringing in civil society actors and engaging widely will be crucial
- Develop Baseline Understanding by 2027 (Research Community, Government)
- It was noted that before operations begin, it is important to demonstrate that the proposed actions will not harm the overall system's goals
- In Situ Mineralization Project by 2027 (DOE, Corporations, Government)
- Implement well-characterized in situ mineralization project with a scale of 100 kilotons
- Locations: Oman, Kenya, Iceland
- Link 50% of global new mine approvals to CDR Requirements
- Government funding linked to community engagement by 2027 (Government, Communities)
- The group suggested that community engagement requirements should be included, similarly to the DOE's approach with DAC hubs
- Monetize CDR in 20% of mines by 2030 (Mining Industry, Government, Standards Bodies, New Technology Providers)
- The group discussed that if financial rewards are present, companies will invest more and accelerate the process.

Breakout Group 2: Costs

Innovation Agenda: We recommend a tripling of an innovation budget by 2030, focusing on use-inspired research, pilots, demos, and applied research. (Government, DOE, Department of Defense 'DOD', American Rescue Plan Act 'ARPA', companies, academics)

Potential Milestones and Relevant Stakeholders:

- Establish a CDR 'cartel' by 2024 (Academic Groups, National Labs)
- Academic and research institutions will play a key role in aggregating and analyzing data to drive down costs.
- Shift monitoring costs to the government through legislation by 2024/2025
- Government involvement in data aggregation and analysis by 2025 (Government Bodies, esp. DOE)
- Announce infrastructure and supply chain investments by 2027 (Government Agencies, Private Sector Investors)
- Achieve 10 megatons of minerals by 2030
- Implement a federated system for data aggregation by 2030 (Academic groups, National Labs, Government Agencies)
- Develop robust infrastructure to support large scale removal by 2040 (Government Agencies, Private Sector Investors)
- Scale up to 100 megatons of minerals by 2040

Report Out:

Group 1

SME Colin McCormick emphasized the critical barriers and enablers for GHGR via rocks. The group identified the lack of a unified MRV system as a significant impediment to scaling both voluntary and policy-driven demand. They also highlighted key system dependencies, such as clean energy and transportation infrastructure for moving large quantities of rocks. The group was particularly concerned with potential ecological impacts, especially in agricultural and ocean systems, and discussed the possibility of linking mining approvals to GHGR actions as a way to create positive unintended consequences.

On the enablers side, the group reiterated the importance of broadly agreed-upon MRV standards, combined with safety measures to ensure both ecological protection and GHGR efficacy. Open questions focused on the potential ecological impacts and how they could influence the social license to operate, with the group stressing the need for ambitious milestones, such as achieving widely accepted MRV standards by 2027. They also discussed the importance of scaling up trials—at the kiloton, megaton, and larger scales—while carefully monitoring ecological effects and engaging the public in understanding these outcomes.

Group 2

Julio Friedmann's (Carbon Direct) report-out highlighted several unique challenges and opportunities related to CDR through carbon mineralization, focusing on both immediate and long-term actions required to advance the field. The primary barrier identified was the lack of sufficient buyers to drive demand and finance projects. This is compounded by a lack of decarbonized transportation infrastructure necessary for moving large quantities of rocks. Among the top risks, Friedmann pointed to human health concerns, such as silicosis, dust, and ecotoxicity, particularly for certain mineral pathways.

To enable progress, the group emphasized the importance of federal procurement, advocating for the government to purchase carbon mineralization credits to stimulate the market. They also highlighted the critical open question of future costs, stressing the need to understand

these costs now to inform present decisions. The group proposed a range of actions to increase buyer engagement, including integrating carbon mineralization into compliance markets immediately and enhancing buyer sophistication through education and standards. Additionally, they called for tripling innovation budgets by 2030 to support research, pilot projects, and large-scale demonstrations, with a goal of scaling up to 10 megatons of minerals by 2030 and 100 megatons by 2040. Friedmann also underscored the need for data transparency and infrastructure development to build confidence and manage system costs as the field grows.

CDR Land

State of Play:

During a lightning talk at the Scaling GHG Removal Workshop, Dave Hillyard from the Carbon Technology Research Foundation ('CTR') discussed various CDR strategies involving land and biomass. In particular, the talk focused on utilizing biomass to sequester carbon, highlighting key approaches such as biochar, biooil, bioenergy with carbon capture and storage ('BECCS'), biomass storage, and timber building projects. Hillyard also emphasized the need for technological innovation to enhance traditional conservation and restoration efforts, aiming for increased efficiency and scalability in carbon sequestration.

The speaker noted the significant biomass demand required to scale these technologies, which raises concerns about land use, agricultural practices, and climate impacts. The potential of marginal lands and engineering biology to increase biomass productivity was also discussed. Despite substantial funding for living biomass and BECCS, Hillyard pointed out that current investment levels are insufficient to meet the long-term needs for research, pilot projects, and scaling.

The presentation also touched on specific challenges and opportunities for each approach. For biochar, there is a wide range of commercial and pilot activities, with potential for significant scale-up if issues such as energy efficiency in pyrolysis and feedstock availability are addressed. Biooil is at an earlier stage, with companies like Charm Industrial making strides but still requiring substantial investment to overcome barriers related to biomass sourcing and process optimization.

Hillyard highlighted BECCS projects like those at Drax and Stockholm Exergi as examples of large-scale initiatives, but stressed the need for further technological advancements in carbon capture and storage to make BECCS truly scalable. He also discussed the emerging field of biomass direct storage, which involves low-cost and replicable methods for long-term carbon sequestration, though challenges remain in ensuring storage durability and meeting regulatory requirements.

In terms of scaling and market integration, the speaker underscored the importance of establishing effective policy support, securing access to necessary resources, and developing robust MRV systems. He raised concerns about potential negative impacts on ecosystems and the risk of mitigation deterrence if CDR is overly relied upon as a substitute for emission reductions. The talk concluded with a call for greater research and development, investment in the agri-economy, and the creation of a differentiated carbon market to support the scaling of land-based CDR technologies.

Key Insights[6]:

Top-Voted Response from Breakout Group 1

Top-Voted Response from Breakout Group 2

Question 1: Barriers and Roadblocks through 2050:

- MRV systems development by 2026 to ensure accurate measurement and verification of carbon removal
- Increasing biomass yields significantly by 2040
- Addressing competition for waste biomass between CDR and other applications

Question 2: System Dependencies through 2050:

- Research funding for developing policies and technologies to support CDR by 2025
- How the Science Based Targets initiative ('SBTi') and GHG Protocol evaluate biological carbon removal compared to insets and beyond value chain carbon removal efforts

Question 3: Risks or Unintended Consequences through 2050:

- Increasing land conversion and biodiversity loss due to CDR practices
- MRV quality impacting market confidence and the risk of market collapse

Question 4: Enablers and Game Changers through 2050:

- Federal procurement and funding mechanisms for large-scale carbon removal
- Subscale demonstrable projects that open sociocultural license to operate, leverage local economics versus carbon pricing, and de-risk policy change.

Question 5: Open Questions and Uncertainties through 2050:

- Quantifying and valuing land opportunity costs for CDR and balancing ecosystem impacts
- Efficiency and scalability of increasing soil carbon persistence by 2028

Deep Dive Top Barrier/Roadblock[7]:

Breakout Group 1:

- Effective MRV standards need to be in place by 2026/2027 for different biomass-related carbon removal technologies. Confidence in the durability and permanence of these technologies is crucial for successful scaling.
- Many critical milestones have dependencies related to good quality data and research. Only with this data and research can we define the right policies, regulations, and incentives for biomass storage solutions. Therefore, these milestones are co-dependent on addressing key knowledge and research gaps.

Breakout Group 2: Biomass Availability

Any given projection for biomass availability is promising, but conflicts arise between different paths and definitions of sustainability.

Proposed Actions:

- Supply chain tracing is essential to ensure transparency and accountability in biomass sourcing.
- Defining what constitutes "waste" and "sustainable" biomass sources is necessary, including the need for counterfactual scenarios and consideration of indirect incentives.

---

[6] *For the full list of key insights, please see the Appendix - here*

[7] *Limited data was available for Group 1's deep dive session, so the summary may not fully capture all aspects of their discussion.*

- Regional outcomes should be based on policy to mitigate the risks associated with policy changes.

Key Stakeholders

- New contracts and deals should be enabled by various stakeholders.
- Ratings agencies can assess leakage risks but are not subject matter experts.
- Financiers should frame biomass availability as a risk but are not experts.
- Environmental NGOs can provide expertise.
- The Commodity Futures Trading Commission should address policy and regulatory issues.
- California's LCFS and municipalities also play a crucial role.

Deep Dive - Top Open Question/Uncertainty:

Breakout Group 2: Do We Have Enough Land?

- The availability of land for biomass-related carbon removal projects is uncertain. Building confidence through small-scale pilot projects is essential. These projects don't need to scale rapidly or extensively initially but must address indirect consequences and frame early efforts to mitigate concerns.
- Defining standards for carbon efficacy, such as avoidance, is necessary. Funding should prioritize high-risk, high-reward short-term projects that can scale up without causing harm.
- Repeat studies on the best use of biomass are not needed. Instead, a vertically engaged approach involving research and public information campaigns is important.
- There is a need to narrow the focus regionally to build confidence. Small-scale projects can provide signals about ecosystem impacts, though larger scale efforts might reveal long-term consequences.
- Addressing land-conversion issues and considering other sector activities is necessary. Multiple small projects can inform the scaling process, but significant financial investment is required.
- The basic use cases need better understanding, including potential consequences of extensive biomass removal, such as impacts on soil and wildfire risks. Standards are necessary to gain community and critical support, informing about the relative merits and demerits of biomass CDR.
- There is urgency in moving forward with concessionary capital and developing reforestation as part of the land-use portfolio. The U.S. has significant opportunities, but globally, availability varies.
- Effective public engagement and policy education are crucial. USDA's extensive resources and existing programs need updates to include CDR potential. Public engagement with science is essential to update current programs.
- Capital requirements for small-scale projects are significant. There needs to be a push for an "arms race" in development and funding to achieve 2030 goals. While investment returns are essential, concessionary dollars also play a vital role.
- Philanthropic dollars can be attracted if there is a coalescence around another type of removal that needs regional testing. Proof of concept is necessary to establish market viability.

Proposed Actions:

- Define standards for carbon efficacy, focusing on avoidance and other metrics, which will guide best use practices for biomass.
- Increase funding for high-risk, high-reward short-term projects. Design large projects that do no harm and start with smaller scale implementations to gather necessary data and insights.
- Ensure vertical engagement, from research to public information campaigns, to create awareness and understanding of biomass use in carbon removal.

Methane and Nitrous Oxide Removal[9]

State of Play:

During a lightning talk session at the workshop, Rob Jackson from Stanford University and Erika Reinhardt from Spark Climate Solutions presented on the topics of methane and nitrous oxide removal, respectively, emphasizing the critical roles these gases play in climate change and the emerging strategies for their mitigation.

Methane Removal:

Jackson began by highlighting the necessity of methane removal due to its high potency as a greenhouse gas, being over 25 times more effective at trapping heat in the atmosphere than CO_2 over a 100-year period. Methane levels are not only rising but accelerating, with significant contributions from human activities such as agriculture and fossil fuel extraction, as well as potential feedbacks from natural sources like thawing permafrost and tropical wetlands. The speaker emphasized that addressing methane is a crucial short-term strategy for mitigating climate impacts, as reducing atmospheric methane could potentially lower global temperatures by up to 0.5°C.

Methane removal strategies include both physical extraction from the atmosphere and chemical conversion to less harmful substances. Techniques under consideration involve enhancing natural oxidative processes, such as boosting the concentration of hydroxyl ('OH') radicals in the atmosphere to accelerate methane breakdown. Other approaches include deploying photocatalytic or thermocatalytic reactors that can process ambient air and convert methane into CO_2. Jackson pointed out that no commercial-scale methane removal technologies are currently available, and significant challenges remain, such as the need for effective MRV, regulation, and public acceptance of technologies that might involve releasing catalysts into the atmosphere.

Nitrous Oxide Removal:

Following Jackson, Erika Reinhardt addressed the nascent field of N_2O removal. N_2O is a potent greenhouse gas with a global warming potential approximately 300 times that of CO_2 over a century, and it is also a significant ozone-depleting substance. The primary source of N_2O emissions is agricultural soil management, especially through the use of fertilizers. The speaker noted that current trends in N_2O emissions are not aligning with the Intergovernmental Panel on Climate Change ('IPCC') models, which assume ongoing reductions. This discrepancy underscores the need for both mitigation and removal strategies.

---

[8] *Due to limited information, insights from the CDR Land report out were integrated into the Deep Dive section*

[9] *The topics of methane and nitrous oxide removal were combined in this session due to their similar status as potent greenhouse gases with significant short-term climate impacts that are at the very earliest stages when it comes to removals technology development. Grouping them together is not intended to diminish their importance but rather to highlight their parallel challenges and the urgent need for innovation in both areas.*

Potential methods for N_2O removal were also discussed, focusing on the breakdown or conversion of N_2O into less harmful compounds. While this field is in its infancy, with very few dedicated research efforts and no established technologies, exploratory approaches include enhancing microbial processes that naturally degrade N_2O in soils or developing catalytic systems that can operate at low N_2O concentrations. Similar to methane removal, the development of effective MRV techniques will be crucial for ensuring the success and scalability of these technologies.

Key Insights[10]:

Top-Voted Response from Breakout Group 1

Top-Voted Response from Breakout Group 2

Question 1: Barriers and Roadblocks through 2050:

- Clarifying the value proposition for CDR buyers
- Developing funding structures specifically for CH_4 and N_2O removals
- Developing physical substrates and formats to optimally contact and transfer CDR to catalysts or biocatalysts by 2030

Question 2: System Dependencies through 2050:

- Energy and materials required for capture technology
- Immediate focus on integrating CO_2, CH_4, N_2O, and hydrogen removal technologies

Question 3: Risks or Unintended Consequences through 2050:

- Co-produced gases; reducing one GHG can inadvertently increase another
- N_2O cascade effect, underestimating natural dynamics by 2035

Question 4: Enablers and Game Changers through 2050:

- Philanthropic funded research to assess potential
- Investment in research coordinated and accelerated to scale strategically

Question 5: Open Questions and Uncertainties through 2050:

- Practicality and feasibility of CH_4/N_2O removal technologies and their integration with other climate mitigation strategies.
- Economic feasibility and the potential impact of natural emission feedbacks on the necessity of CH_4 removal

Deep Dive - Top Barrier/Roadblock[11]:

Breakout Group 2: Lack of Current Solutions

Objective: progress from TRL 1-2 to TRL 4

Milestones and Relevant Stakeholders:

- Immediate call for proposals for research (government)
- Coordinate investment to accelerate development of CDR solutions without being overly selective, ensuring integration of research into the full potential impacts (positive and negative) of open system approaches, and co-designing with impacted communities immediately (government, academia, philanthropy, other stakeholders)
- Establish research center of excellence in the next 2-3 years (national labs, academics, government)

[10] *For the full list of key insights, please see the Appendix - here*

[11] *Due to an oversight, data from Group 1 in the Methane and Nitrous Oxide deep dive session was not collected.*

Deep Dive - Top Open Question/Uncertainty:

Breakout Group 2: Open System Intervention Governance and Decision-Making

Milestones and Relevant Stakeholders:

- Start an intercomparison project now, spanning 6-7 years, to characterize earth system impacts of potential approaches (international modeling centers, government funding).
- Implement earth system modeling with various milestones around measurement and modeling inclusion to understand natural system methane feedbacks (government funding, government agencies, academia, philanthropy).
- Conduct field testing over the next 5 years to develop methods for appropriate handling of interventions (nonprofits, stakeholders, government agencies).
- Establish proposed frameworks within 5-10 years to guide the deployment of open system interventions (UN Environment Programme, US Department of State, oversight commission).
- Create a roadmap over the next 5-10 years to plan pilot projects that integrate community and regulatory feedback (nonprofits, stakeholders).

Report Out

Group 1

SME Rob Jackson summarized group 1's discussion, which highlighted a lack of basic scientific understanding and the absence of clear funding structures as significant barriers. They proposed a milestone of achieving a cost of $100 per ton of carbon dioxide equivalent by 2030 for both methane and nitrous oxide, emphasizing the need to understand the specific leverage points, such as growth rates for microbes or quantum yields for photocatalysts, necessary to reach this goal.

The group also noted the poor understanding of methane sinks and recommended a stronger atmospheric monitoring plan for methane and nitrous oxide by 2025. This would involve not just basic monitoring but also considering the impacts of the hydrogen economy on methane's lifetime. The group stressed the importance of understanding natural processes before intervening, reflecting concerns about the confusion surrounding the appropriate metrics and currency for these gases, such as whether to focus on short or long timescales or to use radiative forcing as a measure.

Uncertainties and open questions were centered around the need for a pathway-specific research roadmap for methane and nitrous oxide removal by 2025. The group called for sensitivity analyses to identify key leverage points for different technologies, emphasizing the need for clarity in the potential co-benefits and negative byproducts of various approaches. They also discussed the importance of rigorous MRV, particularly in open-air settings, to ensure that interventions do not harm the ozone layer or produce harmful byproducts like carbon monoxide. Finally, the group expressed skepticism about the feasibility of significant progress without the development of a methane or nitrous oxide market or regulatory mandate, considering this a critical uncertainty for the future of these efforts.

Group 2

SME Erika Reinhardt's (Spark Climate Solutions) report-out began by outlining the recurring themes shared with other GHGR groups. The primary barrier identified was the lack of fully characterized, scalable, and safe solutions, with the current state of technology being at a very early TRL stage. This uncertainty about which approaches will eventually succeed presents a significant challenge to scaling efforts.

The group discussed system dependencies, particularly the development of appropriate pull mechanisms, noting that while market-based mechanisms are desirable in some cases, they may not be suitable for large-scale open system interventions, which require careful consideration of alternative approaches. Social license was also highlighted as crucial for both research and potential future deployments.

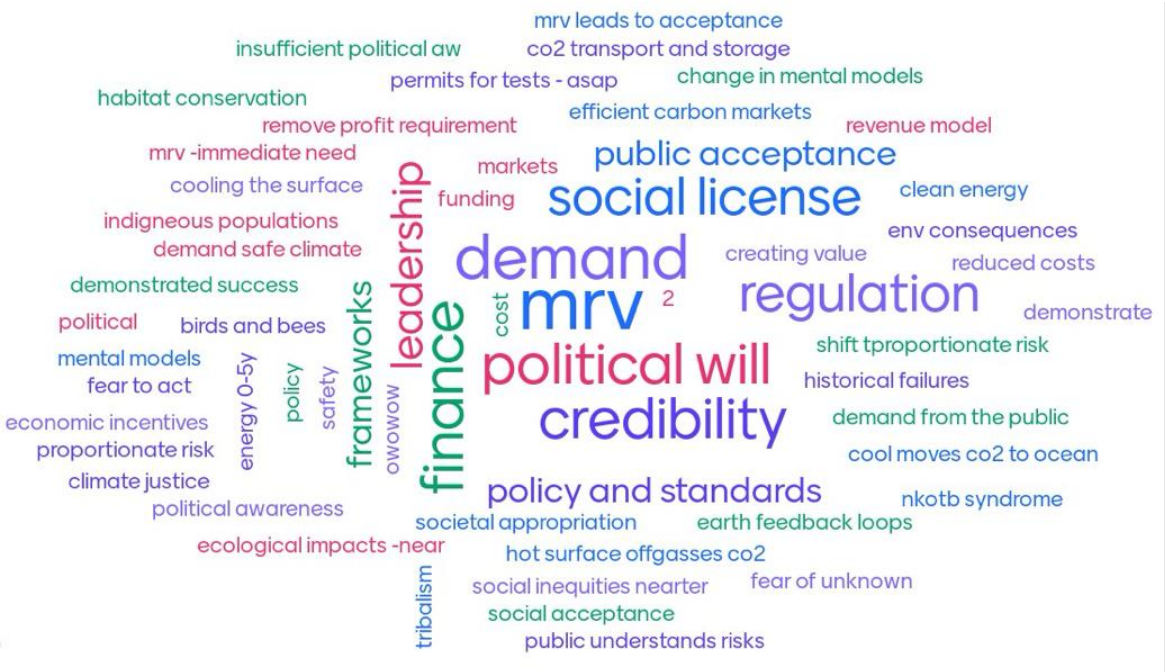
Top risks included the potential large-scale impacts of open system atmospheric methane removal, which remain poorly understood and require thorough investigation. The group identified coordinated investment in research as the top enabler, with nearly unanimous support for accelerating research in this field. They also highlighted the importance of integrating research with governance and community engagement to ensure that both scientific and social factors are co-developed.

Critical milestones discussed included a significant increase in research funding, ideally led by government but supported initially by philanthropic efforts. The group called for the establishment of centers of excellence and coordinated government investment to advance the field. Additionally, they emphasized the need to develop pathways for field testing and to understand what international or national frameworks for deployment might look like, particularly given the broad potential impacts of some approaches at scale. Finally, the group recognized the synergies with GHGR, particularly in areas like ocean and rock-based methods, and stressed the importance of collaborative learning and shared frameworks across these fields.

Virtual Breakout Session

The virtual breakout group adopted a broader approach during the Day 1 breakout session, considering the wider landscape of greenhouse gas removal strategies rather than focusing on a single technology. This allowed them to explore cross-cutting issues, including systemic barriers, dependencies, risks, and enablers, as well as the most pressing uncertainties that could impact the scaling of GHGR solutions by 2050. Interactive polling tools were used to gather wide input on key questions, which was followed by a deep dive session where participants identified the themes of political will, environmental impacts, and financing to discuss in a more focused manner.

Question 1: Barriers and Roadblocks through 2050:



Question 2: System Dependencies through 2050:

Question 3: Risks or Unintended Consequences through 2050:

Question 4: Enablers and Game Changers through 2050:

Question 5: Open Questions and Uncertainties through 2050:

Deep Dives

Political Will:

- The group highlighted the lack of political will linked to the nexus between economic growth and extractive capitalism. The need for regenerative capitalism and nature-based solutions was emphasized, with the point that everyone will need to contribute to funding CDR solutions.
- It was noted that three elements affect political will: short-term election cycles, fear, and job creation. Methane removal might be more politically viable than carbon removal due to immediate visible benefits.

- The importance of framing the issue as securing a safe climate for future generations was stressed to garner political support. It was pointed out that future generations, the primary beneficiaries, cannot finance climate restoration, implying the financial burden falls on the current generation.
- Emphasis was placed on framing the goal as "climate repair" to set realistic expectations and focus on making the climate better than it currently is.
- The necessity of demonstrating CDR technologies at a feasible scale was underscored to convince the public and policymakers. Aggressive funding for top solutions was proposed to achieve a scale that allows for impact assessment.
- The challenge of solving the free rider problem was raised, where everyone benefits from cheaper energy without directly contributing to the costs of CO2 reduction.
- The need for clear, positive framing of CDR efforts was emphasized, highlighting the long-term benefits for future generations and framing it as a moral imperative to provide a safe climate for children and grandchildren.

Environmental Impacts:

- The importance of considering multiple layers of biological, chemical, and physical responses in CDR projects was stressed. Potential negative impacts like oxygen minimum zones from macroalgal cultivation and toxic leachates from minerals were highlighted.
- The necessity of demonstrating CDR technologies at a reasonable scale to understand their real-world environmental impacts was emphasized.
- Safe transitions from lab to field experiments were advocated for, establishing criteria for pilot projects to ensure they are viable and environmentally safe.
- Collaboration between technologists and policymakers from the start was recommended, aligning innovation and policy curves to mitigate uncertainties and environmental impacts.
- The role of academic researchers in driving the CDR startup community was highlighted, with a suggestion for better communication to counter skepticism and reveal the true drivers behind carbon removal initiatives.
- Effective communication on the environmental benefits of mining for CDR and the distinct impacts of different CDR pathways was noted as essential. Clarity in framing these conversations was emphasized.
- The necessity of involving bureaucrats and interagency coordination was pointed out, stressing that future CDR projects must account for the impact on nature and likely require a hybrid approach of technology-based and nature-based solutions.
- Engaging local communities through town halls and local journalists before deploying CDR technologies was suggested to gain social license and avoid community resistance.
- The need for honesty in communication was highlighted, emphasizing that CDR efforts will involve significant sacrifices, including massive mining operations and potential ecosystem disruptions, which need to be transparently communicated to gain public trust.
- It was pointed out that comprehensive environmental monitoring and baseline assessments are essential for understanding the long-term impacts of CDR interventions, particularly in ocean environments where impacts can spread globally over time.

- The importance of involving trusted voices, such as scientists, in advocating for CDR was emphasized to build credibility and trust in the community.

Financing:

- Funding for CDR should focus on regenerative solutions and circular economies, drawing inspiration from nature where nothing goes to waste.
- The difficulty of securing funding for climate restoration was noted, as future generations, the primary beneficiaries, cannot finance it, leaving the burden on the current generation.
- It was pointed out that governments and corporations do not directly benefit from climate restoration, making it challenging to secure their financial support.
- The need for criteria to transition CDR technologies from the lab to pilot projects safely was discussed, with the suggestion that securing funding for these transitions is crucial.
- Synchronizing technological innovation with policy development was highlighted as important to secure funding and support for CDR projects.
- Involving diverse teams to evaluate CDR projects comprehensively was noted as necessary to ensure funding decisions are informed by multiple perspectives.
- Revealing the true drivers behind carbon removal initiatives was emphasized to secure broader financial support and counter skepticism.
- More structured programs to engage scientists in communication, market shaping, and policy discussions were called for, suggesting this could help secure funding by building social license.
- The importance of involving interagency coordination and educating bureaucrats to secure long-term funding and support for CDR projects was stressed.
- Engaging local communities and stakeholders early in the process was suggested to secure social license and financial support for CDR projects.
- The need for non-dilutive investments and paid pilots to advance TRLs for CDR innovations was highlighted, emphasizing the importance of derisking intellectual property at national labs through global scaled acceleration.
- Acknowledging the necessity of addressing the financial aspects and job creation associated with CDR projects, the group discussed the potential of converting agriculture from a greenhouse gas source to a sink as a means of securing funding and support.
- The idea of integrating carbon-free energy into the capital and operational expenditures for CDR projects was discussed, emphasizing the importance of ensuring that CDR technologies do not compete with grid power and create conflicts of interest.

Report Out:

Virtual Group

SME Aaran Patel highlighted the broad, cross-cutting discussion his group had, which included international perspectives and focused on reframing the narrative around GHGR as a development-first opportunity, particularly in low and middle-income countries. One key point raised was the importance of moving beyond just co-benefits framing to emphasize possibilities for co-design and co-ownership. This perspective advocates for considering GHGR not only in terms of environmental benefits but also as a catalyst for income, job creation, and development gains, particularly in sectors like agriculture and fisheries.

The group identified social license as a major barrier, emphasizing the need for a unified industry stance on the narrative around GHGR benefits and trade-offs. They discussed the

importance of engaging scientists more actively in communication efforts and the necessity of having cross-border conversations on issues like permitting and siting. They also highlighted the value of using polling to gather tangible insights on public attitudes toward GHGR technologies.

Regarding uncertainties, the group focused on the environmental impacts of various GHGR approaches, particularly those related to DAC, such as potential effects from pollen, dust, and microbes. They agreed on the need to move experiments from the lab to real-world demonstrations, with academia playing a crucial role in building trust and credibility. The group also underscored the importance of an iterative and integrated approach to these challenges, including the parallel development of MRV systems, the transition from lab to real-world applications, and ongoing assessment of both benefits and risks.

Day 1: Afternoon Plenary Session

Day 1 Insights

Objective:

Following the breakout sessions, all groups reconvened in a plenary session to share out their consolidated findings and address overarching questions related to the previous breakouts. An interactive polling tool was used to gather real-time input on key questions, including identifying any overlooked aspects, gaps in the conversation, and potential threats to the effectiveness of GHG removal strategies. Participants were also encouraged to explore common solutions that could address multiple challenges across different areas.

Key Insights:

Has anything been overlooked? Is anything missing in the conversation?

- The role and implications of hydrogen as a secondary greenhouse gas, including issues with leaking hydrogen, which is counterproductive to methane removal efforts
- Governance challenges, such as international collaboration, the need for an International GHG Removal Agency, and ensuring equitable distribution of funding, particularly from the Global North to the Global South
- The importance of climate and environmental justice, emphasizing specific discussions on these topics and the role of climate justice in scaling CDR efforts
- The involvement of impactful actors, the role of philanthropy in driving demand, and engaging public engagement expertise and funding at the National Science Foundation
- The role of the oil and gas industry, the need for diverse market-shaping organizations, practitioners, and developers
- The urgency of CDR as a critical solution to prevent a worse future, and the need for positive messaging to emphasize its feasibility
- Addressing critical technological bottlenecks and specific scientific challenges to accelerate progress
- Comparing the potential and cost of different CDR methods (air, ocean, land, rock) and prioritizing which paths to pursue
- The role of the voluntary carbon market ('VCM') in policy-driven demand and the potential for compliance markets to stimulate demand
- The need for international coordination and governance to achieve scale, and exploring opportunities for shared infrastructure, cost sharing, and business model synergies
- Balancing the development of policy and science and utilizing social life cycle assessments to measure social impact

- Addressing colonial attitudes towards CDR, involving the Global South in discussions, and focusing on workforce development and implementation strategies
- The critical role of independent science by trusted entities to explore and control potential environmental health impacts of CDR
- Exploring strategies and implications for the use of offsets
- The impact of increasing one GHG in response to the removal of another, and addressing moral hazard arguments
- Tackling the challenge of scaling up CDR and ensuring continuous coordination between private and public sectors
- The role of marketing communications and PR in scaling GHG removal efforts, and the importance of community engagement
- Setting clear goals for minimizing temperature increases or maximizing negative emissions by specific points
- Integrating CDR into broader climate mitigation and adaptation strategies to avoid viewing it in isolation
- Evaluating total storage capacities of conventional subsurface and ocean storage, and addressing gigaton-scale transport and storage requirements for DAC
- Addressing the need to separate GHGR targets from emissions reduction goals
- Raising public awareness about CDR and recognizing innovative efforts happening outside the US
- Addressing mismanagement of energy production with less energy-intensive practices, and creating economic value through job creation and industry growth

What is one big thing across the board that threatens the success of GHG removal efforts?

- Need for consistent and rigorous MRV, including standardized frameworks, alignment with finance, political will, social acceptance, and addressing high MRV costs
- Challenges with societal acceptance, including public acceptance and opposition, political will, vested interests, political resistance to climate tech, NIMBY attitudes, global will, and overall lack of will
- Issues surrounding responsibility and funding, including the question of "who pays," the need for government-level cooperation, poor governance and leadership, and societal demand
- Insufficient market demand and funding, including lack of buyers, demand, and financing, as well as risk-intolerant capital and unreliable carbon revenue streams
- Technological and physical challenges, such as ineffective technologies, physical limits, high costs, expensive failures, overregulation, value-added streams, slow progress, and focus derailment
- Need for extensive education and communication, including addressing public confusion, mixed messaging, lack of awareness, urgency, failure to communicate, knowledge gaps, and lack of clarity from the federal government
- Importance of social license and willingness to pay, addressing socioecological risks, bad actors, harmful projects, charlatans, effective technologies, and tackling misperception and misinformation
- Regulatory and governance issues, including lack of clear frameworks, permitting challenges, government cooperation, expensive failures, misalignment of focus, and unintended regulatory consequences
- Addressing real impact on temperature, environmental impact, urgency, and the need for a global framework or roadmap

- Economic feasibility challenges, including project finance issues, proprietary data problems, and slow adaptation rates

What is a common solution that may help in several areas?

- Intergovernmental collaboration and international coordination to support CDR efforts
- Promoting positive and hopeful narratives to inspire action
- Increasing demand through government creation of demand and compliance markets
- Establishing and enforcing standards, including consistent and coherent MRV frameworks that extend beyond carbon
- Implementing a carbon tax to incentivize reductions
- Providing validated data on the benefits and risks of CDR technologies
- Securing funding for early-stage research, environmental monitoring, and more comprehensive scientific studies
- Governance structures and MRV frameworks from a small number of trusted entities
- Encouraging regenerative systems and clean energy initiatives
- Maintaining a positive and proactive attitude towards climate solutions
- Ensuring timely, relevant, and shareable baseline atmospheric and oceanographic measurements
- Investing across the research pipeline to increase the number of viable CDR routes without picking winners
- Coordinated regulatory and funding support for all CDR technologies
- Methane removal to reduce warming, tropospheric ozone, and improve crop yields and community health
- Trusted science on hazards, risks, and best available control technologies (BACT) guidelines
- Securing project finance for CDR initiatives
- Crafting an inclusive long-term vision that goes beyond any single founder, technology, administration, or stakeholder group
- Developing a post-COP/IPCC roadmap aiming to achieve 10GT of drawdown by 2050 through international agreement and action
- Fostering dialogues between environmental conservation groups and CDR advocates at the international level
- Expanding access to low-carbon energy
- Honest discussions about the scale of the climate challenge and the need for education to close the gap in understanding
- Setting national targets for GHG removal proportional to each country's emissions, similar to carbon neutrality targets.
- Establishing a dedicated international agency to drive cooperation, awareness, learning, and policy development for GHG removals, akin to organizations like the International Energy Agency and International Renewable Energy Agency.
- Creating a "Ministry of the Future" to oversee and coordinate future-oriented climate actions.
- Developing a CO2 economy to facilitate and incentivize carbon management and removal.

Day 2: Breakout Session

Objective:

The breakout sessions held on Day 2 mirrored the format of Day 1; however, they were designed to delve into a different lens of the broader ecosystem required for scale, covering topics such as technological and scientific advancements, socio-behavioral impacts and community engagement, policy and regulatory frameworks, financial and market mechanisms, and MRV processes.

As on Day 1, subject matter experts first presented a "lightning talk" in the plenary session. Following this, participants gathered in two breakout rooms per topic, and individually shared responses to the following five questions through a post-it note exercise:

- What are the top 1-3 barriers or roadblocks through 2050, and by when do they need to be overcome?
- What are the top 1-3 systems dependencies through 2050, and by when do they need to be addressed?
- What are the top 1-3 risks or unintended consequences through 2050, and by when do they need to be mitigated?
- What are the top 1-3 enablers or game-changers through 2050, and by when do they need to come into play?
- What are the top 1-3 largest open questions or uncertainties through 2050, and by when do they need to be answered or addressed?

These responses were subsequently voted on by each breakout group to highlight the top issues in each category. Following the voting process, the top voted answers to two of the questions - the barriers/roadblocks and open questions/uncertainties - were further explored in a deep dive discussion session, which aimed to outline pathways and milestones (action, timeline, type of stakeholder) to mitigating these, and to identify GHG removal goals by 2030, 2040, and ultimately, by 2050. The following insights were synthesized from the collective input and discussions recorded during the breakout sessions.

Science and Technology

State of Play

During a lightning talk at the workshop, Nikki Batchelor from XPRIZE highlighted the significant advancements and ongoing challenges in the field of CDR. The talk emphasized the critical need for exponential growth in CDR technologies to meet urgent climate targets, stressing the importance of near-term goals. Batchelor shared insights from the XPRIZE carbon removal competition, noting that around 1,300 teams expressed interest in the competition, with approximately 300 moving forward to develop working demonstrations by 2024.

The speaker also provided a detailed overview of the current state of CDR projects, discussing the various pathways and their TRLs. It was noted that most projects are in the TRL 6 to 8 range, with significant efforts underway in areas like oceanic and air-based CDR, land applications, and ERW. The talk emphasized the importance of progressing from small-scale projects to larger, thousand-ton pilot demonstrations to achieve meaningful impact.

Batchelor highlighted the critical role of modularity and scalability in CDR innovations, along with the potential for product crossovers in fields such as soil enhancement and building materials. It was pointed out that over 60% of teams are exploring product-related aspects of

their CDR technologies, reflecting a trend towards integrating CDR solutions into broader industrial and agricultural applications.

Finally, Batchelor discussed the significant barriers to scaling CDR technologies, including the need for substantial funding, streamlined permitting processes, and the development of robust MRV systems. The importance of addressing these challenges was also underscored, through collective efforts and continuous innovation to overcome the current limitations and realize the potential of CDR in mitigating climate change.

Key Insights[12]:

Top-Voted Response from Breakout Group 1

Top-Voted Response from Breakout Group 2

Question 1: Barriers and Roadblocks through 2050:

- Lack of information sharing due to silos among data, teams, and commercial entities

Question 2: System Dependencies through 2050:

- Land and biomass use efficiency; dependencies on natural systems and biodiversity
- Cost of low-carbon energy and inclusive policies for all types of CDR

Question 3: Risks or Unintended Consequences through 2050:

- Industry collapse if significant portions fail; what happens if half the industry collapses soon?
- Moral hazard of CDR leads to continued emissions and slowing down the energy transition

Question 4: Enablers and Game Changers through 2050:

- Creating a fail-fast culture with data salvage and open science, including an industry agreement to share data about why specific ideas fail
- Regulatory mandate by 2030 and international regulation and trade

Question 5: Open Questions and Uncertainties through 2050:

- Lessons from other fields with nascent technologies or rapid growth to prevent wasted resources and efforts in CDR
- Identifying which technologies are scalable at an affordable social and economic cost

Deep Dive - Top Barrier/Roadblock:

Breakout Group 1: Breaking Down Silos

- Need to bridge gaps between policy makers and tech developers.
- Align material development with process innovation.
- Establish common standards to facilitate collaboration.
- Use of TEAs and LCAs to identify potential barriers and opportunities, while recognizing limitations and advocating for mass and energy balance assessments.
- Quality checks and sensitivity analysis.
- Development of platforms for sharing information on sources and sinks, such as methane.
- Promotion of open-source submissions and transparency in investments.
- Encouragement of sharing data when TEAs fail.

[12] *For the full list of key insights, please see the Appendix - here*

People Problems:

- Overcoming resistance to data sharing across different sectors and disciplines.
- Conducting deep dives within specific pathways for thorough research.
- Addressing geographical challenges to information sharing.

Breakout Group 2: Workforce Development

Challenges and Opportunities:

- Recruiting and retaining talent is a significant challenge as the government struggles to compete with big tech salaries.
- The CDR sector is small, raising questions about where big solutions will come from and the need for more science funding.
- There is a need to integrate expertise from various fields, highlighting where expertise is needed and ensuring adequate funding.
- Engaging people to work in the sector requires strategies, including leveraging philanthropy to attract interest.
- Creating a workforce involves structuring research and education to build an interdisciplinary team.
- Making the field exciting and solving other issues can create incentives for a diverse workforce.
- Academia needs to be modernized to reflect contemporary priorities, with students concerned about job security.
- Collaboration with industry is essential to find and scale solutions effectively.
- Storytelling is crucial, with examples like Bloomberg's Optimist's Guide to the Planet, to promote CDR.

Potential Milestones and Relevant Stakeholders:

- Awareness campaigns should start immediately, involving passionate scientists, smart media companies, and targeting students with prizes and classroom integration.
- The best communication mediums should be identified immediately, and key discussions should be initiated, involving science communication experts and trade groups.
- Over the next five years, academia should modernize its focus on workforce development, involving both academic institutions and start-ups.
- Small, focused groups should address TRL issues by 2025, involving researchers and industry experts.
- GHG roadmaps should be created with outreach efforts by 2025, involving scientists and funding agencies.
- A new narrative for communication beyond academia should be developed by 2026, involving academic institutions and communication specialists.
- An institution-scale fund for CDR/GHG removal should be established by 2027, involving the federal government and philanthropic organizations, and a major film about CDR should be produced.
- Related blue-collar jobs should be uplifted by 2037 through efforts by the government and unions.

Deep Dive - Top Open Question/Uncertainty[13]:

Breakout Group 1:

Potential Milestones and Relevant Stakeholders:

- Build an Open-Source Data Repository (nonprofits, national academics, universities, government)
    - Create an urgent information sharing model
    - Use AI to balance sharing information and navigating data
    - Include big banks and auditors
- Identify and secure a leader to drive collaboration by 2024
- Initiate convenings in 2024 using forums like Slack or Discord
- Establish a platform for open collaboration by 2024
    - Develop the foundational platform and integrate incentives by 2025
    - Develop a milestone-driven approach for research and state agreements by 2025
- Consider the establishment of a collective entity or organization

Breakout Group 2:

- Interdisciplinary options should be evaluated early to identify viable technological paths, involving research institutions and industry stakeholders.
- Pragmatic approaches should focus on avoiding the worst consequences and hedging bets with multiple technologies, involving policymakers and technology developers.
- Four to ten shovel-ready technologies should be selected for immediate implementation, involving technology developers and funding agencies.
- Early-stage evaluations, such as TEAs and LCAs, are necessary to prioritize technologies, involving research institutions and government agencies.
- Project developers, such as Deep Sky in Canada and independent developers, play key roles in technology development.
- Goals should be clarified, distinguishing between short-term and long-term success, involving all stakeholders including researchers, developers, and policymakers.
- The CDR sector's small size creates uncertainty about solutions and highlights funding issues.
- There is a need to enable various types of work and pair them with funding to attract expertise.

Report Out:

Group 1

SME Nikki Batchelor provided an overview of the group's discussion, which emphasized the significant risk of scaling the wrong technologies, particularly due to the siloed nature of learnings and inaccessible data across different sectors. They also highlighted the competition for resources, such as energy and land, as a critical dependency that must be managed efficiently as the system scales.

One of the main concerns discussed was the potential consequences of the first wave of failures in GHGR projects, and how to foster a culture that embraces "failing fast" to accelerate learning and adaptation within the community. The group explored the need for sophisticated, open-source data platforms that can facilitate knowledge sharing and collaboration, drawing parallels to initiatives like the weekly COVID calls hosted by Google.

---

[13] Both breakout groups broadened their focus to cover a wider range of topics during this portion of the deep dive sessions.

They stressed the importance of creating a centralized, AI-powered repository to store and disseminate the latest research findings, weathering rates, and other crucial data. This platform would also need to highlight outstanding research questions and incentivize further investigation through attached funding opportunities.

The group also discussed the timing and process of consolidating efforts to scale the most promising technologies, raising concerns about who should make these critical decisions. They suggested that this might be guided by market forces, but recognized the need for deliberate and well-informed decision-making to ensure the best outcomes. Additionally, the idea of integrating research milestones into offtake agreements was proposed as a way to drive progress in priority areas. Finally, the group considered the possibility of creating an IP and data salvage company to preserve knowledge from projects that fail, ensuring that valuable insights are not lost but instead contribute to the broader learning ecosystem.

Group 2

SME Tim Bushman presented his group's report-out, which focused on several key areas necessary for scaling GHGR technologies, particularly emphasizing the importance of workforce development and the academic pipeline. The group identified the underdeveloped talent pipeline as the top barrier to scaling, stressing the need for academic programs that can train a skilled and ready workforce. They discussed how to attract talent into the GHGR space, especially from disciplines like AI and machine learning, by framing GHGR as an exciting, problem-focused endeavor that offers opportunities for interdisciplinary collaboration.

The group also discussed the importance of making GHGR appealing to younger generations by introducing relevant subject matter in schools and improving storytelling to motivate interest in this field. Additionally, they raised concerns about scalability, noting that the industry needs to think more deeply about how to assess and achieve scale by mid-century, considering factors like total system cost, energy requirements, and supply chain robustness. The group emphasized the need to explore a broad set of solutions early on but acknowledged that difficult decisions would eventually need to be made about which technologies merit further investment.

In terms of system dependencies, they highlighted the importance of clean energy availability and supply chain readiness, while also addressing the potential risks of failed trials in the public domain and their impact on public perception. The group saw hybrid systems and business model synergies, such as integrating GHGR with other clean tech sectors like geothermal or clean hydrogen, as potential game changers.

Finally, in their deep dives, they discussed the role of academia, philanthropy, and labor unions in workforce development, as well as the need for a global data and knowledge hub to facilitate shared learning and monitor the progression of technologies across time. This hub could be led by a global government consortium or philanthropically driven, ensuring a collective understanding of what is viable and how the industry is advancing.

Socio-Behavioral and Communities

State of Play:

In a lightning talk on socio-behavioral aspects and communities, Holly Buck from the University at Buffalo delved into the complex dynamics between communities and technologies, particularly in the context of carbon removal. The speaker began by exploring the concept of "community," noting its varied definitions that can range from geographical areas to shared interests or identities. The speaker emphasized the need to understand the social

relations within these communities, including power dynamics and historical contexts, which significantly influence public support for technologies like enhanced weathering.

The talk highlighted the importance of viewing technologies not just as standalone entities but as part of broader socio-technical systems that involve multiple stakeholders, from farmers to industrial workers. It was pointed out that public acceptance of technologies often hinges on the relationships and perceived impacts within these systems, rather than the technologies themselves. This holistic perspective is crucial for understanding and addressing community concerns and for fostering meaningful engagement.

Engagement, Buck noted, is often framed by a "ladder of participation" model, which spans from non-participation and tokenism to partnership and community control. It was argued that true engagement is a continuous, two-way process rather than a one-time event. This process must be thoughtfully managed to build trust and ensure that community voices are genuinely heard and integrated into decision-making.

The concept of environmental justice was also addressed, explaining that it encompasses distributive and procedural elements, as well as being an aspiration for equitable decision-making and outcomes. Buck underscored the need for transparency and inclusive practices, especially in light of historical grievances related to carbon markets and biofuel projects that have sometimes failed to deliver promised benefits.

To effectively scale carbon removal technologies, the speaker emphasized the need for social support and public mobilization. It was noted that while the term "scale" often resonates with a technical audience, it can be daunting to the public, who may feel disempowered by large-scale projects. Therefore, Buck suggested that community-scale initiatives could foster greater acceptance and engagement by demonstrating tangible local benefits.

Key Insights[14]:

Top-Voted Response from Breakout Group 1

Top-Voted Response from Breakout Group 2

Question 1: Barriers and Roadblocks through 2050:

- Lack of public understanding of CDR and the power of industry incumbents, with low general awareness among key stakeholder groups and the need for simplifying science and technology to make it more accessible to community members
- Addressing trust issues and power imbalances, existing harms to communities, and mistrust of government and academics

Question 2: System Dependencies through 2050:

- Abundant zero-carbon energy and resilience to climate impacts
- Integration of CDR into the educational system

Question 3: Risks or Unintended Consequences through 2050:

- A deployment goes awry, creating sector-wide public ill will
- Unintended or intended health tragedies and CDR deployment in vulnerable locations

Question 4: Enablers and Game Changers through 2050:

- Models for community ownership and decolonizing CDR, including creating a community-owned model to ensure benefits are shared equitably and involvement is genuine, and reframing concepts of ownership to include public or co-op models

[14] *For the full list of key insights, please see the Appendix - here*

- An independent engagement entity to proactively talk to people about CDR, with dedicated funding and supporting structures

Question 5: Open Questions and Uncertainties through 2050:

- How to increase the visibility and acceptance of CDR
- How costs and benefits of CDR will be shared equitably

Deep Dive - Top Barrier/Roadblock:

Breakout Group 1:

- Establishing codes of conduct and a bill of rights that include various groups of actors is essential. These should be implementable and driven by community needs and desires.
- Creating 100+ chairs for social science community-focused CDR research is necessary. This will help gather data and frame the decarbonization discussion effectively.
- Investing in and enabling community-led organizations is crucial for communities to explore issues pertinent to them. This approach helps decrease misinformation and promotes equitable exchange of ideas and discourse.
- Producing four stories per year about CDR projects and their impact on communities through documentaries, long-form journalism, etc., will help raise awareness and understanding.

Breakout Group 2:[15]

- Community mistrust is a significant barrier. More knowledge alone is not the answer; addressing the root of this mistrust is crucial. NIMBY sentiments often come from a position of privilege.
- There is a need for a shared language and terminology across all elements of CDR, addressing technical justice and other social topics at the same level as TRLs.
- System dependencies highlighted include the importance of education and workforce development. Efforts should avoid redundancy in outreach among projects, and there should be clear distinctions between education (one-way, targeting the next generation) and engagement (two-way, interactive).
- Risks and unintended consequences include potential harms to communities, especially rural, racial, indigenous, and other vulnerable groups.
- Game changers include independent, neutral third-party messaging and feedback tailored to the diversity of each community, with a focus on long-term engagement and community ownership. Addressing power imbalances through literal community buy-in and support is also crucial.
- Open questions and uncertainties involve shifting power imbalances, project ownership structures, and funding for independent entities to address these imbalances. Inclusion of impacted communities in the solution-making process is essential.

Deep Dive - Top Open Question/Uncertainty:

Breakout Group 1:

- How to define a successful CDR project and address potential failures in CDR initiatives remains unclear.

[15] *Group 2 conducted a deep dive on each of the five key questions from the ideation phase.*

- Ensuring fair and safe labor practices within the CDR industry is a significant concern.
- Questions about whether the CDR industry is beneficial, how the benefits are shared, and how people perceive those benefits need to be addressed.
- Concerns about the costs of CDR and related policy questions, including government funding for decarbonization and evolving goals for carbon removal, are prevalent.
- Collaboration at a species level is needed to address global challenges and undo the harms caused by capitalism.
- The stability of the global order and its impact on CDR efforts is uncertain.
- CDR is often invisible to the public, much like trash removal. Making the benefits and processes of CDR visible and understandable to communities is essential.
- To reduce uncertainty, it is important to demonstrate tangible benefits for communities and visualize the impacts of CDR.
- Developing and supporting research in social sciences related to CDR is crucial, including the need for funding and national workshops.
- Many social scientists want to engage with private companies but feel constrained in doing so.
- CDR is fundamentally different from other industries and needs to be treated as a public good, similar to environmental cleanup efforts.
- Making CDR visible and relatable to the public through examples and analogies is necessary.
- Moving from social acceptance to social demand for CDR requires research and engagement.
- Determining how much the general public needs to know about CDR and funding research to improve public understanding is essential.
- Providing clear, successful examples of CDR to build public trust and understanding is important.
- Finding and learning from other industries that have successfully addressed similar challenges is useful.
- Developing processes to inform and engage the public on CDR through social science research is needed.
- Considering unintended consequences of global downstream issues is crucial.[16]

Policy and Regulatory

State of Play:

In a lightning talk on policy and regulation, Jack Andreasen from Breakthrough Energy provided an insightful overview of the intricate relationship between policy, law, and regulation in the context of carbon removal technologies. The talk emphasized that effective policy encompasses a broad spectrum of principles and actions that can be enacted by individuals, companies, or governments to drive carbon removal initiatives.

The speaker highlighted the interconnectedness of policy and regulation, using the Class 6 Underground Injection Control ('UIC') program at the Environmental Protection Agency ('EPA') as an example. This program, which facilitates the safe geological storage of CO_2, was made possible through extensive scientific research and policy groundwork. It was pointed out that policy frameworks like the DAC hubs and the inclusion of CDR in the European Union's

[16] *Due to limited information, insights from the Socio-Behavioral and Communities report out were integrated into the Deep Dive section*

Emissions Trading System ('ETS') illustrate how policy and regulation work together to enable large-scale carbon removal.

Andreasen discussed the global landscape of greenhouse gas policies, noting significant variations in how different regions approach carbon removal. For instance, the UK favors contracts for difference, while Southeast Asia is developing geologic storage regimes tailored to its industrial needs. The talk underscored the importance of diverse policy tools—ranging from advanced market commitments to tax credits and federal procurement—to stimulate demand and scale carbon removal technologies.

Reflecting on the past, Andreasen acknowledged the shortcomings of voluntary carbon markets and international trading schemes, citing issues like poor baseline setting, leakage, and inadequate carbon accounting. The speaker emphasized that current and future efforts must coalesce around common standards to create a more effective and reliable framework for carbon removal.

Looking ahead, the speaker expressed optimism about the rapid development of policies and regulations worldwide. Initiatives such as the U.S. Bureau of Ocean Energy Management ('BOEM') the BLM exploring CO_2 storage, and the burgeoning standard-setting activities in the private sector were highlighted. The talk concluded by stressing the need for broad political support for carbon removal technologies, noting that bipartisan backing in the U.S. is crucial for the successful implementation and scaling of these technologies.

Key Insights[17]:

Top-Voted Response[18]

Question 1: Barriers and Roadblocks through 2050:

- Regulatory to market certainty is critical

Question 2: System Dependencies through 2050:

- Lack of understanding about GHGR among policymakers

Question 3: Risks or Unintended Consequences through 2050:

- Policy and regulatory lock-in, creating discontinuity between CDR in 2025 and 2050

Question 4: Enablers and Game Changers through 2050:

- High quality MRV and standards

Question 5: Open Questions and Uncertainties through 2050:

- Technology evolution and the potential for policy imprint and lock-in of specific approaches

Deep Dive - Top Barrier/Roadblock:

- By 2024, the SBTi should include CDR as a separate core target or within existing targets.
- Throughout the 2020s, there needs to be an acceleration and implementation of Article 6.4.
- Between 2025 and 2035, the US should develop a fit-to-purpose CDR permitting regime, involving agencies, legislators, and the workforce.

---

[17] *For the full list of key insights, please see the Appendix - here*

[18] *During the workshop, two initially separate groups on Policy and Regulation were merged into one breakout session. This change in structure was purely logistical and did not impact the outcomes of the workshop.*

- By 2028, the EU should establish a long-term compliance market signal, with support from NGOs and technocratic foundations.
- There is a need for international agreements or enabling the private sector to accelerate policy development globally. Organizations like Global Carbon Market Utility are working towards this, but more net zero public utilities are needed.
- The US is seen as a key player due to the money and incentives available, making it a crucial place for lobbying and setting guidelines for different types of carbon removal.
- The EU is viewed as important for creating a compliance market, with significant demand expected from this market by 2030-2035. Europe's approach to incentives and funding, although currently lacking, could improve with better policy frameworks.
- US technology could potentially be exported and replicated globally, emphasizing the need for effective tax incentives and policy demonstrations.
- Long-term policy development is essential, even as near-term projects are being implemented. Stakeholders include political entities, technocratic NGOs, and community groups.
- There is a need for global collaboration, particularly engaging the global south and leveraging US innovation capabilities. Community engagement without obstacles is crucial.
- The White House action committee's focus on ocean carbon renewal and the need for clear regulatory timelines between 2025 and 2030 were highlighted.
- The EPA, agencies, Congress, and expert bodies need to be involved in setting and achieving regulatory milestones. The EU's certification of carbon removal, expected this year, could accelerate timelines in Europe.

Deep Dive - Top Enablers/Gamechangers[19]:

- The EU should establish demand policy certainty through technocratic NGOs between 2028-2030.
- Government procurement of CDR should be piloted by all G20 members by 2030, focusing on compliance markets and cross-agency procurement in the US.
- There needs to be much more engagement with stakeholders outside the US and EU, including NDCs and creating a coalition of negative emitters. Technology transfer should involve sovereign wealth funds and national oil companies.
- Government procurement and compliance markets are crucial enablers for demand. All G20 members should be piloting CDR by 2030.
- It is essential to include perspectives and participation from outside the US and EU. This involves creating an international engagement organization to support these efforts.
- Strong environmental ministers in countries like Madagascar and Morocco, and participation from countries doing well economically, such as those in the Middle East and China, should be leveraged to provide demand and certainty.
- A mechanism for global participation could be through the NDCs from the Paris Agreement, with governments setting targets that create demand.
- There is a need for international supply channels, technology transfer, and management, as well as involvement in industrial policy.
- The creation of demand by oil-rich countries could be beneficial due to their substantial financial resources.

[19] *The policy and regulatory group opted to focus their deep dive on identifying top enablers and gamechangers, rather than exploring open questions and uncertainties.*

Report Out:

Report Out:

The group, represented by Michael Wara's (Stanford University), emphasized that demand, particularly from voluntary carbon markets, is a critical enabler for achieving scale in GHGR. They also highlighted the need for clarity and consistency in permitting and MRV processes, as well as the importance of addressing social license issues to ensure community support and smoother permitting.

The group also identified several system dependencies, including the need to resolve voluntary carbon market interactions and the importance of training a skilled workforce. They noted that many policymakers still lack a deep understanding of GHGR, which is a barrier that needs to be addressed.

Regarding risks, the group discussed the potential for negative public reactions to failures, whether perceived or real, and the importance of reacting constructively to such events. They also raised concerns about the risk of policy lock-in, where early policy decisions might unduly influence technology choices.

In terms of milestones, the group suggested that achieving clarity around carbon dioxide removal in the SBTi framework by 2024 would be a key enabler. They also pointed to the importance of the EU as a source of demand by 2028-2030 and emphasized the need for a U.S. GHGR permitting process by 2025. A stretch goal for 2030 would be for every G20 member to have a government procurement program for GHGR.

Lastly, the group stressed the need for greater engagement from developing countries in these discussions.

Finance and Markets

State of Play:

In a lightning talk on finance and markets, Nan Ransohoff from Frontier provided a comprehensive overview of the financial landscape necessary to support and scale carbon removal technologies. The talk emphasized the dual need for immediate demand and substantial investment, framing the discussion around the significant financial requirements for both generating revenue and funding projects before they become operational.

The speaker outlined the scale of global demand for carbon removal by 2050, estimating the need for $500 billion annually at $100 per ton of CO_2 removed. It was stressed that reaching these figures will necessitate a robust policy framework across multiple countries, as voluntary markets alone are unlikely to suffice. Even by 2030, an estimated $20 billion per year in global demand is required to support the anticipated 50 to 100 million tons of CO_2 removal annually.

The talk also highlighted the progress made since 2018, noting a significant increase in the funding and demand for carbon removal technologies, although the current levels are still far from the required targets. Ransohoff discussed the role of various financial mechanisms, such as venture capital, project debt, equity, and grants, emphasizing the need for diverse funding sources to bridge the gap between present capabilities and future requirements.

On the investment side, the speaker acknowledged the challenges that carbon removal companies face in securing project finance, even with guaranteed offtake agreements. It was pointed out that these difficulties are not unique to carbon removal but are common across many climate solutions, underlining the need for innovative financial strategies to support these emerging technologies. Ransohoff also discussed the barriers identified in a survey of

conference attendees, such as the lack of voluntary buyers at high prices and the challenges in accessing affordable renewable energy.

The talk concluded by discussing the importance of policy in creating a sustainable market for carbon removal, highlighting the need for immediate actions to support voluntary markets while long-term policies are developed. The importance of building a "patchwork quilt" of policies and financial mechanisms was emphasized, to ensure that carbon removal technologies can scale effectively and meet the critical climate goals for 2030 and beyond.

Key Insights[20]:

Top-Voted Response from Breakout Group 1

Top-Voted Response from Breakout Group 2

Question 1: Barriers and Roadblocks through 2050:

- No reason to buy credits now and lack of SBTi guidance impacting early adoption and investment in CDR technologies
- Need for committed and bankable demand at scale; addressing the lack of political coalition for CDR policy ASAP

Question 2: System Dependencies through 2050:

- Market certainty; impact of public markets and global financial health
- Establishment of consistent methods and standards for reporting

Question 3: Risks or Unintended Consequences through 2050:

- Scandal, failure, or loss of trust
- Suppliers failing due to lack of demand and financial instability

Question 4: Enablers and Game Changers through 2050:

- Strategic communications to elevate the social value of carbon and enhance public awareness and support for CDR initiatives
- $5 billion in pilot funding as grants and project finance by 2027, along with AMCs and scaling pilots

Question 5: Open Questions and Uncertainties through 2050:

- Uncertainty about the health of the global market and the long-term demand for carbon removal.
- SBTi and corporate action/inaction

Deep Dive - Top Barrier/Roadblock:

Breakout Group 1: Voluntary Demand

- Voluntary demand is a barrier because there is no intrinsic reason for companies to buy carbon removal services. Although companies have made voluntary commitments, they have not spent money on permanent carbon removal due to lack of capability, trust issues, and insufficient supply.
- Organizations that guide voluntary markets face challenges such as higher costs compared to cheaper alternatives, lack of directives, and uncertainty about whether they will be celebrated or criticized for their efforts.
- To overcome this barrier, it is necessary to establish whether compliance measures should be created, and to define near-term financial goals (e.g., $2-10 billion in

[20] *For the full list of key insights, please see the Appendix - here*

voluntary dollars). Large companies need to be encouraged to make significant purchases to move the annual voluntary market at lower costs.
- Enhanced weathering and biochar are potential methods for quantifying benefits, reframing financial opportunities as revenue sources, though scaling up these methods could be challenging.
- Companies need to be presented with a good portfolio of options, including temporary removals, while understanding that some initiatives might be harder to implement later and thus postponed.
- Creative framing of benefits and clear guidance from organizations like SBTi are crucial.
- Voluntary rule setters need to collectively comply with established standards, including net zero standards.
- Bundling removal services with big companies through initiatives like Watershed can help, but many companies will face challenges due to high costs. Voluntary markets need to become more demanding of permanent carbon removal, with organizations like SBTi requiring it in their commitments.
- Political coalitions and policy advocacy are essential for driving demand. Efforts should focus on educating banks, policymakers, and other stakeholders about the importance of CDR.
- Ensuring a broader geographic focus and international cooperation is important for achieving milestones. Engaging diverse stakeholders and leveraging philanthropic efforts can help align actions and fix mistakes along the way.
- Timing and capacity are crucial, with a need to increase human resources focused on CDR. Specific and cohesive policy asks, alongside support from different constituencies, are vital for progress.
- SBTi and policy entrepreneurship, along with professional advocacy efforts in regions like the EU, can drive significant advancements. Awareness of political dangers, such as the rise of climate opposition movements, is necessary to navigate challenges effectively.

Potential Milestones and Relevant Stakeholders:

- Achieve $10 Billion in voluntary funding in the next 5 years (big companies, standards setters)
- Requires big purchases from large companies, reframing the benefit of purchases, and involvement of standards setters and industrial insetting.
- Achieve $15 Billion in yearly funding by 2030 (philanthropies, established companies, industry groups)
- Requires involvement of philanthropies, established companies, and industry groups. Ensuring alignment in policy asks and engaging more policy makers.
- Achieve $500 Billion in yearly funding by 2050
- Requires increased involvement of philanthropies and industry groups, along with more policy makers to ensure alignment in policy asks.

Breakout Group 2:[21]

- CDR projects are not currently bankable due to their reliance on carbon markets and lack of inherent profitability. To make these projects viable, significant government incentives, such as fixed price rewards, are necessary.

[21] *Group 2 engaged in a discussion that covered a broader range of topics, so the following summary reflects that wider scope.*

- The government is seen as the largest facilitator for making CDR projects viable, emphasizing the importance of favorable tax laws and deployment incentives.
- Corporate standard setting and signals are needed to ensure voluntary demand certainty, allowing CDR market growth irrespective of policy developments.
- There is a significant knowledge gap among companies and investors regarding CDR, and better education and information dissemination are necessary.
- Regulatory capital treatment and mandates for infrastructure investment, including carbon-specific investments, are needed to facilitate market development.
- Different CDR methods must be differentiated, with clear communication on high-durability versus low-durability credits to stakeholders.
- Effective storytelling about CDR successes and challenges is crucial to engage unions, farmers, and local task forces, thereby building a diversified coalition.
- The formation of political coalitions and clarity in regulatory frameworks are essential to overcome the lack of regulatory support and drive progress in CDR deployment.
- Pushing corporations to invest more in CDR can be achieved through compliance policies, rating systems, and voluntary standard setting.
- Public perception needs to be shifted to see CDR as a viable investment opportunity, with initiatives to educate and attract investors.
- Different use cases for various CDR methods must be developed to meet specific demands, ensuring an enduring market for each method.
- Efforts should focus on both regulatory compliance and voluntary markets to drive demand for CDR, with a focus on creating a balanced portfolio approach.
- There needs to be a broader focus beyond the US to include international coalitions and efforts in CDR.
- Engaging diverse stakeholders, including unions, farmers, and local task forces, is crucial for a successful CDR deployment.
- Campaigns to educate banks and investors about CDR are necessary, as new industries often need to explain their value proposition to potential investors.

Deep Dive - Top Open Question/Uncertainty:

Breakout Group 1:

- The main uncertainty revolves around who will pay for carbon removal in the long term, with estimates suggesting a need for $225 billion per year.
- Part of the challenge is shaping the narrative and exploring underutilized avenues, such as strategic communications that link national security to CDR by suggesting governments invest in air removal instead of weapons.
- A diversified approach is needed, including public procurement, integrating CDR into LCFS, and exploring different policy domains. Europe can serve as a model for large-scale regulation.
- The question of long-term buyers remains after bridging the gap with $10 billion in voluntary markets. There is a need for more concrete policy bets and creative approaches to sustain demand.
- The EU has a 2031 deadline for integrating carbon removal into the ETS. In the US, funding increases will likely require decreases in other sectors, with considerations for tax credits and mandates for companies to pay.
- Targeted initiatives in California should include mandates for carbon removal purchases and addressing environmental justice concerns through successful demonstration projects.

- The adoption of the social cost of carbon and incorporating CDR into procurement decisions by the US government can drive demand. The political economy should diversify interest groups to support CDR initiatives.
- Identifying promising geographies for CDR initiatives and working to decrease costs are crucial steps. Mapping out where to focus efforts can help streamline initiatives.
- A table of potential initiatives, including CBAM and tax credits, should be developed. Workshops and reports on these policies can help flesh out the path to achieving significant funding goals.
- Actions needed include investing in CDR as an investment, creating a diverse set of policy bets, convening stakeholders to strategize on reaching $285 billion by 2050, and ensuring a compelling narrative for policymakers.
- A communication campaign focused on CDR is necessary, with efforts from organizations like Carbon180. Training executives and ensuring visibility of successful programs can drive momentum.
- To address these uncertainties, broader policy identification, seeding more policy advocates, publicizing successes, and reducing costs per ton are essential steps.

Report Out:

Group 1

SME Nan Ransohoff's report-out emphasized a focus on the need for voluntary demand to bridge the gap until long-term policies are in place, which are essential for reaching targets like $20 billion by 2030 and up to $500 billion annually by 2050. The group highlighted global financial markets and clean energy as key dependencies and expressed concerns about the risk of a "Solyndra effect," where a high-profile failure could deter investment.

To address these challenges, the group discussed increasing policy capacity to support diverse GHGR strategies and emphasized the need for clear guidance from standard setters like SBTI to encourage corporate investment in permanent GHGR. They also stressed the importance of engaging large companies like Microsoft and Google to scale commitments.

On the compliance side, the group identified the need for creative policy development, building global human capacity, and publicizing successful projects to maintain positive momentum. They set milestones, aiming for $10 billion in voluntary commitments by 2030 and scaling compliance-driven investments to $15-20 billion annually by 2030, with a long-term goal of $100 billion to $1 trillion by 2050.

Group 2

SME Ryan Orbuch provided an overview of his group's discussion on financial markets, which focused on how demand can be grown for GHGR and which mechanisms can support it. The group identified two main levers: increasing corporate demand for GHGR and exploring non-corporate mechanisms like policy incentives, trade policies, and other financial instruments to generate revenue for projects.

On the corporate side, the group emphasized the importance of strengthening guidance from organizations like SBTI to better incorporate GHGR into net-zero claims. They saw this as a high-leverage point for philanthropic efforts. On the policy side, they discussed building a larger coalition to support GHGR, which could help advance trade policies and integrate GHGR into industries like agriculture, shipping, and mining.

The group also explored the ongoing tension between durable GHGR solutions and nature-based approaches, such as avoided deforestation. They suggested that alternative funding mechanisms, like international development finance or debt-for-nature swaps, could alleviate

the pressure on carbon credits to be the sole funding source for nature-based solutions, helping to balance the needs of both camps.

In terms of meaningful milestones, the group highlighted the importance of actual project deliveries to create momentum. Successful deliveries would not only substantiate future offtakes but also support project finance, permitting, and the tangible benefits of job creation and community impact. This, in turn, would help build political support and reduce the abstraction surrounding GHGR efforts.

In summary, the group recommended focusing on improving corporate standards like SBTI for better GHGR integration and exploring diverse funding mechanisms beyond carbon credits, such as insetting, trade policies, and other financial tools.

Measurement, Reporting, and Verification

State of Play:

In a lightning talk on MRV, Anu Khan from Carbon180 discussed the crucial role of MRV in ensuring accountability and transparency in carbon removal initiatives. The talk emphasized that MRV is essential for validating the impact of carbon removal projects, which in turn supports contractual enforceability, regulatory compliance, and the achievement of just outcomes. It was noted that effective MRV is vital for unlocking capital flow, enabling more ambitious climate policies, and ensuring equitable climate solutions.

The speaker also highlighted the need for a broad approach to MRV, encompassing not only project-level accounting for carbon credits but also jurisdictional and global scales. This comprehensive view is necessary to evaluate ongoing projects, initiate new ones, or reassess existing ones. It was pointed out that the complexity of MRV should be seen as a strength, provided it reflects the diverse expertise and technical requirements of different sectors rather than unnecessary complications.

Discussing the current state of MRV, Khan identified three key groups involved in the ecosystem: private entities in the voluntary carbon market, government bodies in compliance markets, and technical authorities or research institutions. The importance of collaboration among these groups was stressed to develop robust MRV frameworks and ensure the accuracy and reliability of carbon removal data. Recent trends were also noted, such as the growing role of policy-driven demand and the increasing involvement of jurisdictions in creating their own MRV standards, as seen in the UK, EU, and Canada.

The speaker addressed the barriers to effective MRV, including the need for more scientific research, particularly in open-system carbon removal pathways, and the development of reliable sensor networks for accurate measurement. The talk also highlighted the risks of fragmented MRV landscapes and financial conflicts of interest, which can undermine trust and lead to issues such as over-crediting. The importance of interoperability across different standards and industries was underscored to facilitate seamless integration of MRV systems.

For scaling MRV, Khan suggested focusing on enabling technologies like advanced sensors and positive feedback loops between data collection and modeling. The need for transparent and accessible data was emphasized to help build a trustworthy MRV system that operates efficiently in the background. The talk concluded by posing critical questions for the future of MRV, such as balancing scientific uncertainty with cost and urgency, fostering transparency while protecting intellectual property, and determining who should be accountable for climate claims backed by MRV.

Key Insights[22]:

Top-Voted Response from Breakout Group 1

Top-Voted Response from Breakout Group 2

Top-Voted Response from both Breakout Groups

Question 1: Barriers and Roadblocks through 2050:

- Data and information disclosure/transparency
- Scientific basis, especially for open systems

Question 2: System Dependencies through 2050:

- Need for regulation on data disclosure and global governance for MRV
- Establishment of consistent methods and standards for reporting

Question 3: Risks or Unintended Consequences through 2050:

- Risk of fraud and loss of public trust due to unethical practices in MRV

Question 4: Enablers and Game Changers through 2050:

- Intergovernmental alignment on standards/MRV
- Regional to global MRV sensor network

Question 5: Open Questions and Uncertainties through 2050:

- How to balance reliance on modeling versus field data for MRV
- Determining the necessary frequency and duration of monitoring for leakage

Deep Dive - Top Barrier/Roadblock:

Breakout Group 1: Data and Information Disclosure

- Data disclosure involves establishing baselines and ensuring transparency and accountability in data collection and sharing
- Data systems need to incorporate government and industry standards, ensuring interoperability and considering non-carbon components with clear metrics for evaluation
- Comprehensive data collection should encompass various greenhouse gases, not just carbon
- Data collection must adhere to a protocol and standard, defining its purpose while considering non-carbon components
- Sensor innovation is crucial, focusing on developing super low-cost, abundant methane sensors with high sensitivity. While high sensitivity is valuable, a larger number of lower-resolution sensors may also be effective
- Funding for sensor development should involve government, philanthropy, academia, industry, research communities, and intergovernmental organizations
- A gap analysis is necessary for sensor development and deployment
- Governments and philanthropic organizations need to financially support sensor availability and development
- Intergovernmental commissions like the IOC under UNESCO should play a role in setting standards and priorities, with funding enhancing their capabilities
- Governments should negotiate to collect ocean data beyond their borders and address other fields like air pollution, biochar, and renewables

[22] *For the full list of key insights, please see the Appendix - here*

- Industry should lead baseline data collection, collaborating systematically
- Philanthropic investment can pilot research efforts
- A national strategy should emphasize government and private sector collaboration in data collection
- Government-private sector cooperation could pilot data collection protocols for major carbon removal options, reporting to the Greenhouse Gas Information Center run by the EPA and NASA
- Industry coordination, EPA, and the Petroleum Institute should support these efforts.
- Governments and trade groups need to negotiate data access
- MRV standards should include specific fields and data requirements for access
- Sample contract agreements for data collection and availability should be developed and socialized
- Standardized off-take agreements that include data disclosures and legal texts should be created
- The creation of standards for the Internet serves as an example of a successful public-private partnership, suggesting a similar approach for CDR data systems
- Fieldwork is essential for comprehensive data collection
- Mapping data needs for existing datasets is required

Breakout Group 2:

Science:

- There is tension between many unknowns versus a learn-by-doing approach that science can address. Understanding the consequences of market confidence and relating them to certainty and verification levels is crucial.
- Dedicated pilots are needed to generate new data, which leads to scientific solutions and verification.
- Sustained funding is critical as these are long-term projects requiring ongoing efforts.
- Buyers will require higher quality verification over time, necessitating cheaper and more precise measurement tools.

Consensus:

- Identifying use cases for MRV is important, and it should not be limited to just credits. Analogs like the Clean Air Act and Montreal Protocol highlight the need for high precision and accuracy.
- Evaluations should be uncertainty-based, considering the depth of defense risks, including human costs.
- Consensus is needed on metrics like time, mass, and value, which should be quantified and included. The purpose and durability of "a ton" of carbon need clear definitions. Determining the importance of defining a ton for the net flux of carbon is essential.
- Initially, industry standards should lead, with government involvement. Research and deployment should be decoupled to ensure effective determination.

Stakeholders:

- Academics are primary stakeholders in driving research.
- Government and industry are crucial for providing funding.
- People and communities need to be engaged in the process.
- Collaborative initiatives are necessary at regional, national, and global levels to address these barriers and roadblocks effectively.

Deep Dive - Top Open Question/Uncertainty:

Breakout Group 1:[23]

- Cost effectiveness is a major concern. Measuring carbon removal is easy but costly. Poor models meant for carbon as the basic metric can lead to claims outside the certainty band. Allocating specific portions of projects for MRV is necessary. Reducing MRV uncertainty would decrease inefficiencies and costs.
- Determining who is responsible for MRV is crucial. The government could take on this role within a decade, but dependency on the government is not ideal. A public-private cooperation where the government acts as the data manager is suggested, with regular reviews every five years. The aim is to avoid a strictly regulatory system while ensuring effective data management.
- Industry standards bodies and public-private partnerships are key to establishing the necessary architecture for CDR. Regular meetings and cooperation between public and private sectors can help create and maintain standards.
- Philanthropy can play a significant role in the short term by supporting the creation of market frameworks and standards. This could include developing white papers or models to provide a standardized approach to greenhouse gas information and management.
- Reducing uncertainty involves developing cost-effective and efficient MRV systems. Incentives for data management and the establishment of industry standards through public-private partnerships can help achieve this. Philanthropy can support these efforts by funding initiatives that create and standardize data management frameworks.

Breakout Group 2: Carbon Cycles

- Data-driven MRV needs to be evidence-based to increase trust. Establishing baselines is crucial to avoid complexities and uncertainties about what constitutes a ton of carbon. Incorrect baselines could lead to significant issues.
- We measure carbon in concentration but are more concerned about flux. Research and development are needed to improve methods for measuring fluxes and to develop better earth system models, possibly using AI and machine learning.
- Investments are required to improve supply chains for instrumentation to make these advancements addressable.
- There is a need to ensure that striving for perfection does not impede progress, as seen in voluntary carbon markets. Scientific consensus can help develop thresholds.
- Defining claims and liability is essential to create clarity and accountability.
- It is important to ensure that all relevant stakeholders are involved in the discussions.
- Incentives and transparency are crucial to building trust and effectiveness in CDR efforts.
- Research organizations focused on these issues can provide a good model for addressing these challenges.

[23] *Group 1 engaged in a discussion that covered a broader scope of topics rather than focusing on one top open question or uncertainty.*

Report Out:

MRV 1

SME Anu Khan's readout of group 1 identified several key barriers, such as the lack of clarity on MRV's purpose and insufficient funding across all MRV steps—from sensors to data verification. The group emphasized the need for a clearer understanding of what data is required, suggesting a philanthropically funded gap analysis to map these needs and explore existing datasets that could be leveraged. The group proposed several recommendations for data collection, including government and philanthropic funding for detection tools like sensors and satellites, and a public-private partnership focused on site-specific data needs. They also discussed the importance of data disclosure, advocating for mandated disclosure of certain data types and standardized contracts to facilitate this process.

Regarding system dependencies, the group highlighted the significance of liability assignment in influencing MRV design and noted concerns about policies that might not be fit for purpose. They called for coordinated efforts across GHGR organizations and governments, particularly in the U.S., to develop a unified GHGR strategy that includes MRV. Finally, the group raised critical open questions, with the overarching theme being the purpose of MRV. This question drives further inquiries into who should conduct MRV, the costs involved, the scope of MRV, and how to assess additionality. They also suggested that AI and machine learning could accelerate progress if data collection challenges are adequately addressed.

MRV 2

SME Peter Minor provided an overview of his group's discussion on MRV, which focused on the scientific challenges and the need for clarity and consensus in the GHGR space. The group identified significant barriers, including the scientific gaps in measuring and monitoring GHGR projects and the tension between moving forward with existing unknowns and the need to learn more through ongoing monitoring.

A key objective discussed was the importance of building confidence among stakeholders, including buyers and taxpayers, who ultimately bear the risks of any errors in MRV. The group emphasized the need for sustained funding that matches the long-term nature of these challenges and called for buyers to play a role in raising MRV expectations.

The group also highlighted the lack of consensus on what constitutes a ton of carbon dioxide removal, including the definitions of durability and the broader purpose of MRV beyond just crediting. They expressed uncertainty about the best way to address these issues but suggested that gathering more subject matter experts could be a starting point.

Regarding solutions, the group called for better R&D, improved monitoring tools, and a clearer scientific consensus on MRV thresholds. They also discussed the importance of defining claims and liability, as well as the need for incentives and transparency to build a robust MRV system. Finally, they acknowledged the tension between striving for perfection and avoiding the pitfalls of the voluntary carbon markets.

Virtual Breakout Session

On Day 2, the virtual breakout session began with participants identifying the top barriers and roadblocks, as well as the most pressing open questions and uncertainties within the broader context of scaling technological greenhouse gas removal his initial phase set the stage for a facilitated discussion, where the group delved deeper into these challenges. The session culminated in the development of concrete actions and recommendations aimed at addressing the identified issues and advancing the broader goals of the workshop.

Key Insights:

Question 1: Barriers and Roadblocks through 2050:

- The need for consistent, technically verified, and enforceable MRV systems, supported by policy and public authorities, at all scales.
- Addressing data gaps and data availability, which are critical for effective MRV implementation.
- Ensuring MRV systems are robust, credible, and able to evaluate side effects, environmental impacts (including methane), and human impacts.
- The necessity for creating long-term, stably growing demand, with a goal to settle this demand before 2030, through compliance markets or public procurement within the next 5-10 years.
- Building social support and public demand, which are essential for driving investment and market creation, with specific focus on carbon-free energy, CO2 pipelines, and carbon pricing.
- Overcoming the challenge of low public awareness and acceptance of carbon pricing, carbon-free energy, and CO2 pipeline projects by 2025.
- Establishing comprehensive and cohesive governance frameworks, including firewalls and socio-environmental safeguards, with multidisciplinary and cross-sectoral coordination for a whole systems approach.
- Creating effective carbon markets and ensuring governance mechanisms are in place to support them.
- Securing patient capital for early R&D, as well as sufficient early R&D investment to develop a range of CDR options.
- Funding for pilot plants and securing short-term finance from public, private, and philanthropic sources within the next 5 years.
- Capital to build production facilities for CO2-based products now, and the need to identify and build new supply chains as an ongoing effort.
- Addressing potential negative environmental impacts, ensuring safety, and conducting further research on socioeconomic impacts.
- The need for further research on trustable technologies, and the evaluation of side effects.
- Overcoming the challenge of identifying viable and tested solutions that can scale to the required level by 2035.
- Increasing public awareness and acceptance of the costs and techniques of CDR by 2025.
- Widening participation and growing public understanding of the need for GGR, as current knowledge levels are far too low.
- Building social license for CDR activities and ensuring ethical considerations are adequately addressed.
- Addressing the lack of leadership in driving CDR initiatives forward.
- Ensuring a meaningful goal, such as restoration, to guide CDR efforts.
- Coordinating efforts between private and public institutions, including the de-risking of science and technology by around 2040.
- Overcoming inconsistent standards and the need for technically consistent and verified MRV solutions.
- Addressing the cost of CDR technologies and the lack of a portfolio of viable, tested solutions, while continuing to uncover innovation.

- Ensuring the transport and storage infrastructure for CO2 disposal is in place to support large-scale deployment.
- Determining whether enhanced methane oxidation works and whether CH4 removal can be enhanced without causing environmental damage within the next 5 years.
- Proving that CDR is not intended to replace emission reductions, but to complement broader climate action efforts.

Question 5: Open Questions and Uncertainties through 2050:

- How will the safety of CDR technologies be ensured, especially considering specific risks like the interaction between freshwater and oceans in ERW?
- Which CDR approaches are ready for deployment, and what technologies can perform effectively in the real world, making them scalable?
- How can public understanding and acceptance of GHGR be improved, given that without public demand, scaling to 10Gt seems unlikely in the current political climate?
- How can governance systems evolve to lock in strong MRV, establish effective carbon markets, and ensure global governance beyond MRV?
- What carbon prices are necessary, and how will carbon markets enable the successful deployment and scale-up of CDR/GGR technologies?
- Which CDR approaches need to be de-risked, and what criteria should be used to prioritize technologies that can deliver on temperature reduction and at least one social challenge?
- What is the expected time to impact on temperature reduction for various CDR technologies, and how will we identify sufficient methodologies to scale impactful CDR?
- What happens if we cannot reach gigatonne scale for CDR, and how will we address this challenge?
- How can multi-scale measurements of background GHG removal, especially over oceans, be achieved, considering the need for whole system modeling in MRV to ensure safe and speedy deployment?
- What will it take to achieve social license for CDR technologies, and how will general public perception affect the industry's advancement?
- How can clear demand signals for product-based removals be created, and how can confusion due to different MRV metrics be addressed?
- What role will finance play in scaling CDR technologies, and how can we catalyze funding for emerging industries like methane removal, considering whether it is too soon to fund commercial entities in this space?
- How can innovation pipelines be created, and how can we ensure sufficient investment in a wide range of R&D solutions to uncover viable technologies?
- What are the potential environmental and social side effects of upscaling CDR, and how can we balance the need for rapid growth by 2030 with the risks of moving too fast before fully understanding these risks?
- How can large-scale cross-sectoral testing and piloting initiatives be funded, and what will be the role of national regulatory frameworks that need to be set by 2030?
- What material and energy requirements are needed to scale CDR technologies, and how can these challenges be met?
- How will permanence be managed in human carbon sink management, considering the uncertainties in future background earth system GHG flows?
- How can we avoid issues like the "great carbon land grab" and greenwashing in CDR?

- What will it take to establish compliance markets?
- How can we address the challenge of asymptotic carbon pricing?
- How will governance and institutions need to adapt to support the scale-up of CDR technologies?
- What policy drivers of urgency are necessary to influence the next round of NDCs at the Brazil COP?
- How can we ensure long-term effective demand for CDR technologies is established before 2030?
- How will the general public perceive GHGR, and what strategies can be employed to increase social acceptance and reduce the challenges of advancing the industry?

Discussion Notes:

- Significant uncertainties exist around carbon markets and finance, particularly for early-stage tech companies and project developers.
- Concerns about the longevity of carbon markets post-2030 hinder venture support, preventing projects from reaching the demonstration stage and stalling advancements in carbon removal technologies.
- The analogy of carbon removal to traditional waste management was discussed, suggesting adopting similar funding mechanisms. However, CO2's global impact and longevity complicate direct analogies, making it challenging to secure funding.
- Differentiating between various emissions (CO2, methane, nitrous oxide) and recognizing the distinct methods required for each is crucial.
- Effective governance is crucial for the success of carbon markets. Voluntary systems are insufficient; mandatory regulations and policies are necessary for scalability.
- The EU ETS and the Canadian carbon pricing model were cited as examples of effective governance frameworks.
- Sector-specific strategies are needed to align carbon removal methods with existing regulations and subsidies.
- Biochar aligns with agriculture, while BECCS fits within the power sector. The concept of a "sectoral approach" was both supported and critiqued, noting practical benefits and pushback from less ambitious countries.
- Access to startup capital is a significant barrier, especially in developing regions. Philanthropic investments often focus on immediate impacts, leaving a funding gap for transitional technologies.
- Blended finance, involving a mix of public and private capital, was suggested as a solution.
- A network of CDR funders, including philanthropies, incubators, and early-stage investors, could address financial challenges faced by greenhouse gas removal entrepreneurs.
- Developing and deploying MRV tools is essential, such as advanced spectrometers and sensors to measure methane at ambient levels, particularly in marine environments. Partnerships with organizations to deploy MRV tools like satellites and buoys were recommended.
- Successful MRV can catalyze legislation, financing, and social acceptance, evolving through complex negotiations and phased adoption.
- The tension between asset definition and quantification of greenhouse gas removal, alongside social and ecological issues, was acknowledged.
- Frameworks to enforce social and environmental safeguards, such as those from the National Capital Project at Stanford, were suggested.

- Funding is urgently needed in the next three to four years of technology deployments to overcome current barriers. Philanthropic money could significantly reduce these hurdles.

Actions and Recommendations:

- Develop clear, enforceable policies where the cost of carbon removal is internalized, similar to waste management systems. This would provide necessary incentives for stakeholders to invest in carbon removal technologies.
- Incorporate biochar into agricultural subsidies and BECCS into power sector regulations to leverage existing frameworks, facilitating the adoption and scaling of carbon removal technologies.
- Develop financial models combining equity, debt, and philanthropic grants to support first-of-a-kind carbon removal plants. Engage large incumbents with expertise in deploying large-scale projects to facilitate collaboration between startups and established industries.
- Form an international body to coordinate greenhouse gas removal efforts, involving policymakers, scientists, engineers, and financiers. Focus on capacity building, data sharing, and supporting global innovation, potentially involving organizations like Future Earth and the Belmont Forum.
- Prioritize the development and deployment of MRV tools to ensure accurate measurement of carbon removal. Fund advanced sensors and spectrometers, especially for challenging environments like oceans, to build trust and credibility in carbon removal projects.
- Sensitize financial institutions and concessional capital providers to the importance of investing in carbon removal technologies, highlighting long-term risks of inaction and potential environmental and economic benefits.
- Encourage public-private partnerships to fund demonstration projects and provide platforms for showcasing various carbon removal technologies. This could involve land donations, matching funds, and in-kind contributions.
- Set specific timelines and milestones for implementing these actions. Aim to have an international coalition in place within two years, develop sectoral integration strategies within five years, and achieve significant MRV tool deployment within the next decade.
- Effective MRV can drive legislation, financing, and social acceptance, evolving through complex negotiations and phased adoption.
- Define and quantify greenhouse gas removal assets while incorporating social and ecological considerations.
- Frameworks must enforce social and environmental safeguards, quantifying impacts in environmental justice and ecosystem services, utilizing methodologies like those from the National Capital Project at Stanford.
- Start with incremental processes, recognizing that greenhouse gas removal projects may not yet have significant environmental impacts. Layer in comprehensive processes as project scales grow.
- Given methane's near-term impact, pilot projects in methane removal are vital. Partnerships with research organizations, philanthropy, and industries like shipping to deploy measurement tools such as satellites and buoys are recommended.
- Balance socializing issues with concessional capital providers (MDBs and DFIs) and building robust business models. Capacity building efforts could mirror organizations like the International Energy Agency and International Renewable Energy Agency, assisting governments with training programs and governance processes.

- Align removal technologies with sectoral approaches to leverage existing finance structures, integrating BECCS into power sector financing and biochar into agricultural subsidies. Emission standards could account for negative emissions, working with current government interventions.

Report Out:

Virtual Group

SME Aaran Patel reported on his group's extensive virtual discussion, which spanned topics such as MRV and finance and markets. In particular, the group emphasized how effective MRV could serve as a catalyst for other critical areas such as legislation, financing, and social acceptance. The group drew analogies from energy efficiency standards and building codes, highlighting the importance of independent organizations in developing and iterating these standards.

The group also explored the tension between defining and quantifying GHGR and addressing social and ecological issues, stressing that these should not be treated as externalities in the emerging market. The group discussed the need for frameworks to enforce social and environmental safeguards, particularly in areas like environmental justice and ecosystem services. They referenced existing methodologies, like Stanford's National Capital Project, while acknowledging the complexity of integrating these processes incrementally as GHGR scales.

The group also highlighted the importance of pilots, especially in methane oxidation, noting that expanding satellite and buoy deployments would be vital. They suggested that partnerships between various organizations, including research bodies and shipping companies, could accelerate progress. Additionally, they called for philanthropy to play a key role in supporting these efforts, along with the involvement of the IPCC and other experts.

In the finance space, the group discussed the need to educate concessional capital providers, like MDBs and DFIs, about greenhouse gas removal while simultaneously building robust business models. They proposed capacity-building efforts, potentially through new institutions, to align removal technologies with sectoral approaches, leveraging existing government frameworks and subsidies.

The discussion concluded with an open question about the evolution of carbon markets, drawing comparisons to waste management. The group emphasized the need to balance reductions and removals in the market transformation, leveraging decades of experience in VCMs while scaling compliance markets through taxes and regulations. Governance was identified as crucial to this scaling process.

Day 2: Afternoon Plenary Session

Insights

After the breakout sessions on Day 2, all groups reconvened in a plenary session similar to the one held on Day 1, where breakout insights were shared for the benefit of all. An interactive polling tool was used once more to gather real-time input on key questions, including identifying any overlooked aspects, gaps in the conversation, and major threats to the effectiveness of greenhouse gas removal strategies. Additionally, "table spotlights" were introduced, where selected participants from different groups were asked to share their insights on these questions.

Based on the readouts from Day 2, what was overlooked?

- Addressing secondary GHG effects of hydrogen and the potential for methane removal to reduce warming
- Developing a comprehensive media strategy to support CDR efforts and address worldwide public backlash against climate measures based on costs
- Leveraging the capacity of the National Science Foundation and "Public Engagement with Science" expertise to move from generalities to specifics in CDR initiatives
- Implementing specific technical innovations required for adequate MRV and establishing consistent, coherent MRV frameworks that extend beyond carbon
- Increasing input from international perspectives and enhancing international governance, including developing multi-stakeholder standards with third-party certification
- Addressing competing global goals such as GHG reductions, SDGs, and biodiversity conservation
- Setting priorities and ensuring granularity in discussions to cover all relevant details.
- Combining multiple GHG technologies, promoting cross-talk among different GHGs, and critically evaluating proposed CDR technologies
- Evaluating geographic distribution of deployment potential and its impact on income/job creation, and addressing real uncertainties of CDR effectiveness, especially in ocean-based methods
- Exploring the role of synthetic biology in CDR and developing low-cost, selective, durable, and recyclable materials
- Creating a roadmap for achieving 285 Mt/year removal by 2030 and learning from existing mature standards such as those by EPA or OSHA
- Preparing for the possibility that world politics might sideline the CDR sector and engaging with non-US markets and the Global South
- Recognizing the responsibility of past emitter countries towards developing/global south countries and facilitating North-South benefit transfer
- Reframing the climate challenge to emphasize that removal is the only way back once net zero is achieved and ensuring accountability of progress to youth
- Creating a public sequestration utility and addressing the non-fungibility of GHGs
- Considering the opportunity cost of DAC with renewables and incorporating more non-US thinking into CDR strategies
- Utilizing gamification to engage broader audiences and addressing issues of distributional justice
- Enhancing global coordination and participation in multilateral fora

- Reconciling the use of significant energy to fix a problem caused by energy mismanagement and exploring the role of nuclear energy for the decarbonization of industries
- Developing strategies to de-risk once MRV reveals harm and/or ineffectiveness and conducting studies on non-carbon unintended consequences to establish controls and maintain trust
- Addressing the challenge of companies selling offsets before offsetting their own emissions and overcoming the lack of political will
- Promoting positive, hopeful narratives to inspire action and addressing public confusion about CDR
- Securing funding for early-stage research, environmental monitoring, and more comprehensive scientific studies, along with philanthropic and impact funding to translate and scale CDR technologies
- Coordinated regulatory and funding support for all CDR technologies, with policies and standards for quality MRV and certification
- Setting national targets for GHG removal proportional to each country's emissions, similar to carbon neutrality targets, and developing a post-COP/IPCC roadmap aiming to achieve 10GT of drawdown by 2050 through international agreement and action

Spotlight 1:

A participant discussed using GWP* (Global Warming Potential Star) as an alternative method for accounting CO2 equivalents. GWP* considers the atmospheric lifetime of greenhouse gases, such as methane, which has a 12-year lifespan. This method accounts for the fact that methane emissions in year 13 would replace those from year one, resulting in no incremental climate impact, unlike GWP 100, which continues accounting for emissions regardless of their occurrence year. The participant highlighted that GWP Star might provide more accurate accounting for methane removal projects and could also be relevant for traditional carbon accounting and LCAs in CDR projects.

Spotlight 2:

A participant discussed the importance of communicating information efficiently and effectively to diverse audiences. They emphasized the need for tailored communication strategies for different sectors, such as the SBTi for the financial sector, and asked how similar strategies could be applied to corporations and communities. The participant also highlighted the challenge of coordinating these efforts to ensure efficiency on an international scale.

Spotlight 3:

A participant highlighted the need for broader international involvement in greenhouse gas removal efforts. They suggested that framing the issue as involving only the global south is inaccurate, as many significant economies outside the US, such as China, Australia, and the Middle East, are not developing countries. The participant emphasized the importance of including these diverse regions in the conversation to effectively scale greenhouse gas removal initiatives.

Spotlight 4:

A participant stressed the need for a roadmap to 2030, highlighting the 285 million tons target proposed by RMI as a game changer. They emphasized building strategies around this target, including aiming for 5 billion tons through pilot projects across land and ocean. Additionally, the group suggested providing a thousand checks of $100,000 each to start-ups as a way to close the gap and achieve these goals.

What is one big thing across the board that threatens the success of GHG removal efforts?

- Issues with MRV, including poor and mistrusted systems, oversimplifying MRV increasing uncertainties in risk and effectiveness, and the need for improved practices
- Lack of demand, weakening demand, no effective demand, and the absence of compliance markets
- Lack of commitment from various stakeholders and the challenge of matching demand to need
- High costs associated with solutions and lack of capital, impacting the ability to scale projects
- Political factors including the impact of Trump in office, political fatigue, volatility, and the role of OPEC
- Lack of public support, trust in solutions, and the absence of effective propaganda. NIMBYism, climate apathy, and the challenge of addressing moral hazard and overpromising
- Inefficient technology, lack of clean energy, and issues with leaky hydrogen.
- Potential for catastrophic project failure and the risks associated with net-zero disadoption
- Safety concerns, the prevalence of picking flashy technology over practical solutions, and the need for immediate project financing
- Apathy towards climate issues, north-south inequality, and the prevalence of armed conflicts deprioritizing climate action
- Lack of resources to scale projects, slow economic growth, and the differentiation between NPO and for-profit entities
- Lack of a clear business model, lack of 'switchability,' and the cost of avoided emissions
- Unrealistic or unfounded claims, lack of trust in solutions, and the presence of bad actors
- Opportunities for fraud, regulation issues, and the inability to regulate effectively
- Lack of political will, unwillingness to engage, and insufficient community expertise
- Finance and government messaging issues, including the challenge of who pays for climate initiatives
- Insufficient science and the need for science to be connected with business
- The survival of startups in the climate space and the urgency of addressing these issues before it is too late

Spotlight 1:

A participant highlighted the issue of insufficient clean energy to support greenhouse gas removal efforts. They emphasized the need to increase the deployment of clean energy projects to address the broader challenge of powering the electric grid, carbon dioxide removal technologies, and hydrogen production.

Spotlight 2:

A participant identified two main challenges: the lack of demand policies for CDR and the issue of long-term project bankability. They pointed out that CDR projects require long-term financial commitments, typically around 20 years, but current incentives like the 45Q tax credit only provide 12 years of support, leaving a gap that banks are hesitant to finance. The participant emphasized the need for comprehensive carbon pricing mechanisms, such as

cap-and-trade or carbon taxes, to ensure project viability. Additionally, they noted the challenge of community opposition, which can hinder the development of CDR infrastructure.

Spotlight 3:

A participant discussed the challenges associated with MRV. They suggested reframing the MRV challenge to focus not only on accuracy but also on reproducibility and identifying opportunities. For example, they proposed reframing nitrous oxide abatement efforts as air quality enhancement initiatives, highlighting the dual benefits of reducing greenhouse gases and improving air quality.

What is a common solution that may help in several areas?

- The need for significant financial investments, specifically $5B allocated for pilot funding by 2025, and leveraging opportunities for derisked investments linked to R&D to ensure a predictable pipeline of funds
- Emphasizing the importance of public support and acceptance, which is crucial for securing RD&D financing and further investment in CDR projects
- Highlighting the financial implications of climate damage (the counterfactual) as a critical factor in justifying investment in CDR technologies
- Strategies to gain public support and improve public sentiment toward CDR, including targeted communication and educational campaigns on platforms like TikTok and YouTube
- Establishing centers in each state to provide public and companies with the necessary expertise, data collection, and outreach to foster better understanding and support for CDR
- The need for a better-educated public on the specifics of CDR
- The necessity of clear governance structures and regulatory clarity, particularly concerning the role of Article 6.4 and the establishment of an international compliance market for CDR
- Inclusion of CDR in the international climate action political agenda, with initiatives and leadership from groups like G7/G20 to drive policy and action
- Development and implementation of multi-stakeholder standards that are applicable globally, and leveraging established bodies like the North American Carbon Program (NACP) and the National Academies of Sciences, Engineering, and Medicine (NASEM)
- Emphasizing the importance of transparency in data and research, particularly in developing carbon sensors and monitoring systems
- Conducting thorough research to identify potential environmental health hazards and risks associated with CDR technologies, ensuring safe and responsible implementation
- Focusing on technological advancements that can deliver immediate reductions in temperature, and grounding these innovations in robust scientific research
- Exploring the co-benefits of CDR technologies, such as producing valuable byproducts alongside carbon removal
- Promoting regenerative design practices in agriculture, mariculture, and aquaculture to enhance sustainability and carbon sequestration
- Innovative solutions like seawater farming and inland seawater evaporation lakes, specifically looking at locations like the Salton Sea, Quattara Depression, and Danakil Depression, to utilize seawater solutions for carbon removal
- The importance of establishing global carbon markets and a GHG monitoring, measurement, and information system that is specifically designed with GHG removal in mind

Spotlight 1:

A participant discussed the importance of strengthening and empowering past and existing efforts in CDR and GHGR. They emphasized the need for coordination and facilitation across science, technology, and policy domains. They highlighted the contributions of organizations like the National Academies, the NACP, and the Ocean Carbon & Biogeochemistry Program (OCB). The group stressed the importance of bridging the gap between scientists, carbon market participants, and finance professionals, advocating for transparency and inclusivity in the process to effectively scale GHGR solutions.

Spotlight 2:

A participant highlighted a crucial need across all sectors of CDR: addressing scientific questions related to the environmental health dimensions of each sector. They emphasized the importance of identifying these questions early in the development process, before scaling up, to ensure that potential solutions are well-informed. The participant advocated for providing guidance on best available control technologies to prevent unintended consequences.

Virtual Spotlight:

A representative from the virtual group raised concerns about the use of GWP as a metric. They noted that GWP has significant limitations, particularly in approaches that combine long-lived and short-lived potent greenhouse gases. They also emphasized that if the goal is to accurately assess climate impact, relying solely on GWP may not fully address the issue, potentially leading to a misunderstanding of the overall climate risk.

Virtual Plenary Session: Back to the Big Picture

During the "Back to the Big Picture" activity, the virtual breakout group revisited the key themes and discussions from the past two days. Using an interactive polling tool, participants were asked to reflect on and discuss three critical aspects: identifying synergies, recognizing conflicts, and determining top priorities moving forward

Synergies:

- The importance of iterative, purpose-built MRV systems and social engagement in ensuring the quality and credibility of CDR technologies, which in turn drives demand
- Greater collaboration across different CDR technologies to maximize effectiveness and scale
- The need for better coordination between MRV, policy guidance, and funding to support the growth of CDR
- The critical nature of robust policy frameworks and the current lack of depth in policy, which could inhibit the expansion of CDR technologies
- Synergies between different political processes at domestic, national, and international levels to create comprehensive policy support for CDR
- The necessity to scale markets for products that can store carbon removed via GHGR
- Encouraging the development of products that provide co-benefits, such as removing CO2 while adding value, to drive market demand and acceptance
- Understanding and managing social and ecological risks associated with GHGR technologies to build social license and public trust
- The importance of social participation in MRV to ensure community engagement and acceptance
- Recognizing the urgency of the situation

- Consensus on the need for action, focusing on the most promising first steps and achieving early wins through co-benefits
- The need for dedicated financing mechanisms, including synergies between voluntary carbon markets and compliance markets, to support the deployment and scaling of CDR
- The narrative around CDR options needs to be clearer, highlighting benefits such as job creation, tax revenues, and innovation
- Engaging diverse communities of interest, nations, and international communities to foster collaboration and shared goals in climate action.

Conflicts:

- The ongoing advancements in science and technology related to CDR and their associated socioecological impacts need more focus.
- There is a critical tension between the need for accurate and complete MRV systems and the urgency to make progress in carbon removals (tons in the ground/ocean)
- A conflict exists between stakeholders who want to deploy GHGR technologies ahead of governance and social ecological risk assessments and those advocating for safeguards in field trials and deployment
- The urgency of addressing climate issues clashes with the expectation of having perfect knowledge of the entire earth system
- Disparities exist between the timescales that investors operate on and the natural carbon cycle, with a noted lack of accountability for permanence in the voluntary market
- The need to define clear goals for carbon removals, such as how many gigatons should be removed by 2030
- Concerns about the oil and gas industry using technology to prolong the use of fossil fuels rather than transitioning away from them
- A significant gap exists between the need for immediate action on climate issues and the lack of sufficient incentives to motivate such action
- The tendency for many companies to seek out ‘cheap’ offsets rather than investing in more robust and potentially more costly solutions

Top Priorities:

- Expanding understanding of the need for GHGR
- Emphasizing the urgency of regulation immediately
- Early R&D investment from now to 2030, with a focus on building social license and governance for larger scale field trials by 2025
- Emphasizing the timescale from now to 2030 for critical actions, including funding MRV and demand
- Drawing in arts, humanities scholars, and artists to enrich the conversation around GHGR
- Support for pilot demonstrations of new technologies, including financing to deploy pilots to learn engineering and MRV from now to 2030
- Education of wealth owners to support these critical areas, establishing multi-stakeholder standards to build trust and legitimacy, and promoting fast failure with lesson sharing
- Identifying effective methods that will fully scale by 2040 and supporting early-stage company funding from now to 2030
- Investing in funding for lab to pilot phases, FOAK deployments, and TRLs 2-5

- Demonstrating measurable and visible climate-related success for the public, aimed for the period 2040-2050
- R&D funding to prove technology efficacy and conduct scale-up analysis, and moving research to the field as soon as possible
- Scaling and funding nature-based CDR projects to remove billions of tons of CO2 and create employment, targeting the world's largest project with 25 million+ jobs in Africa over the next 26 years
- Coordinating the scientific community to set standards for measurement and monitoring by 2030
- Establishing a price on carbon by 2030-2040 at the latest
- Planning for financial mechanisms from 2030-2040, including self-standing financing like carbon markets, to ensure steady demand and support for high-impact climate tech in emerging markets transitioning from lab to market

Mapping Out Short-Term Priorities

In the preceding 'Back to the Big Picture' session, participants looked to identify the needs across the entire ecosystem of solutions and the milestones to achieve scale by 2050. The highest priority items were the focus of the "Mapping Out Short-Term Priorities" portion of the plenary session, where in-person participants were grouped by table number to collaboratively develop key priorities and milestones, focusing on the actions and organizations needed to achieve these goals, but focusing on the timeline by 2030. This exercise encouraged each group to conduct a deep dive into specific milestones, identifying actions, stakeholders, and timelines essential for driving progress. Meanwhile, the virtual group had the opportunity to further explore and refine the key themes they had identified earlier in their discussions.

Plenary Session:

Spotlight 1:

Table 6 emphasized the importance of forming messaging coalitions across different CDR approaches (e.g., direct air capture, ocean-based, rock, and land). They highlighted the need for tailored messaging to address the unique challenges, pros, and cons of each approach. The urgency of raising awareness about CDR's potential was also stressed, with a call to involve organizations like the Data Coalition to coordinate these efforts. The table suggested leveraging the influence of Hollywood and artists to reach a wider audience and effectively communicate the critical role of scaling CDR.

Spotlight 2:

Table 4 focused on discussing potential sources of project funding for the next six years, to deploy CDR projects in various environments (specifically ocean, land, air and rock). Key players identified included XPRIZE, Microsoft, Stanford, RMI, Ocean Vision, International Biochar Initiative, and Cascade. The importance of moving beyond pilot projects was emphasized, with the goal of achieving 285 Mt/yr. by 2030. The table stressed the need for rapid innovation and growth, highlighting the role of MRV in validating projects and engaging communities and policymakers.

Spotlight 3:

Table 8 discussed the need for funding demonstration projects through sources like the DOE, CDC, and the UNFCCC's Clean Development Mechanism. They emphasized the importance of restructuring funding mechanisms to accelerate project timelines. Organizations such as NSF, NOAA, and Climate Solutions were noted for their roles in research and monitoring impacts. The table advocated for increased information sharing within the CDR community, suggesting that mandatory or anonymous data sharing could enhance collaboration and problem-solving.

Spotlight 4:

Table 10 focused on driving greater international collaboration and commitment to CDR solutions. They emphasized the importance of creating localized groups within countries to leverage their unique competitive advantages, using Kenya as an illustrative example. To facilitate broader engagement, the table proposed organizing international forums to involve key regions such as Kenya, India, and Latin America in the global CDR effort. In addition to these actions, the table advocated for aligning global priorities with CDR solutions from 2030 to 2040, particularly through collaboration with entities like the UNFCCC and the DOD. The discussion also touched on the development of international compliance markets by 2030 and the establishment of a technology transfer fund between 2030 and 2040, facilitated by international government agencies. They suggested drawing lessons from past successes, such as the efforts to address ozone depletion, and considered the potential role of international courts and polluter taxes in driving global compliance.

Spotlight 5:

Table 12 aimed to have a diverse basket of CDR technologies validated and ready for commercial scale by 2030. They emphasized the importance of establishing long-term demand signals that would begin to materialize post-2030. A key milestone identified by the group was securing pledges for 285 megatons of durable CDR by 2025, with these commitments being enforceable by 2027. By 2030, they projected that public and private buyers would need to procure at least 285 megatons of durable CDR, at an average cost of $200/ton of CO2, to stay on target. Additionally, the table highlighted the critical need to characterize global geological storage capacity by 2026. This mapping effort would inform deployment strategies and ensure the scalability of CDR technologies as they move towards commercial viability. The group also proposed offering 100 prizes of $100,000 each to organizations within the CDR sphere, followed by a $5 billion funding initiative to scale the most promising solutions.

Spotlight 6:

Table 14 identified the creation of corporate demand as a top priority, urging the Science-Based Targets initiative to include CDR targets for 2030. They emphasized the role of public support for net zero and Paris Goals, advocating for high-level marketing campaigns with trusted partners. Philanthropic organizations were mentioned as a key player in supporting these efforts to ensure CDR becomes a widespread policy action rather than a niche activity for Fortune 500 companies.

Spotlight 7:

Table 16 emphasized the need for a $100 billion carbon removal ecosystem by 2030, funded by both public and private capital. Drawing on DARPA's investment strategy, they suggested funding a diverse array of technologies to ensure a broad foundation for innovation. By 2035, they envisioned having 50 viable GHGR technologies, with a goal of scaling the 10 most promising ones by 2050, each capable of operating at a scale of 1 gigaton per year. The table also underscored the importance of establishing and formalizing carbon markets and MRV

systems by 2030, involving governments, academia, and the private sector. They highlighted the need for strategic communication, access to clean energy, and knowledge sharing as crucial elements in the journey to scale the industry to a $1 trillion per year operation by 2050. Lastly, the group prioritized securing funding to develop carbon markets, MRV systems, and fostering innovation through R&D as essential steps to bridge the gaps and meet scaling targets.

Spotlight 8:

Table 19 focused on addressing fundamental research gaps specific to different CDR pathways. They advocated for demonstrating the scalability of lab-scale solutions and collecting data through adaptive management strategies. The table emphasized the inclusion of diverse research institutions, such as HBCUs, community colleges, and minority serving institutions, with increased federal funding to support these efforts. They also highlighted the importance of engaging communities in the research and development process.

Spotlight 9:

Table 20 emphasized the need to deploy CDR pilot projects with a focus on inclusivity and global participation. They stressed the importance of understanding community benefits and the value proposition of CDR. The table highlighted the potential for public pushback and advocated for equity-focused messaging to gain public support and mitigate resistance. They underscored the importance of investing resources to understand the impacts and drive meaningful community engagement.

Virtual Session:

Technology and Innovation:

- The group discussed the need for a sectorial approach involving scientists studying climate tipping points and feedback loops to inform criteria for investment in climate technology. A form of prioritization for funding based on the latest climate science is crucial.
- There is a significant gap in expertise and funding in emerging markets for high-impact climate tech. This is especially true for the transitional phase from technology development to market deployment. Philanthropic investments typically focus on immediate impact rather than long-term translational work.
- One participant mentioned a startup working on methane measurement technology for the oil and gas industry but noted funding challenges. This highlights the domino effect where lack of funding inhibits the use of MRV tools.
- In the UK, the CO_2RE (Greenhouse Gas Removal Hub) coordinates GHGR research, predominantly CO_2 and methane, with a 35-million-pound program looking at whole systems understanding. However, this effort is UK-focused and lacks an international dimension.
- Suggestions were made for an international consortium or coalition, ideally situated in the global south, to coordinate efforts, share data, and support innovation globally. Organizations like Future Earth and the Belmont Forum could play a role in this.
- Carbon to the Sea was mentioned for funding initiatives in Europe and the US, including Dalhousie and Woods Hole Oceanographic Institution. The importance of involving both industry and researchers in projects like electrochemical release of alkalinity with desalination plants was emphasized.
- There is a need for more geochemists in both ocean and rock CDR projects. Current academic programs are not sufficiently engaging in CDR, indicating a gap in funding and cultural awareness.

- Drawing parallels to the International Renewable Energy Agency, it was suggested that an international body focused on GHGR could provide funding, facilitate policy exchange, and support global climate policies.

Coordination and Collaboration:

- Emphasis was placed on the importance of coordination between policymakers and technologists from the beginning. Complex contracting mechanisms and innovative financial models involving equity, debt, and philanthropic grants were highlighted.
- The role of incumbents with large-scale deployment expertise and infrastructure was mentioned as crucial for facilitating collaboration between startups and larger industries.
- The idea of public-private incubation programs was suggested. These programs would provide non-dilutive capital for scientifically validated technologies, enabling entrepreneurs to understand the impact of their technologies in larger systems and helping unlock new business models. Programs like the USDOC's Trail to Commerce and Impel were mentioned as examples.
- The importance of regional climate modeling for assessing the viability of CDR projects was mentioned. Public-private partnerships for data mining and display platforms were proposed to make this information publicly accessible.

Finance:

- The need for an international coalition or consortium to coordinate technology research and innovation alongside policy development was highlighted. This body should involve policymakers, scientists, engineers, geochemists, and other stakeholders.
- A parallel to the IRENA was drawn, suggesting that a similar international body for GHGR could provide funding, facilitate policy exchange, and support global climate policies. This would help answer key questions before 2030 in all parts of the world.
- Expertise in complex contracts and innovative financial models combining equity, debt, and philanthropy was identified as crucial for deploying first-of-a-kind CDR plants. Developing this expertise or bringing existing experts together was recommended.
- The involvement of large-scale incumbents with deployment expertise and infrastructure was suggested as a means to facilitate collaboration between startups and established industries.
- Public-private programs and incubation initiatives were recommended to provide non-dilutive capital for scientifically validated technologies. These programs would help entrepreneurs understand the impact of their technologies and create new business models.
- A demonstration platform in Washington, D.C. was proposed as a tangible site for showcasing various CDR technologies. This would require government backing, public-private partnerships, and potentially land donations.
- Focused research organizations or funding structures that bring together experts from different fields (e.g., cement, critical minerals, chemical engineering, geology, metallurgy) were suggested to streamline research on optimizing kinetics for geochemical approaches.

The Last Word

The "Last Word" activity marked the final session of the workshop, bringing together all participants—both in-person and virtual. In this closing exercise, each participant was asked to contribute a single word in response to the question, "What will it take to reach our 2050 goal?"

In One Word, What Will it Take to Reach our 2050 Goal?

Closing Remarks and Next Steps

Over the course of two days, the Strategy Workshop on Scaling Greenhouse Gas Removal gathered over 500 experts to explore and identify the critical knowledge gaps and actions required to achieve 10 Gt/y of removal by 2050. It outlined milestones for various technology-based GHGR removal methods, such as CDR (air, ocean, rock, and land) and methane and nitrous oxide removal, alongside the broader ecosystem required for scale, such as technological and scientific advancements, socio-behavioral impacts and community engagement, policy and regulatory frameworks, financial and market mechanisms, and MRV processes.During the workshop, participants convened to address the barriers, systems dependencies, unintended consequences, enablers, and open questions to scale. Additionally, participants laid the groundwork for new partnerships and funding opportunities, all aligned with a common goal.

The Bezos Earth Fund extends its deepest gratitude to the researchers, entrepreneurs, policymakers, funders, and all participants whose invaluable contributions shaped the discussions and key outcomes. Special thanks to the organizers, speakers, and facilitators who ensured a smooth and productive event.

The progress made here sets a promising path forward to achieving the ambitious but critical need to scale greenhouse gas removal to over gigaton level by 2050. The insights and strategies gathered during this workshop, built on work that has come before, provide a solid foundation for ongoing collaboration and progress. Thank you once again for your participation and unwavering commitment to this crucial endeavor.

Acknowledgements

We would like to thank our collaborators at U.S. Department of Energy and at Stanford University, as well as Bezos Earth Fund staff for their hard work and input in the development and execution of this workshop, including Darcie Martinson, Meghana Palepu, Marianne Fives, Claire Pfitzinger, Eda Lee, Rocío Lower, Dan Schoenfeld, Dave Burton, Brian Cimagala, Anna Hedlund and Erin Jones. Special thanks to Erik Ivester for all his contributions in drafting this summary report.

Appendix

Day 1 Breakout Session Full Response List

CDR Oceans

Question 1: Barriers and Roadblocks through 2050:

- Gaining social acceptance and public engagement (ocean justice, starting 2025)
- Addressing basic science knowledge gaps
- Ensuring sufficient demand for removals at scale by the 2030s and market demand (price, volume, long-term)
- Creating national policies, particularly in developing countries, to address technology skepticism and responsibility by 2030
- Obtaining licenses to operate and addressing permitting issues for R&D, finance, and overcoming technology hurdles
- Providing 100K checks for startups between 2025 and 2029
- Achieving shared understanding of costs and benefits
- Implementing model-based quantification for abiotic factors by 2030
- Navigating legal barriers (especially Marine Areas Beyond National Jurisdiction 'ABNJ')
- Gaining permitting clarity starting in 2025
- Bridging the time lag between scientific and policy communities
- Establishing robust and reliable MRV systems (certainty, confidence, consensus)
- Managing high costs compared to land-based options
- Addressing pH outfall limits in government permits
- Addressing public concern and narrative confusion, such as moral hazard and climate denial
- Maintaining a sustained sense of urgency in addressing climate change
- Managing the risk of widespread social rejection across technology classes due to poorly executed projects
- Managing the complexity of systems and the diversity of ocean environments
- Overcoming fear of change and inertia
- Demonstrating technology readiness levels ('TRLs') and proof of concept, and developing reliable autonomy technology
- Enhancing research coordination to accelerate the surfacing of learnings and establishing a robust research ecosystem by 2025
- Providing evidence on the duration of sequestration and overcoming life cycle assessment ('LCA') challenges to improve MRV and scaling efficiency
- Addressing issues with compensatory offset models to prevent double-counting and other critical incentive problems
- Securing funding for infrastructure scale-up and training a skilled labor force

Question 2: System Dependencies through 2050:

- Understanding and monitoring ocean circulation and natural nutrient supply
- Improving ocean modeling and addressing commercial market dynamics
- Ensuring skilled labor force availability and robust supply chains for materials and equipment
- Minimizing ecological impacts and consulting with communities (e.g., Indigenous first nations)
- Implementing marine spatial planning starting 2025 and developing coastal infrastructure (ports, etc.) by 2028

- Establishing fit-for-purpose permits and permitting for open ocean activities (immediate to 2030)
- Balancing market viability (profit vs. climate)
- Sourcing necessary materials (iron sulfate, alkalinity, ships, etc.)
- Balancing and prioritizing renewable energy allocation by 2035
- Increasing grid capacities and achieving GHG-free electricity
- Implementing low carbon processes and inputs by 2030
- Ensuring availability of resources such as renewable energy, rocks, and alkalinity
- Managing resources (e.g., minerals, land, nutrients, ocean open platforms) efficiently
- Addressing energy and resource competition alongside a growing population
- Developing better baseline data and improving data quality
- Establishing sensor calibration and standard
- Enhancing public engagement by 2025
- Ensuring responsible deployment of technologies by 2025
- Establishing robust regulation and compliance standards
- Formulating national and international policies and regulations by 2030
- Securing permits for field research by 2025
- Observing and utilizing the stimulation effects of seaweeds

Question 3: Risks or Unintended Consequences through 2050:

- Harm to regulatory and supporting ecosystem services
- Potential for wealth creation for CO_2 removers and new colonization (ocean grab by powerful entities)
- Public opposition and lawsuits (NIMBYism, Greenpeace-level opposition)
- Risk of environmental backlash and failure to scale mCDR
- Inaction (doing nothing) and lack of co-benefit design (ocean modification mitigation)
- Potential breakdown of existing marine governance systems and unintended consequences on positive impacts (fisheries, aquaculture, storm mitigation)
- Continued use of fossil fuels, as carbon removal makes continued emissions acceptable
- Early employees leaving the industry by 2029
- Burnout of a generation of founders by 2029
- Oceans left out of post-2030 plans
- Industry backlash due to onerous carbon prices by 2025
- Impacts on fisheries that hurt food security for vulnerable populations
- Rogue actors
- Irreversibility or destabilization of the Nitrogen/Carbon/Phosphorus/H_2O cycles
- Ecosystem interactions and biogenic feedback loops
- Effects on competing uses
- Potential negative impacts on marine ecosystems and local communities
- Social backlash
- Positive effects on fisheries, aquaculture, and storm mitigation

Question 4: Enablers and Game Changers through 2050:

- Creating global scale MRV sensors and modeling communities, and advanced chemical oceanographic sensors
- Implementing MRV rebates (including baseline measurement and continued monitoring) and securing funding at scale

- Establishing diverse project financing (venture, equity, corporate, grant/philanthropy, government procurement) by 2025
- Achieving public good funding for CDR by 2040 and UN international consensus
- Forming required agreements and leveraging strong and single nation actors
- Conducting pilots/test beds for CDR scenario parameterization and securing high seas permits
- Reaching international agreement on mCDR and compliance market and international MRV standards
- Building epistemic communities and integrating with existing infrastructure (desalination, coastal nuclear) by 2025
- Developing integrated policy for mCDR (understanding how by 2025, enacting by 2035) and securing long-term offtake agreements by 2025
- Alkalinity production at scale by 2030
- Risk financing to reduce project finance risk by 2028
- Delivering economic and social benefits to local communities
- Measuring carbon increases
- Certification methodologies
- Financing more research immediately
- Establishing a $5 billion project pilot fund by 2026
- Providing 1000x $100,000 checks for startups by 2024
- Lifting the "experimental only" cap on funding access
- Collaborating with coastal communities to co-design mCDR projects that provide meaningful co-benefits and align with their priorities
- Establishing a value for CO_2 removal
- Implementing a price on carbon production
- Ensuring data transparency and public science learning from field trials
- Reduce reliance on credit markets
- Coastal and Marine shipping and logistical infrastructure
- Establishing a capable workforce

Question 5: Open Questions and Uncertainties through 2050:

- Understanding the ocean biological carbon cycle, air-sea flux dynamics, and mixed layer to deep ocean transport
- Addressing ecological impacts of mCDR and nutrient robbing by 2028
- Improving the ability to forecast long-term impacts and iterating to scale safely and responsibly
- Getting answers before it is too late (feedback loops, runaway impacts) and evaluating cost-effectiveness for GHG removal
- Determining payment mechanisms for ocean or atmospheric CO_2 and verifying mCDR methods (additionality, durability)
- Understanding public perception of climate intervention and standardizing credit retirement across deployments
- Developing global policy/regulations for open ocean (2030 to 2040)
- Assessing public perception of climate intervention
- Standardizing credit retirement across deployments
- Evaluating the value proposition for investors
- Planning to grow 50% year over year to 2030
- Determining funding mechanisms

- Establishing international regulations
- Defining “residual” emissions
- Engaging stakeholders for project feedback, varying by project scale
- Ensuring equity and social acceptance by 2030
- Scaling up engagement and public deliberation
- Developing multilateral governance for the high seas
- Establishing demand mechanisms for mCDR
- Conducting risk analysis
- Understanding the efficacy of each approach
- Determining suitable MRV measurement and permanence certainty levels
- Assessing technological feasibility and maximum thresholds
- Verifying basic science underpinning the technologies
- Evaluating ecological impacts at different scales and locations
- Addressing inability to forecast long-term impacts and getting answers before feedback loops lead to runaway impacts
- Physical size dependency, resources, and space
- Scaling up public engagement and deliberation
- Ensuring transparency in public science learning and addressing greenwashing and mitigation deterrence issues
- Establishing a legal regime at international, domestic, and local levels
- Avoiding social rejection of mCDR and understanding community concerns and regulations on industry involvement

CDR Air

Question 1: Barriers and Roadblocks through 2050:

- Addressing high costs associated with DAC, including initial and ongoing expenses, by 2025
- Ensuring reliable and low-carbon energy sources to meet substantial energy needs of DAC urgently
- Preventing market fragmentation by 2030 to support cohesive CDR solutions with integrated policy and market strategies
- Shaping sufficient government market and establishing supportive policies by 2030
- Building a robust supply chain and infrastructure for DAC, including testing in diverse climates and geographies, within the next 10 years
- Overcoming public resistance, including NIMBY and NINBY (‘Not In Nobody's Back Yard’) sentiments, to facilitate project implementation
- Providing immediate availability of clean, continuous, and abundant renewable energy sources
- Increasing public awareness and education about DAC and its benefits compared to other CDR solutions by 2025
- Streamlining permitting processes for new DAC installations by 2030 to support timely deployment
- Coordinating market development and innovation to effectively integrate the capture, removal, and utilization of CO_2 by 2030
- Demonstrating durability and reliability of geologic storage and ensuring access to durable storage

- Clarifying liability frameworks and securing sufficient risk capital for early commercial companies
- Resolving technical challenges such as kinetics of desorption and feedstock availability
- Securing political tolerance for short and mid-run economic costs
- Establishing standardized CDR frameworks and financial backstops for startups
- Ensuring market viability and establishing a profitable price on carbon
- Early failure leads to derailing early efforts
- Implementing carbon-free energy procurement or methods for energy-intensive steps during periods of low-carbon power
- Ensuring availability of renewable energy and reducing costs by 2025
- Demonstrating the uniqueness and value of DAC compared to point source capture
- Addressing delays in early deployments and scaling down the CDR cost curve
- Developing a full market model for integrating capture, removal, and utilization
- Lowering the cost curve to $100/ton

Question 2: System Dependencies through 2050:

- Ensuring immediate availability of clean energy sources, including renewables and nuclear, with a focus on political will and valuing CO_2 removal
- Developing secure and scalable CO_2 storage solutions by 2025
- Establishing supportive policy and regulatory frameworks to enable DAC technologies, including streamlined permitting processes and necessary infrastructure development by 2030
- Building infrastructure such as CO_2 transport and storage systems to support large-scale DAC deployment by 2030, with emphasis on the role of developers, pricing, margin, and risk tolerance
- Securing political and economic will by 2025 through supportive policies, financial incentives, and addressing socio-political trade-offs and pluralism
- Developing proper market and trading mechanisms, including insurance tools and clear standards for CO_2 trading by 2030
- Engaging stakeholders effectively to build support and understanding for DAC and CDR initiatives by 2025
- Fostering global cooperation and governance to support the successful implementation and scaling of DAC technologies
- Ensuring availability of sustainable feedstocks and low-carbon energy sources for DAC operations, with systems in place by 2030
- Accelerating the permitting process and creating a supportive regulatory environment for DAC for timely project implementation by 2030
- Connecting human capital with existing sectors
- Ensuring location, environment, and social justice considerations in DAC projects (who benefits from investment, jobs, etc.)
- Developing power interconnects pipelines
- Ensuring availability of cheap carbon neutral energy

Question 3: Risks or Unintended Consequences through 2050:[24]

- Moral hazard concerns, where reliance on DAC might reduce the urgency for broader decarbonization efforts, continuing fossil fuel use
- Technological and market skepticism, with potential failures in scaling DAC technologies leading to market distrust and stalling further development
- Risks of ecological damage and negative health impacts, including increased air pollution and potential harm to human health from DAC operations
- The possibility of early catastrophic project failures could undermine public trust and support for DAC technologies, requiring risk management strategies by 2025
- Political partisanship and opposition could create inconsistent policy support and hinder DAC initiatives, emphasizing the need for non-partisan backing
- Market consolidation among large emitters could stifle competition and innovation
- Fracturing of climate strategy coalitions due to conflicting interests and priorities
- Increased infrastructure and energy demands could lead to higher environmental and economic costs, requiring comprehensive planning and investment by 2030
- Lack of public buy-in and perception of DAC as a "false solution" could limit acceptance and support for DAC projects
- Prolonged or permanent decrease in ambition and pressure to reduce GHG emissions
- Technological lock-in of sub-optimal technologies
- Over-focus on future energy access versus near-term progress on initial deployments
- Failure of Office of Clean Energy Demonstrations/Bipartisan Infrastructure Law projects poisoning the well for future efforts
- Revitalization of fossil fuel companies, prolonging reliance on fossil fuels
- Risks of CO_2 leakage and NIMBYism
- Inability to mobilize society quickly enough, leading to slow progress
- Long-term viability and risk management concerns, including potential liability and reversals of CO_2 storage

Question 4: Enablers and Game Changers through 2050:

- Large-scale government procurement of CDR for hard-to-abate industries, with initial testing in the 2020s and scaling in the 2030s, including support for clean energy buildout and technological breakthroughs like nuclear fusion, and ensuring project bankability
- Technological innovation breakthroughs in thermodynamics, heat/energy efficiency, membrane efficiency, and low-heat materials for DAC to improve efficiency and scalability
- Development of robust markets for CDR products with specific financial mechanisms like off-take markets, government purchasing of CDR credits/products, and support for technologies with co-benefits across multiple sectors (e.g., water quality, soil nutrients)
- Supportive policies for early deployment of DAC technologies with clear regulatory guidelines, including state-level policies and international guidelines under Article 6.2 and 6.4 for CDR trading
- Increased involvement of public and philanthropic entities in funding DAC initiatives, with specific procurement processes and financial support for pilot projects by 2025

[24] *Responses from Group 1 regarding Question 3 (Risks or Unintended Consequences through 2050) were not collected during the workshop.*

- Development of necessary infrastructure for CO_2-storage and transport with government-backed risk management and specific insurance mechanisms for storage durability
- Effective community engagement processes to build support for DAC projects and ensure public buy-in
- Innovation in CO_2-based products to create additional market value, with specific strategies for market creation and product innovation
- Achieving significant cost reductions through economies of scale and technological improvements, targeting $100 per ton CO_2 storage with detailed strategies for cost reduction
- Establishing long-term demand signals and stable carbon pricing mechanisms, with specific policies for carbon taxes and price stability
- Proactive and ongoing collaboration across the emerging ecosystem for DAC, with detailed plans for engagement and collaboration
- Increased investment in DAC technologies and infrastructure, highlighting specific investment strategies
- Development of scalable, affordable firm clean power solutions to support DAC operations
- Innovation of more efficient electric furnace technologies to improve DAC processes
- High participation and involvement of the cement industry in DAC initiatives
- Establishment of a test center network by 2025 to support early-stage development and scaling of DAC technologies
- Formulation of residual emissions policies by 2030 to guide long-term planning and compliance
- Implementation of Country Carbon Border Adjustment Mechanism ('CBAM') policies to support international carbon trading and regulation
- Emphasizing storage durability warranty and insurance mechanisms for long-term CO_2 storage reliability
- Securing more strings-attached funding for early DAC companies as soon as possible
- Implementing strategies to reduce capital expenditure
- Developing CO_2/H_2O selectivity technologies by 2035
- Ensuring material and process recyclability for DAC technologies by 2035
- Advancing membrane technology for efficient CO_2 extraction
- Addressing potential infrastructure shortfalls for DAC deployment and expansion

Question 5: Open Questions and Uncertainties through 2050:

- Evaluating the competitiveness of DAC relative to other CDR technologies in terms of cost and scalability
- Understanding the long-term economic impacts and viability of DAC, including potential market demand and cost reduction strategies
- Strategies for managing public perception by 2025 and securing support for DAC to ensure sustained public buy-in
- Ensuring reliable energy production, siting, delivery, and scaling markets for needed inputs and feedstocks (e.g. amines, proton-exchange membranes for electrochemical DAC)
- Addressing the substantial energy and resource demands of DAC to ensure reliable supply and sustainability
- Developing clear regulatory frameworks to support the deployment and integration of DAC technologies

- Ensuring continuous funding and support for the development and innovation of DAC technologies, with an emphasis on financing models
- Evaluating the environmental impacts and safety of DAC projects to ensure minimal negative effects
- Exploring the long-term viability and market demand for DAC technologies within the broader context of CDR solutions
- Understanding the role of DAC within the broader climate strategy and how it integrates with other CDR solutions
- Need for global cooperation and governance to effectively scale DAC and manage associated risks
- Addressing specific challenges such as energy supply, land use competition, and regulatory frameworks to support the scale-up of DAC by 2030
- Assessing the potential for DAC to carve out market share relative to other emerging CDR technologies and evaluating long-term competitiveness
- Who pays and how? How secure and permanent is storage? How to be resilient through potential near-term setbacks and failures
- Creating efficiencies through a systems approach
- Exploring the feasibility and implications of siting DAC offshore
- Focusing on low-hanging fruits and technology enablers such as ethanol plants
- Addressing feedbacks via physical and technical cycles
- Establishing regulatory frameworks to incentivize demand for DAC
- Improving Class VI well permitting speed to accelerate deployment
- Determining the "take off" point of market maturity for commercialization
- Evaluating the implications of uncertainty and liability for reversals of CO_2 storage

CDR Rock

Question 1: Barriers and Roadblocks through 2050:

- Lack of clear regulatory frameworks and standards/protocols for markets, with a focus on establishing regulations and compliance mechanisms immediately and by 2030
- Energy requirements and the availability of workforce and equipment
- Project financing and capital limitations, coupled with high costs of MRV and proprietary data holding back science and trust
- Permitting challenges and structures needed to support applications
- Availability of minerals at the necessary scale and timeline to open new mines
- Buyer demand for certainty and investor understanding
- Slow reactivity of abundant rocks
- Public confusion, lack of awareness, and opposition, necessitating sufficient social and community engagement to allow scaling by 2040
- Soil interaction issues and frameworks for evaluating impact on natural resources, soil, and air
- Mine valorization challenges and historical mine tailings issues
- Availability of drilling equipment and workforce, combined with slow adaptation rates in the mining and agricultural industries
- Public support and buy-in
- Farmers' reluctance to adopt enhanced rock weathering (‘ERW’) and inertia in ERW uptake
- Limited government awareness and understanding

- Mismatch between the best rocks and leading academic labs
- The need for fast funding for non-consensus approaches
- Feasibility of co-product generation, such as critical metal recovery, by 2035
- ERW's lag time between credits asked and delivered
- Overemphasis on per-ton crediting as the primary form of finance by 2024
- Geological specificity needs to be built before scaling is possible and must happen by 2025
- Market signals sufficient for project finance by 2030-2035

Question 2: System Dependencies through 2050:

- Growth of the mining industry as a significant opportunity
- Benefits for farming and agriculture
- Policies with a four-year duration
- Knowledge opacity regarding mining operations
- Government access to rocks and experimental sites
- Ownership of material and interaction with the food system
- Location considerations, including where to crush, deploy, and source materials
- Competing uses of rocks
- Enthusiasm for rock resources
- Co-location of storage and renewable energy sources
- Development policies integrated with energy development policy in the global south by 2035, considering ERW's potential in these regions
- Insurance for financing providers
- Availability of a trained workforce along the supply chain
- Federal agency coordination and multi-sectoral cooperation

Question 3: Risks or Unintended Consequences through 2050:

- Perverse incentives for mining and backlash against significant involvement of large mining companies
- Job creation, skills development, and labor practices in mining
- Runaway carbonation effects and hazardous runoffs
- Risk of contaminating food sources, including dust and toxic dust issues, and potential alkalinization of drinking water
- Social acceptability and misalignment between community expectations and delivered benefits by 2035
- Environmental impact of mining, including impacts on water quality, increased river alkalinity, and emissions
- Need for well-characterized impact on soil and human health by 2029
- Underestimated project costs by 2035
- Displacement of better soil health practices due to financial incentives for selling credits
- Exacerbation of injustice in the global south (neo-colonialism, eco-colonialism)
- Cannibalization of supply chains
- Delays in deployment, leading to failure in meeting removal expectations
- Rocks causing the stabilization of soil organic carbon, releasing more CO_2 than removed
- Weathering dates falling short of investor confidence
- Misspent resources
- Bad incentives from voluntary carbon markets affecting CDR

Question 4: Enablers and Game Changers through 2050:

- Insetting opportunities
- Creating an open-source global soil atlas and providing research funding credits
- Co-funding unit economics and resource recovery, such as low-concentration nickel tailings
- Development of better and cheaper sensors and models for MRV, including advanced models using computing and machine learning
- Integration with regenerative agriculture practices and benefits from farm policies
- Requiring companies to buy back the CO_2 they emitted over the next 30 years and providing tax incentives for corporate buyers
- Early success stories to boost public acceptance and establishment of free power test pilot labs
- Technology-driven positive narratives
- Development of standards and standardization of fit-for-purpose MRV across jurisdictions
- Permitting improvements and strong community engagement infrastructure for CDR-Rock by 2029
- Environmental impact assessments in various ecosystems and energy star-like MRV/LCA to create a gold standard and de-risk CDR value
- Co-benefits and co-product generation that reduce reliance on carbon pricing
- New policy signals for pilots and demonstrations
- Systematized approach to community engagement and engagement of the global south
- Advances in public data and transparency, including space monitoring
- Mapping of co-benefits and geographic application

Question 5: Open Questions and Uncertainties through 2050:

- Conditioning new permits on performing CDR with tailings
- Social acceptability and community engagement standards
- Transportation challenges for suitable rocks not located near farms or coasts
- Suitability of paradigms beyond compensation for ERW
- Commodity markets for minerals and metals
- Impact on human health from small particles
- Transformation of soil from a carbon sink to a carbon source
- Stakeholder buy-in from farmers and mining companies
- Economic opportunities in developing countries
- Risk of scaling ideas and missing significant opportunities
- Availability of on-site power
- Low-carbon energy supply needed for rock-based approaches
- Additionality on a LCA basis versus the build rate of zero-carbon energy production over time
- Systemic public outreach and education
- Availability and established supply chains for minerals, including rock waste streams
- Risk of losing momentum after the first gigaton of CO_2 removal
- Participation of the mining sector and resource extraction
- Accurate resource and reserve assessments by 2027
- Community reception and involvement in large-scale deployment
- Geopolitical implications
- Scale of deployment impacts on the earth system beyond carbon removal

- Practical considerations for land use, soil type, sensor and lab capacity, infrastructure, and agriculture
- Political responses from community, province, and nation-state levels to scale-up efforts by 2040

CDR Land

Question 1: Barriers and Roadblocks through 2050:

- Ensuring the permanence of carbon removal processes by 2030
- Addressing carbon durability and permanence in soils and biomass
- Gathering data and develop methods to measure the durability and permanence of carbon storage
- Implementing system-level accounting for carbon cycle impacts at the project level
- Managing competition for land and resources, particularly by 2040
- Ensuring availability and productivity of biomass for CDR
- Securing access to sustainable feedstock and biomass supplies
- Achieving Operational Scalability of Advanced Technologies ('OSAT') for CDR in the US by 2030, targeting 1 to 2 Gt of CO_2 removal by 2050
- Mitigating risks associated with technological innovations in CDR
- Identifying and optimize the best uses of biomass for carbon removal
- Evaluating the sufficiency of land to support both population needs and land-based CDR
- Developing models to understand and manage the impacts of land use changes on CDR
- Establishing a framework for the best use of biomass
- Reducing the costs of pyrolysis technologies by 2030
- Communicating non-climate benefits of CDR to relevant stakeholders
- Ensuring an adequate and reliable supply of feedstock and biomass
- Setting benchmarks for carbon yield per unit area by 2035
- Developing benchmark solutions for land-based carbon sequestration by 2030
- Implementing effective storage solutions for biochar by 2030
- Establishing clear criteria for evaluating the effectiveness of CDR approaches
- Creating market incentives for landowners to participate in CDR by 2030
- Providing clear policy guidance to support CDR activities
- Developing financing mechanisms for CDR projects that lack established markets
- Establishing a global market for land-based CDR services by 2030, in line with Article 6 of the Paris Agreement
- Resolving the food versus fuel competition by 2035
- Managing competing demands for land resources by 2030
- Addressing conflicts between CDR and wildfire/forest management
- Balancing trade-offs between forestry, food security, and public perception
- Clarifying definitions for what constitutes biomass for CDR
- Addressing uncertainty and skepticism about the durability of carbon sequestration
- Overcoming challenges in site selection and community acceptance for CDR projects
- Taking immediate action to increase carbon retention time in soils and improve soil microbiome health
- Addressing competition for "waste biomass" between CDR and other applications
- Managing over-allocation of biomass resources

- Securing concessional capital to move quickly, at scale, and provide back-stop financing to bridge the valley of death
- Establishing incentives or regulations for CDR by 2040
- Mitigating disincentives from SBTi and other voluntary regulators for the purchase of CDR
- Valuing biomass for its carbon content more than for the electrons it can produce by 2030
- Conducting full LCAs for crops with long production time frames, like forestry
- Shifting land use from corn-ethanol to more ecologically beneficial crops by 2035
- Developing a track and trace system for certified biomass waste by 2035
- Addressing supply constraints and logistics for biomass by 2030-2040
- Ensuring availability of skilled workers for CDR projects
- Encouraging corporate insetting practices for CDR
- Securing funding and accelerating the development of infrastructure for CDR projects

Question 2: System Dependencies through 2050:

- Policy support for CDR and efficient MRV
- Workforce requirements for biomass transport and processing
- Sufficient carbon storage capacity and transition to a zero/low carbon grid by 2030
- Business case development for CDR, farmer and societal acceptance, and clear narratives for public and stakeholder engagement
- Regulation of carbon markets by 2028 and policy frameworks for alternative biomass uses
- Research on soil microbiome and plant interactions and systemic dependencies on agriculture
- CO_2 transport and injection infrastructure including permitted, trusted, and available CO_2 reservoirs
- Clean and cheap energy availability and transmission infrastructure for CDR facilities
- Supply chain optimization for biomass, including distribution and location for harvest and processing
- Competition for subsidized crops like wheat, corn, and adjustments for systemic dependencies to incorporate agricultural CDR applications
- Water rights
- Transportation logistics for biomass feedstock
- Finite sustainable biomass supply by 2030-2040 and how it interacts with agriculture business models, financing, and generational land use
- Equipment manufacture and deployment for large-scale pyrolizers
- Dependencies on system-wide impacts including the interplay between small-scale and large-scale biomass processing
- Acceptance of gene-edited CRISPR crops by 2040
- Developing low carbon collection and transport systems for biomass
- Implementing necessary land use changes to support CDR
- Preventing greenwashing by ensuring companies do not reclassify existing waste as CDR
- Balancing food and textile production with waste and purpose-grown biomass
- Class UI permits for true negative emissions by 2030
- Farmer and societal acceptance, incentives, and benefits for CDR
- Workforce and manufacturing availability for CDR projects

- Advancing R&D to address the reversal of CO_2 storage by 2030
- Safeguards in markets to prevent undesired consequences of CDR

Question 3: Risks or Unintended Consequences through 2050:

- Policy incentives failing to support biomass solutions and increasing CO_2 emissions from ecosystems
- Resource competition between CDR and food production, and risks of carbon storage reversal
- Poor public acceptance of genetically modified crops and CO_2 storage infrastructure
- Market distortions affecting land, food, and biomaterials, and potential job losses due to land use shifts
- Land consolidation exacerbating rural poverty, and risks of large-scale ecological impacts
- Re-releases of stored CO_2 or methane from biomass-based CDR and disruptions in bio-product markets
- Public opinion turning against CDR, competition with food production, and profitability issues in deforestation for biomass
- Overharvesting and unsustainable biomass practices leading to deforestation
- Local environmental impacts, including soil degradation and resource allocation conflicts for biomass
- Unexpected CO_2, Methane ('CH_4') re-releases
- Indirect land use change
- Risks of creating invasive species
- Potential catastrophic incidents undermining sector support, like large-scale consolidation of land and bio product market disruptions
- Adverse events slowing progress, including land grabs by investors speculating on carbon farming and large-scale ecological disasters
- Risks of poor project implementation and ineffective technological solutions
- Corporate greed and bad players in the CDR market
- Focusing on maximizing chances of success rather than merely optimizing net-zero pathways
- Incentivizing myopic activities that increase the flow of CO_2 from living ecosystems to the atmosphere
- The elimination of biodiversity
- Mitigating risks from poor implementation that could undermine support for CDR
- Ensuring food security
- Regulatory risks for gene-edited crops and microbes
- Disruptions to ecosystems and habitats caused by engineered plants and microbes
- Societal acceptance of gene-edited crops and microbes
- Monitoring and managing land use shifts due to CDR
- Preventing harmful agricultural, forestry, and cultivation practices for biomass production
- Assessing the impact of waste biomass sourcing on soil carbon and biodiversity
- Avoiding investments in CDR strategies without long-term demand or workforce readiness to prevent stranded projects and sunk costs
- Ensuring that funding does not deviate from important but expensive CDR solutions like DAC

Question 4: Enablers and Game Changers through 2050:

- Potential of fusion energy for large-scale CDR and establishing a carbon tax or market
- Prototyping and scaling CDR projects through public-private R&D partnerships
- Innovations in biological systems such as engineering plants for better CO_2 retention and reduced fertilizer use by 2030
- Building coalitions with farmers and landowners by 2030 to integrate CDR into agricultural practices
- Developing robust hydrogen markets for carbon capture and storage ('CCS'), deploying small-scale biomass processing systems, and ensuring low-cost CO_2 transport solutions
- Consistent policy support at state and federal levels for long-term CDR success
- Financial incentives for soil carbon sequestration, and advances in synthetic biology for CO_2, CH_4, and N_2O removal
- Global regulatory approval for gene-edited organisms by 2027 to support CDR innovations
- Effective biomass supply chain tracing, integration of CDR credits into compliance markets, and utilizing degraded land to minimize leakage by 2027
- Consistent policy signals
- Low-cost CO_2 transport and injection
- Advances in photosynthetic efficiency
- Tangible voluntary carbon markets
- Addressing land opportunity costs for CDR conversion, and ensuring land-based CDR is cost-effective and beneficial for multiple stakeholders
- Potential for specific regional solutions like using graded land for biomass sourcing and developing standards for biomass waste
- Emphasizing environmental co-benefits of CDR projects
- Highlighting biomass carbon removal and storage ('BiCRS') for emissions reduction and realizing multiple goals with the same biomass
- Stressing the importance of gene editing and the U.S. Department of Agriculture's ('USDA') non-regulation of genetically engineered plants
- Developing enhanced cultivars that can grow in inhospitable climates and conditions
- Shifting the economy towards a "carbon management economy" and investing in early R&D
- Facilitating cross-skilling of agricultural and mining workers
- Implementing policy and regulatory shifts, leveraging renewable fuel standards, and providing debt-free financing or long-term procurement commitments
- Recognizing the role of agriculture companies in CDR now
- Ensuring supply chain tracing for biomass, addressed by 2030 to 2040
- Encouraging growers by highlighting new revenue streams and land improvement benefits
- Addressing the challenges of inexperience and long operation times in biomass processing
- Promoting investor stewardship policies
- Encouraging philanthropic debt to support CDR initiatives
- Mobilizing natural science research funding and public engagement with science
- Launching education campaigns to overcome anti-biomass views
- Implementing farm subsidies and a new USDA Conservation Reserve Program by 2029
- Seizing opportunities in renegotiating new LCFS in California by 2024

- Addressing Bureau of Land Management ('BLM') issues by 2030
- Realizing economies of scale for BiCRS through shared data and mass manufacturing for small-scale biomass conversion and carbon capture facilities
- Moving beyond funding CDR activities through compensatory offsets and market mechanisms
- Managing land use effectively for CDR projects
- Improving crops, fields, climate resilience, and conversion efficiency
- Recognizing desertification in rich countries as a negative stimulus that may force action
- Innovating to enhance farmer profits by making carbon more valuable than bioenergy on existing crops
- Creating near-zero input carbon crops
- Engineering microbes or plant/microbe interactions to increase carbon, weathering, yields, and decrease farmer inputs
- Developing better models for carbon in agricultural soils
- Demonstrating a "killer app" land CDR project that is profitable as soon as possible

Question 5: Open Questions and Uncertainties through 2050:

- Comprehensive life cycle assessments for CDR
- Establishing pathways to gigaton-level carbon removals
- Establishing MRV standards for land-based CDR and assessing the impact of climate change on carbon retention
- Balancing biomass extraction and ecosystem regeneration, and exploring co-benefits and trade-offs of land CDR
- Long-term demand and viability of carbon credits
- Public acceptance of new climate technologies
- Determining best practices for biomass use, addressing food system needs under climate constraints, and exploring regional implications of CDR
- Reducing leakage risks in biomass CDR, ensuring viability of co-locating biomass production with BECCS by 2027, and addressing regional disparities in CDR implementation
- Potential ecological impacts of large-scale CDR projects
- Demand projections for carbon removals
- The role of government versus private sector in CDR adoption
- The future role of bioenergy, evaluating the long-term effectiveness of engineering solutions, and ensuring appropriate biomass harvest rates by region
- Understanding systemic impacts on food, feed, and fiber sectors and developing guardrails to capture land opportunity costs in CDR development
- Clarity on if an increase in stable soil carbon is possible, reproducible, and scalable
- Specifically addressing the balance between biomass extraction and ecosystem regeneration
- Discussing scenarios for co-benefits in land CDR
- Assessing the need for 100 years of durability by 2027
- Exploring systems-level impacts for food, feed, and fiber under climate change
- Guardrails to protect development and avoid unintended consequences
- Clarifying what biomass-based CDR entails
- Evaluating the feasibility and scalability of engineering solutions
- Scaling of soil carbon MRV by 2030

- Establishing standards and frameworks for BECCS
- Determining if there is enough waste biomass to scale or if more purpose-grown crops are needed
- Assessing land availability to support both population needs and land CDR
- Modeling indirect land use changes
- Determining the highest value use case for biomass in a supply-constrained future, emphasizing the 2030-2040 timeline
- Understanding competitive uses for biomass and the differing opinions within DOE
- Evaluating the impact of climate change on the efficacy of land CDR
- Addressing the value transfer from the Global North to the Global South
- Simplifying technologies for storing biomass carbon and addressing inexperience
- Understanding the impact of climate change on biomass productivity and species resilience
- Assessing the effectiveness and measurability of ERW for CDR
- Establishing appropriate biomass harvest and removal rates for different regions
- Determining the deployment rate needed to reach climate goals
- Clarifying the best use of biomass
- Addressing food system needs specifically
- Reducing leakage risks in biomass CDR
- Emphasizing the timeline for collocating purpose-grown sustainable biomass with BECCS by 2027
- Establishing MRV for open systems, especially ERW and biochar
- Understanding the capacities biotech brings to speeding and scaling land CDR

Methane and Nitrous Oxide Removal

Question 1: Barriers and Roadblocks through 2050:

- Addressing the lack of demand for CDR technologies
- Clarifying market potential and overcoming investment limits by 2050
- Building awareness and creating a clear narrative for CDR benefits
- Improving economic validation of climate impact over time
- Managing political perceptions of atmospheric methane removal ('AMR') from methane mitigation by the 2030s
- Building field awareness and securing research funding by 2025
- Enhancing scientific understanding and technical maturity for CDR
- Improving understanding of sources and sinks for CDR
- Focusing on pre-commercial fundamental R&D to be overcome by 2030
- Addressing energy demand challenges for processing large volumes of air to mitigate CH_4
- Securing social license for open system interventions within 15-20 years
- Addressing regulatory barriers from the London Convention and London Protocol by 2040
- Developing infrastructure and creative deployment solutions to scale CDR from 2030 to 2050
- Addressing cost barriers for CDR technologies
- Countering the mitigation deterrence narrative
- Filling non- CO_2 science gaps and advancing nascent gas sorption technologies

- Considering timescale-dependent impacts, such as global warming potential ('GWP') 25 vs. GWP100
- Exploring innovation and cost-reduction for mass transfer limits
- Achieving technical breakthroughs for viability and scalability within 10 years
- Finding solutions for treating or concentrating dilute CH_4/N_2O streams
- Overcoming activation energy limitations for CH_4 oxidation as soon as possible
- Building deeper system understanding of open system applications
- Developing oxidation catalysts that do not require energy input by 2030
- Creating cohesion on how to value CH_4/N_2O, with a clear value proposition by 2025-2030
- Avoiding the imposition of unrealistically high standards on new technologies
- Scaling methods operating at times 2 ppm by 2035 and large-scale deployment by 2040
- Addressing significant ongoing releases, production, and leakage contributing to mitigation needs urgently
- Considering the dependence of N_2O on fertilized global food security
- Facilitating the engineering of methanotrophs and methane monooxygenases ('MMO') as soon as possible
- Integrating CH_4/N_2O approaches with CDR without overlooking the unique aspects of each gas
- Overcoming the influence of incumbent fossil energy players sooner rather than later
- Conducting trade-off assessments, payback time calculations, and socio/environmental impact assessments immediately
- Improving measurement and attributability over the next ten years
- Addressing the mindset that roadblock thinking is itself a roadblock and overcoming it early in the development of this new industry

Question 2: System Dependencies through 2050:

- Dependencies on low-carbon energy sources and the need for infrastructure to support the deployment of CDR technologies
- Integration with agricultural systems, carbon removal infrastructure, and processes expected by 2030
- Interaction with regulatory systems, including the need for policies to support technologies like iron salt aerosols and bioengineered microbes
- Funding structures for innovation and regulatory frameworks
- Demand for co-benefits such as air quality improvements and biomass
- Development of partnerships between direct air capture and storage companies
- Dependencies on the mining and agricultural sectors, with potential benefits for these industries
- System-level understanding of the evolving global methane budget and its sources and sinks
- Need for policies to support the scale-up of transportation infrastructure and supply chains, including decarbonizing transportation systems by 2040
- Dependencies on catalyst inputs and air quality co-benefits, requiring coordination among various sectors and policies
- Lock-in mechanisms like carbon markets and direct government actions
- Establishing market-based incentives for CDR technologies
- Understanding the interactions with solar radiation management (SRM) and atmospheric oxidation enhancement methods as soon as possible

- Addressing the challenges posed by growing energy and food demand
- Implementing a system configuration approach to MRV
- Ensuring viable incentivization and commercialization pathways for appropriate CDR approaches
- Tracking N_2O and CH_4 emissions from biological wastewater treatment by 2030
- Developing massive infrastructure (e.g. ships for deployment, energy to operate) that also serves other societal purposes
- Facilitating methane/N_2O removal with CDR technologies (e.g. iron for AMR and CDR Ocean) as soon as possible
- Creating durable, cheap, high-resolution gas and aqueous sensors as soon as possible
- Understanding the intersection of CDR with food, crops, and livestock by 2050
- Funding regulatory deals to support CDR technologies
- Addressing dependencies on biofuels and fertilizers, particularly regarding N_2O
- Developing the ability to move air for some CDR pathways
- Investigating the effect of hydrogen on methane lifetime

Question 3: Risks or Unintended Consequences through 2050:

- Risks of over-reliance on technological solutions, which might not be feasible outside models or labs.
- Social license and public perception challenges associated with open system interventions and large-scale deployment.
- Difficulties in regulating startups with low barriers to entry, potentially leading to unchecked and risky deployments.
- Potential for economic incentives to drive harmful or ill-advised deployments, creating moral hazards.
- Mitigation deterrence and competition among different GHGs for removal technologies.
- Environmental impacts of mining and unintended consequences like increased river alkalinity or ecosystem disruption.
- Concerns about health impacts from dust and toxic substances, including potential risks to food and water quality.
- Misalignment between community expectations and the actual benefits delivered, with significant risks to social acceptability by 2035.
- Financial risks related to underestimating project costs and failing to meet removal targets.
- Need for thorough assessments of technical approaches to avoid feedbacks that deplete ozone or increase other GHGs.
- Risks of social and environmental injustices, particularly in the global south, and the need for equitable solutions.
- Effects of environmental and scenario-specific conditions on CH_4/N_2O lifetimes and chemical reaction mechanisms
- Risk of abuse of fields for emissions reduction deterrence
- Ensuring accurate accounting of CH_4/N_2O sources and mitigation efforts by 2025
- Bio-systems designed to solve CH_4 issues that might cause N_2O problems
- Ecological impacts of geoengineering projects
- Selectivity bias in supporting solutions as soon as possible
- Ensuring that CO_2 is not ignored while focusing on CH_4 and N_2O mitigation
- Implementing comprehensive life cycle impact assessments, including payback time and net benefits

- MRV uncertainty regarding mitigation efficacy
- Uncertainty in iron salt aerosol effectiveness for methane removal as soon as possible
- Technical approach-specific Earth system risks, particularly for open-system interventions
- Conducting thorough assessments of effectiveness and risks by 2030
- Mitigating air pollution, ozone layer impacts, and addressing environmental justice issues immediately

Question 4: Enablers and Game Changers through 2050:

- Bridging solutions to open systems and nature-based interventions, including geo-engineering approaches
- Development of methane sorbents and atmospheric radical stimulation technologies
- Breakthroughs in CH_4 mitigation and integration with carbon removal systems for cost and energy efficiencies
- Co-benefits of improved air quality and the financial market, supporting a shift in perceptions and policy acknowledgment
- Significant coordinated R&D efforts within the next five years and development of standards for fit-for-purpose MRV
- Establishment of a sufficient carbon price and social license to operate, recognizing CDR as a public good
- Early success stories and policy signals for pilots and demonstrations to boost public acceptance and engagement
- Standardization of MRV across jurisdictions and creation of better and cheaper sensors/models for monitoring
- Systematized approach to community engagement and the need for infrastructure and policy support for large-scale deployment
- Funding and market incentives to support the development and scaling of removal technologies, including integration with regenerative agriculture
- Recognition of CDR as a critical part of climate strategy, necessitating significant investment and policy support by 2030
- Ensuring high spatiotemporal resolution sensors to monitor all reactive nitrogen species in water, air, and soil
- Developing catalysts that don't require massive perturbations of atmospheric oxidation capacity by 2035
- Achieving scientific acceptance of the need for exploration in CDR
- Finding effective ways to concentrate CH_4 from open wetlands/oceans and convert it by 2040
- Appending treatment to DAC to ensure a net positive impact on climate and infrastructure
- Enhancing solutions to treat 2-10ppm cost-effectively by 2030-2035
- Focusing on the development of scalable technology
- Achieving technical breakthroughs to advance CDR technologies
- Providing regulatory support for GHGR (CH_4, NO2, etc.)
- Developing technology to decrease \$/CH_4 or \$/N_2O, or to decrease uncertainty
- Implementing low-cost heat recovery methods
- Ensuring actual demand for the technology beyond researcher support
- Developing markets and providing pull-side funding (advance market commitments 'AMC', prizes, etc.) to drive CDR adoption

Question 5: Open Questions and Uncertainties through 2050:

- Lack of a clear methane market and challenges in defining equivalence and fungibility of different GHGs.
- Need for detailed understanding of the costs, scalability, and impacts of large-scale deployment.
- Questions about who will decide the implementation of geoengineering and the associated liabilities.
- Risks of moral hazard and mitigation deterrence, with interactions between different forms of climate response.
- Challenges in scaling technologies to achieve significant reductions in GHGs and the need for comprehensive stakeholder buy-in.
- Understanding the impacts of CH_4 removal on air quality and broader environmental benefits or costs.
- Need for improved earth system modeling to assess the long-term impacts and benefits of removal technologies.
- Ensuring basic research to support the development and deployment of CH_4/N_2O removal technologies
- Defining what "feasible" means in the context of CH_4/N_2O removal
- Addressing the challenges posed by fugitive emissions in the hydrogen economy
- Assessing the relevance of CH_4 removal as a function of CO_2 removal scale
- Evaluating the feasibility of different approaches, including engineering closed systems and understanding the full radiative forcing, LCA, and ecosystem services impacts of open systems
- Developing regional deployment decision-making pathways for larger-scale open-system approaches
- Improving the understanding of natural methane sources and evolving sinks
- Determining the optimal scale for (de)centralization efforts in CH_4/N_2O removal vs. current production
- Optimizing synergies between various technological solutions for GHG removal
- Addressing challenges and synergies for combined CO_2, CH_4, and N_2O removal
- Establishing appropriate field-testing pathways within the next five years
- Understanding the relative roles of CH_4/N_2O conversion vs. separation
- Investigating the ecological impacts of CH_4/N_2O removal technologies as soon as possible, with a target of 2030

Day 2 Breakout Session Full Response List

Science and Technology

Question 1: Barriers and Roadblocks through 2050:

- Insufficient data availability and sharing for early R&D in methane and nitrous oxide
- Disincentives and lack of platforms to facilitate data exchange
- Innovators often don't know the critical problems to address
- No uniform reporting standards or venues such as test centers, Techno-Economic Analysis (‘TEA’) and LCA
- Lack of awareness among students about GHGR fields, and insufficient educational resources for climate-focused careers
- Silos in research and data among teams and commercial entities
- Stovepiping in research application and deployment

- Lack of specialization and commercialization in carbon project development and tech/R&D
- Absence of uniform reporting standards and venues for sharing critical data such as test centers, TEA, and LCA
- Need to improve unreliable analyses to inform R&D better
- Significant disincentives to share data
- Lack of platforms to facilitate data exchange
- Early R&D for methane and nitrous oxide slowed by lack of data availability and sharing
- Connecting physico-chemical mechanisms to carbon transformations and tracking is complex
- Rapid commercialization of the CDR space limits pre-commercial innovation
- Need for support in prototyping and the 'science of scale-up'
- Lack of coordination across government, academia, and industry at national and international levels, particularly in the next five years
- Insufficient support at the state level
- Missing shared key performance indicators and milestones to determine the scale and timing of technology deployment, entities such as philanthropies could have a role in funding and advancing high-risk, high-reward research.
- Limited awareness of methane removal in scientific communities
- Lack of dedicated funding for novel research focused on climate solutions
- 'Valleys of death' prevent early-stage technologies from scaling
- High energy requirements for capture systems, especially for dilute sources like DAC
- Under-valuation of biological CDR opportunities
- Need for clear stakeholder assumptions and understanding complexities and uncertainties in predicting technology success
- Challenges in connecting fundamental R&D funding to applied research
- Limited specialization and commercialization in the field
- Ensuring a systems focus in research and implementation
- Connecting characterization studies to the regional availability of resources for GHGR
- Utilizing data from test centers to improve research outcomes and share findings
- Addressing challenges faced by would-be innovators in identifying the most important problems to address
- Emphasizing the need for sufficient workforce numbers and addressing competition
- Enhancing state-level support for robust regional backing
- Addressing complexities related to direct/indirect land-use change, leakage, and other consequential LCA concepts
- Clarifying total environmental cost (LCA) and addressing uncertainties
- Increasing collaboration on SAT with large private sector companies to leverage scale and resources
- Improving public acceptance of novel technologies and facilities
- Incorporating supply chain considerations in the design of CDR technologies
- Creating industry pull mechanisms similar to those in big pharmaceutical companies to support startups
- Overcoming real or perceived socio-political or technical risks hindering funding for biotech R&D
- Securing funding by 2030 to support long-term climate initiatives
- Addressing the high costs of engineered CDR solutions
- Clarifying what "scale" means in the context of CDR

- Overcoming regulatory barriers for marine alkalinization
- Establishing clear financial mechanisms for valuing CH_4 removal
- Improving energy efficiency of CDR technologies
- Developing robust materials and systems for long-term viability
- Addressing cost-related issues in materials and energy
- Ensuring broad policy support for comprehensive climate action

Question 2: System Dependencies through 2050:

- Competition for energy, feedstocks, and the need for integration with natural systems like plants, crops, soil microbiomes, and biodiversity
- Dependencies on the extractive and mining industry for resources and integration of CDR into broader systems, including adaptation strategies and co-benefits
- The fragility of systems and the need for robust supply chains, transport, and storage infrastructure to predict market needs
- Importance of clean energy and transport systems, and integration with renewable energy, especially for ocean-based CDR
- Dependencies on low-GHG and affordable energy, and macroeconomic factors like availability of capital
- Workforce development and public support to advance technologies and integrate them into existing systems
- Financial markets need to advance up the TRLs to support scaling of solutions
- Integration of earth system measurement networks and better modeling to understand impacts of CDR
- Policies need to support CDR across different types
- Understanding environmental effects of CDR
- Ensuring reliable mineral supply chains
- Addressing water and water rights issues
- Securing science funding to support CDR research
- Developing infrastructure to transport materials (feedstock & products)
- Ensuring availability of low-cost carbon neutral energy
- Utilizing machine learning for sorbent/catalyst material discovery, developed over the next several years
- Considering secondary GHG effects (e.g. H_2)
- Establishing clear international regulatory standards for interventions
- Coupling between approaches to impact their effectiveness as soon as possible

Question 3: Risks or Unintended Consequences through 2050:

- Risk of scaling incorrect technologies due to pressure to move fast without sufficient data
- Resource inefficiency and environmental perturbations from large-scale CDR implementations
- Low barriers to entry allow single actors to prematurely scale technologies, potentially causing harm to the industry and environment
- Stability and availability of government funding across administrations to support R&D projects
- Poor understanding of earth system limits and the scalability of interventions, potentially leading to overcrediting of removals due to inadequate MRV
- Potential public health and environmental hazards from process byproducts and shifts in ecosystem services

- Foreseen GHG releases and changing oxidative capacity in the atmosphere due to interventions like hydrogen leakage
- Failed trials undermining public and political support for CDR technologies
- Overreliance on a few technologies may lead to suboptimal outcomes and missed opportunities for diverse solutions
- Framing CDR and bioeconomy efforts narrowly, potentially diverting attention from actual decarbonization efforts
- Geologic CCS stimulates methanogenesis
- Ecological and planetary health impacts
- Carbon blinders causing loss of sight of other ecosystem goals and goods
- Achieving net zero does not equal full-scale removal
- Atmospheric (air) CDR induces ocean release of CO_2
- Unexpected environmental, ecological, and human health impacts
- Tech deployment not being net negative due to uncertainties in modeling and poor MRV
- Focusing on a singular solution
- Advancing a technology that isn't scalable (TEA, LCA)
- Tech developed without considering risks to communities

Question 4: Enablers and Game Changers through 2050:

- Long-term policy support for carbon removal
- Government and philanthropic funding for large-scale, coordinated atmospheric methane research
- Clear MRV baselines for oceans and land with effective tools and models for measurement and verification
- Land efficiency and innovation opportunities, including integration with renewable energy systems
- Bridging industry and research to address high TRL questions and foster collaboration
- Public demand by 2040 and promoting debate about the positive and negative effects of CDR and GHG removal strategies
- Support for workforce development with a comprehensive understanding of CDR technologies and their implications
- Developing benefit and society-focused applications rather than just carbon markets, such as food production, increased soil fertility, increased yields, and new revenue streams for farmers
- Ensuring as many demonstrations as possible to mitigate risks against failure
- Utilizing predictive analyses to inform R&D progress and next steps
- Advancing genetic engineering to optimize CO_2 uptake, including the ability to stack multiple genes or traits in carbon capture crops and biomass
- Integrating mine tailings CDR with the battery industry
- Combining marine CDR with desalination efforts for synergistic benefits
- Encouraging subdisciplinary research to explore niche areas and innovative solutions
- Creating centers that bridge technology, policy, and community frameworks to advance CDR technologies
- Matching intellectual property with founders to expedite the commercialization of new technologies
- Focusing on GHG removal strategies that grow alongside other clean tech industries
- Developing scalable, low-cost, selective, and durable materials for carbon capture
- Creating systems that can remove multiple GHGs by 2040

- Developing robust local ocean models specific to CDR applications
- Facilitating collaboration to unblock academia and deliver specific, implementable R&D for industry, and fostering ambitious cross-sector coalitions
- Redirecting fossil fuel subsidies to fund CDR research, technology development, and deployment
- Increased use of CRISPR and other gene-editing technologies to enhance soil and plant carbon storage
- Enabling successful science and technology that scales up biomass feedstock for biochar and BECCS
- Establishing international research and data-sharing systems, including with geopolitical adversaries like China
- Creating an easy-to-use database of emissions impacts for different kinds of biomass
- Establishing a large, sustained fund (e.g., $500 million) for procurement to stimulate demand without distorting the market
- Shared and collaborative research gaps and needs to guide new researchers and optimize resource allocation
- Funding demonstrable subscale projects in the near-term to de-risk policy and prepare "shovel-ready" projects when opportunities arise
- Scaling microbial soil carbon sequestration, with clear MRV for soil carbon as a precursor
- Achieving biological breakthroughs in engineering for plant and soil carbon storage, and enhancing weathering processes

Question 5: Open Questions and Uncertainties through 2050:

- Uncertainty on if $100/ton is a reasonable target for carbon removal costs, and if pre-commercial science and technology can explore paths to $100/ton
- How to balance cost and permanence in carbon removal technologies and assess market viability, establishing methodologies to value different removal technologies and manage uncertainty in the marketplace
- Ensuring sufficient and sustained funding to support CDR research and deployment, including quantifying the amount of fundamental US applied research necessary and how to deploy capital across different TRLs and types of solutions to build a portfolio of approaches
- Understanding what policies and incentives are needed to support scalable CDR solutions and ensure societal willingness to pay for these technologies
- How to create a strategic patchwork of approaches to manage energy and resource demands effectively
- How to prevent lock-in of suboptimal technologies and ensure a dynamic and adaptive policy framework
- How to ensure the integration of CDR into broader climate strategies, considering potential social license and pushback even during R&D phases and understanding how the climate responds to GHGR and the implications for CDR strategies
- How to prioritize locations for piloting, demonstrating, and scaling technologies to maximize impact
- How to enable near-term community-scale projects that inform and de-risk policy decisions for larger-scale implementations
- The need for comprehensive MRV across different methods and how it will evolve by 2026
- How to foster social consensus and build broad support for scalable CDR technologies

- Identifying if a focus on permanence is holding us back from solving the issue, and if we should prioritize shorter-term solutions
- Securing political will and commitment to drive long-term support for CDR initiatives
- Assessing the impact of new CO_2 equivalency metrics like GWP on GHG accounting
- Exploring the feasibility of statistically engineering the biology of the carbon cycle
- Evaluating the impacts of the H_2 economy on CH_4 levels, including fugitive hydrogen
- Determining the extent and potential growth of the H_2 economy and its implications for GHG management
- Encouraging cross-disciplinary research to understand interactions between deployed CDR interventions
- Adopting a top-down approach to identify scalable solutions and guide resource allocation
- Determining the optimal timing for stakeholder engagement to maximize impact and support
- Clarifying roles and responsibilities for selecting approaches, allocating funding, and conducting outreach
- Evaluating the availability of patient capital to support long-term CDR projects
- Developing strategies to scale while maintaining open sharing of scientific and technological barriers to further innovation
- Creating a culture that celebrates failure and encourages learning and adaptation within the industry
- Defining appropriate test durations to ensure robust evaluation of CDR technologies
- Deciding whether to evaluate feasibility and scalability of early-stage technologies (e.g., CH_4 N_2O) before committing to research, development, and deployment ('RD&D') or using RD&D to identify realistic options
- Assessing the potential for rock land retention of CO_2 and its effectiveness as a CDR strategy
- Ensuring that equity, environmental, and energy justice considerations are integrated into CDR development to maintain social acceptance
- Considering the acceptance of durability of less than 100 years in the near term to allow currently affordable CDR approaches to scale
- Identifying the timing and methods for scaling up rapidly, selecting the most promising technologies, and mobilizing community support
- Understanding the role of basic and low TRL fundamental research in advancing GHGR technologies
- Evaluating the geopolitical impacts on supporting technology development and scaling of CDR solutions
- Assessing material lifetime recyclability to ensure sustainability of CDR technologies
- Determining appropriate scaling factors to optimize the deployment of CDR technologies across different regions and conditions

Socio-Behavioral and Communities

Question 1: Barriers and Roadblocks through 2050:

- Emphasizing the importance of community engagement, ensuring project developers have the necessary skills, demonstrating clear benefits for communities, and avoiding overpromising and underdelivering to build trust.
- Ensuring shared acceptance and understanding within communities by 2030

- Addressing misinformation and providing clear, trusted educational materials about CDR.
- Navigating political and industry pushback, particularly from the oil and gas sector, and addressing concerns about profit motives over public good
- Managing partisan politics to ensure consistent support for CDR initiatives
- Tackling income inequality and CO_2 infrastructure NIMBYism by increasing awareness, education, and trust.
- Addressing community disinterest in long-term CDR activities and securing early buy-in.
- Combating entrenched innumeracy and asymmetric information between firms and communities
- Promoting a shared language and understanding of CDR concepts among stakeholders and clarifying differences and benefits between CCS and CDR
- Human bias towards present and near-term issues, making it difficult to gain support for long-term projects
- Real and recent history of industry-driven ecosystem and social harm
- Issues of local pain for global gain and moral hazard concerns, where CDR might be seen as conflicting with emission reduction efforts
- Colonialism and its impact on trust and acceptance
- Failed democratic systems and limited access to resources
- Lack of workforce skilled in CDR technologies and community engagement
- Unclear permitting processes and lack of policy enforcement hindering CDR projects
- Limited uptake of CDR practices by farmers by 2030
- Mitigation deterrence concerns by 2028 affecting the adoption of CDR
- Community sentiment around climate change influencing acceptance of CDR
- An overly domestic or Global North lens limiting the inclusivity of CDR strategies
- Lack of focus on capacity building for communities to engage with CDR initiatives
- Proof of environmental accountability and robust MRV systems
- Language and framing of “roadblocks” hindering progress in CDR discussions
- Spatial use conflicts arising from competing land uses for CDR
- Lack of funding for engagement and social science, which hinders effective community interaction and buy-in
- Dominance of private sector leadership in the CDR field, potentially skewing priorities towards profit over public good
- Limited shared acceptance and understanding within and between communities and stakeholders

Question 2: System Dependencies through 2050:

- Safe operating thresholds and standards, akin to an "Food and Drug Administration (‘FDA’)" for CDR
- Infrastructure requirements, including CO_2 transport systems and integration with renewable energy sources
- Supportive policy regimes and consistent funding streams
- Clear boundaries of downstream CDR activity and frameworks for community engagement
- International frameworks like Article 6 of the Paris Agreement for global carbon trading
- Building and scaling a well-paid CDR workforce and ensuring public and social license for CDR projects

- Acceptance of alternative business and economic models to support deployment
- Changing media landscapes and how information will be shared and received in the future
- Care and support for climate action framed broadly to ensure inclusive and equitable approaches
- Wealth inequality, workforce development, and trust systems for MRV
- MRV compatibilities for accounting and environmental impacts, ensuring comprehensive and reliable measurement, reporting, and verification systems
- Private financing and availability of patient capital in a world focused on decarbonization and resilience needs
- Severity of climate impacts and integration of these considerations into system dependencies
- Robust permitting and regulatory environments, ensuring the resilience of policy regimes and the presence of good faith actors
- Understanding and communicating the value proposition of CDR, highlighting its economic and environmental benefits
- De-politicization of climate change and making it a bipartisan issue to ensure broad and sustained support
- Understanding of land and resource use by communities to align CDR initiatives with local needs and priorities
- Acceptance of CDR land use by demonstrating its benefits and addressing concerns
- Consistent funding streams and financial models that support long-term CDR projects
- Public and social license for CDR projects through transparent and inclusive engagement strategies
- Independent groups to represent and educate communities about CDR, building trust and support
- Broad framing of climate action to garner widespread support and address equity issues
- Well-paid, skilled workforce to support the scaling and implementation of CDR technologies
- Adaptation to changes in the media landscape and evolving methods for sharing and receiving information about CDR

Question 3: Risks or Unintended Consequences through 2050:

- Community backlash and loss of trust if a CDR project fails or causes harm
- Community price distortion, where CDR activities affect local resources like feedstocks, water, and land
- Community distrust due to overpromising and underdelivering on benefits
- Insufficient acceleration of RD&D, leading to CDR being seen as a failure
- Risks of moving too fast or too slow in deploying CDR, with potential for polarization and loss of bipartisan support
- Risks of CDR being captured in partisan politics and becoming a contentious issue.
- Potential negative environmental impacts, such as CO_2 migration into water tables or unintended harm to ecosystems
- Health impacts from CDR byproducts and unknown local environmental consequences
- CDR activities leading to land dispossession and impacts on local communities
- Concerns about higher bars for climate-related industries, leading to demonization and social backlash against viable CDR ideas
- Risks of CDR being seen as a “fig leaf” for the fossil fuel industry

- Global impacts "downstream" from CDR activity, affecting ecosystems and communities beyond the immediate area of deployment
- Risks of losing democracy while achieving GHG removal, with concerns about centralization of power and decision-making
- Entrenching current power dynamics or making them more inequitable through forced international development and sustained power imbalances
- Continuing colonial or imperialist knowledge-sharing practices with the global south, potentially perpetuating existing inequalities
- Entrenched injustices from climate colonialism and further entrenching existing social and economic disparities
- Profit motivation potentially leading to suboptimal CDR activities that prioritize financial returns over environmental and social benefits
- Community concerns sensationalized in the press, potentially leading to misinformation and heightened public opposition
- Need to make choices between CDR and other environmental or social harms, balancing trade-offs to ensure holistic benefits

Question 4: Enablers and Game Changers through 2050:

- Tangible "poster child" projects that deliver real non- CO_2 benefits and demonstrate successful CDR implementations
- Co-development of CDR projects with environmental justice communities and normalizing research co-development with local communities
- Establishing codes of conduct for research, business, and policy to ensure ethical and responsible CDR deployment
- Government funding for climate and energy engagement to support broad public acceptance
- Developing government standards and procurement processes that prioritize responsible and impact-free CDR
- Developing ultra-cheap CO_2 sensors and utilizing machine learning and artificial intelligence for cost reduction in CDR
- Creating high-quality job opportunities to attract local support and validate the benefits of CDR
- Encouraging the emergence of carbon "unicorns" or significant industry players that can lead the way in demonstrating successful CDR technologies
- Developing frameworks for community decision-making and reducing misinformation by communicating factually correct information through trusted community channels
- Promoting financial flow to low- and middle-income countries and marginalized communities to realize an equitable distribution of benefits
- A real and functioning feedback loop system on a regional level
- Public sequestration authority focusing on public good, health, and safety
- Independent community facilitation funding by the federal government for state and local activities with no control over the message
- Shared set of community-led goals for CDR projects
- Community-led case studies with exemplary processes
- Reframing concepts of ownership to include public or co-op models
- Open sourcing private data to enhance transparency
- Equitable carbon tax and cap-and-trade policies
- Making high-emitters pay for CDR
- Ability to tax the wealthy to support CDR initiatives

- Outlining clear resource and social benefits directly to the community from CDR
- New commercial permits predicated on community engagement
- Identifying non-GHG benefits of more CDR methods
- Research-friendly permit and regulatory landscape
- Political support for CDR initiatives
- Globalized fungible markets for CDR
- Making CDR impact-free
- Building a social science "bench" of CDR experts
- Creating a "DAC community permanent fund" for community benefits

Question 5: Open Questions and Uncertainties through 2050:

- How to prove, demonstrate, and validate that there are no harms from CDR
- What are the local costs and benefits of CDR, including environmental, economic, and social impacts
- How to develop a shared set of values and a common language around community engagement and CDR benefits
- How to design CDR projects that align with community needs and ensure genuine engagement by 2025
- How to manage the uncertainty in government stances on CDR, technology timing, and community benefits
- What is the role of the oil and gas industry in CDR, and should we design projects with their involvement
- How to shift from project developer-led, superficial engagement to meaningful community participation and consent
- How to manage inevitable failures in CDR projects and ensure lessons are learned and shared
- How to define successful CDR projects in the near term, and what will work at scale
- What role social science research will play in understanding and guiding CDR implementation
- How to address the evolving media ecosystem and ensure accurate communication and engagement around CDR
- How to ensure that CDR efforts do not entrench existing power dynamics or create new inequities
- Ecosystem and social feedback loops
- Whether the GHG removal industry can work for both the climate and people
- Labor protections for a large-scale GHG removal industry
- Ensuring genuine community engagement and trust
- Funding and structures for CDR implementation
- Who will pay for CDR and what are the equity impacts
- Building the CDR field and fostering community acceptance
- Whether capitalism is the right system for addressing CDR challenges

Policy and Regulatory

Question 1: Barriers and Roadblocks through 2050:

- Lack of clarity on Article 6 of the Paris Agreement, which is crucial for international carbon market frameworks

- Permitting systems, including the London Convention and London Protocol, are complex and create bottlenecks
- Uncertainty over the durability of existing policies and lack of a clear vision for long-term demand and climate benefits
- Insufficient demand leads to low political will, hindering progress
- Lack of bipartisan champions for CDR technologies in the US, reducing political momentum
- Need for high-quality projects that gain public acceptance and provide community benefits such as jobs and local development
- Insufficient coalitions and a lack of clear statements of national interest in CDR
- Moral hazard concerns, where CDR is perceived as conflicting with emission reduction efforts, necessitating clear rules to avoid undermining these efforts
- Lack of knowledge and public acceptance of CDR technologies, which hampers policy support
- Absence of a policy conflict resolution mechanism by 2030 to address potential issues and conflicts in policy implementation
- Lack of clear country-level obligation allocation for CDR efforts

Question 2: System Dependencies through 2050:

- The evolving nature of climate targets, requiring policies to adapt and stay relevant
- Need for industrial policies that integrate CDR as a key component of climate strategy
- Dependencies on voluntary carbon standards, which require urgent fixes to ensure they effectively support removal credits
- Workforce development critical for the deployment and operation of CDR technologies
- Twin targets: aligning reduction credits with removal credits to ensure comprehensive climate strategies
- Dependencies on the macro environment, including availability of capital, project deployment, and political will influenced by economic and environmental conditions
- Evolving climate targets requiring adaptive and relevant policies

Question 3: Risks or Unintended Consequences through 2050:

- Risk of technology lock-in, where early adoption of specific technologies could hinder future advancements and innovations
- Discontinuity in policy and regulatory frameworks, leading to gaps and misalignments between short-term and long-term CDR goals
- Risk of social license issues, where public opposition to CDR projects could undermine progress
- Potential backlash from the oil and gas sector, which could resist changes that threaten their business models
- Concerns about greenwashing, where false claims of environmental benefits could destroy demand for genuine CDR solutions
- Overreaction to a CDR failure could lead to negative perceptions and reduced support for future projects
- Financial risks related to the costs of implementing CDR, with questions about who will fund the required $0.5 trillion annually
- VCMs being undercut by other demand drivers, leading to market instability

Question 4: Enablers and Game Changers through 2050:

- Government procurement and tax incentives to drive demand

- Development of compliance markets and price support mechanisms to provide financial stability
- Implementation of compliance obligations at both country and industry levels to ensure widespread adoption of CDR practices
- Streamlined infrastructure permitting processes
- Co-location with existing industries to leverage existing infrastructure and reduce costs
- Incorporation of removals into Nationally Determined Contributions ('NDCs')
- Multilateral cooperation and coordination to harmonize CDR standards and facilitate global trade in carbon credits
- Clear rules for accounting for international trading under Article 6
- Bottom-up roadmaps on a country-by-country basis to guide implementation
- Risk insurance to protect investments
- Harmonized standards to ensure consistency and reliability
- Right-sized and aligned CDR strategies to fit policy goals, manage expectations, and establish clear progress milestones
- Mainstreaming CDR with Environmental NGOs
- Public education and support to build awareness and acceptance
- Ongoing engagement to assess the acceptability of CDR techniques and locations
- Abundant renewable energy to power CDR technologies

Question 5: Open Questions and Uncertainties through 2050:

- Role of the United Nations Framework Convention on Climate Change ('UNFCCC') and other international bodies in guiding CDR policy and practice
- Fragmentation of standards and the need for a unified approach to support large-scale adoption of CDR
- Policies to support CDR and expected returns from such investments
- Societal willingness to pay for CDR and the demand for such technologies
- Determining the right entry points for technology acceleration, waste management, co-benefits, job creation, and national security
- Understanding local, national, and international coordination needs
- Impact of inflation and interest rates on the viability of CDR projects
- How to model and facilitate municipal transitions at a regional level by 2030
- How integrated assessment models ('IAMs') may be overly optimistic about reducing emissions, potentially downplaying the need for CDR

Finance and Markets

Question 1: Barriers and Roadblocks through 2050:

- Unreliable demand and insufficient voluntary buyers to bridge the gap to policy-driven markets; immediate need for reliable demand and compliance markets
- Uncertain willingness of the US government and other major countries to enact policies that drive significant demand for CDR
- Limited capacity of the corporate sector to purchase high-priced carbon credits, raising sustainability concerns; determining when and at what level this capacity will top out
- Lack of fast and substantial R&D funding, with concerns over a flat or declining US budget impacting RD&D; need for $1 billion pilot project funding by 2030
- High upfront costs for pilot projects and the need for 5% ROI to attract private investment

- Limited funding for enabling technologies that do not have clear removal streams but are crucial for the broader carbon removal ecosystem
- Challenges in permitting and regulatory uncertainty slowing down project development; need for better permitting processes
- Lack of clear benefits and incentives for key stakeholders
- Low likelihood of comprehensive regulatory measures being enacted to drive demand for carbon removal
- Need for better guidance on scope 3 emissions and addressing non-carbon policy barriers
- Concerns about the competitive disadvantage of carbon removal compared to other climate interventions like SRM
- Institutional investor awareness by 2030 and guidance on pre-purchasing carbon credits by 2025

Question 2: System Dependencies through 2050:

- Geopolitical stability and public support are crucial for maintaining a stable market environment for carbon removal
- Dependence on clean energy and sufficient carbon transport and storage infrastructure by 2030 to support the scaling of carbon removal technologies
- Importance of clear market signals and consistent regulatory frameworks to drive investment and demand
- Permitting reform needed to facilitate project financing and development, with true industry standards required by 2024-2026
- Need for compliance markets and dedicated sensors to monitor and verify carbon removal efforts effectively
- Dependencies on government policies that incentivize carbon removal and integrate it into broader climate action plans
- Access to renewable energy and the role of energy contract language in supporting carbon removal in place of natural gas; need for renewables for clean energy grids immediately
- Integration of carbon removal into existing climate policies and ensuring it is not treated as a separate entity
- Importance of bipartisan support for sustainable long-term policy frameworks
- Dependencies on workforce development by 2030-2040 and financial incentives to ensure viability and scalability of carbon removal projects
- Voluntary standards mandating carbon removal purchasing by 2023 and clarifying insetting accounting frameworks

Question 3: Risks or Unintended Consequences through 2050:

- Risk of early price collapse or failure of initial wave of projects leading to loss of trust and a scandal in the carbon removal market
- Potential for double counting of carbon removals and poor policy decisions that could undermine the credibility of carbon removal efforts
- Concerns over sustainability of carbon removal costs and the potential for early technology lock-in before sufficient MRV is completed
- Risk of failing to meet market expectations for actual carbon removal costs, necessitating bridging funding and creating financial instability; risk of collapse if goals not met by 2030

- Lack of demand policy and political support, leading to a failure to deliver meaningful carbon removal outcomes by 2030
- Risk of selecting the wrong technologies or locking in low standards, which could hinder long-term effectiveness and scalability
- Risk of negative outcomes for natural systems, such as unsustainable biomass sourcing and ecosystem disruption
- Trust issues in MRV systems and political blowback due to rising energy and commodity prices
- Media perception issues and conflicts with environmental groups that could impede carbon removal efforts
- Use of inappropriate financial structures for early-stage technologies, replicating historical patterns of capital flow and leading to inefficiencies
- Tragedy of the commons and rent-seeking behaviors, potentially leading to windfall profits and limiting the CDR portfolio
- Companies walking away from climate commitments

Question 4: Enablers and Game Changers through 2050:

- 1000x checks of $100k for start-ups by 2025 to foster innovation and support early-stage companies
- Successful delivery of carbon removal projects with local benefits and a trusted, accurate record of these deliveries (effective registry)
- Active participation of the global south in the carbon removal supply chain by 2030, transforming the international political economy of CDR
- Integration of carbon removal into existing climate policies and infrastructure (building codes, agricultural food procurement) to ensure it is not treated as an isolated effort
- Payments for practices to incentivize sustainable carbon removal practices and ensure long-term commitment from stakeholders
- Development of a robust compliance market and effective state/regional policies to demonstrate and scale carbon removal strategies
- Significant R&D funding by 2024 to drive innovation and successful demonstrations of CDR technologies
- Creation of innovative financial instruments, such as concession debt and FOAK finance, and risk mitigation tools to support large-scale projects
- Legislation for rigorous, simple, and practical carbon accounting by 2025, with robust and trusted MRV quality assurance
- A coherent climate strategy encompassing carbon removal, nature-based solutions, and emissions reductions, supported by trusted quality assurance systems
- Integrated sectoral decarbonization and removal roadmaps, including insetting and creating a public mindset shift that GHGR is a public good
- Breakthroughs in MRV technologies and the creation of integrated sensor systems to enhance data accuracy and transparency

Question 5: Open Questions and Uncertainties through 2050:

- Uncertainty about the health of the global market and the long-term demand for carbon removal
- Questions about the business model for carbon removal and the reasons for buying carbon credits now
- Challenges in ensuring the success of initial carbon removal projects and achieving ambitious targets like 285 million tons per year by 2030

- Concerns about whether patchwork demand will be sufficient and the need for higher-level unification in policy and market strategies
- Uncertainties about the value proposition for investors and the level of global Gross Domestic Product ('GDP') that carbon removal will consume by mid-century
- Uncertainty about the political will and ability to put demand policies in place, especially in the US
- Questions about the durability of the voluntary carbon market and the need to invest significantly to stay on track for climate goals
- Impact of political cycles, such as US elections, on the stability and support for carbon removal markets
- Availability of workforce to scale up carbon removal technologies and meet ambitious targets
- Specific investment levels required today to ensure we stay on track for future carbon removal goals

Measurement, Reporting, and Verification

Question 1: Barriers and Roadblocks through 2050:

- Challenges in securing funding for MRV activities
- Baseline data collection and aggregation for accurate assessment
- Need for computational resources to handle large data sets
- Lack of scientifically supported standards for MRV
- Need for open-source data and better (durable, cheap, precise) sensors
- Difficulties in establishing accurate baseline data and consensus on standards
- Striking a balance for verifiability, especially for small projects
- Lack of data and challenges with data collection in open systems
- Changing scale of MRV with scale-up of projects
- Balkanization of standards due to the proliferation of different standards and registries
- Need for government cooperation on standards and protocols at various levels
- Lack of a credible system to validate MRV protocols
- Consensus on MRV for different types of carbon removal, such as soil, forest, and BiCRS.
- The role of local models and long-term impact validation
- Addressing non-carbon benefits and impacts in MRV systems
- Managing the risks of bad actors and ensuring workforce competency in using quantification tools

Question 2: System Dependencies through 2050:

- Importance of integrating MRV with existing industry practices
- Need for a central CDR regulator to oversee MRV frameworks
- Public engagement and support for MRV efforts
- Clear strategic communications to build trust in MRV systems
- Transparency in project stakeholder interests and needs for sharing MRV data
- Availability of clean energy to support MRV operations
- Development of dedicated sensors and sensor networks for comprehensive monitoring
- Economies of scale in MRV technology
- Importance of global governance and consequent standards, such as open ocean treaties

- Coordination of liability for shared infrastructure like CO_2 pipelines
- Integration of MRV schemes with NDCs
- Addressing multiple projects and attribution of measured carbon removal
- Ensuring viability of business models for MRV technology and public willingness to pay
- Linking MRV to wider climate actions and policies, including compliance markets
- Expertise in larger market to perform MRV
- Ambition to link reductions in atmospheric CO_2 to reductions in temperature rise
- Need for developing higher resolution modeling of atmosphere and ocean
- Financial value and MRV precision/accuracy
- Whether or not "net zero" remains the dominant paradigm for organizing climate action
- Data synthesis across sensors and other monitoring tools
- Basic science and technology development, especially around oceans and geochemistry
- How regulatory standards drive MRV practice
- CDR industry consensus
- Feedback loop between academia and industry must be tighter and faster
- Importance of third-party MRV oversight to safeguard against conflicts of interest

Question 3: Risks or Unintended Consequences through 2050:

- Public rejection and lack of defensible scientific basis for MRV protocols
- Risk of over-crediting and misattribution in carbon accounting
- High MRV costs could prohibit growth and wide adoption
- Risk of poor MRV practices leading to a crisis of trust in the system
- Lack of sufficient technology infrastructure to scale
- Poor policy decisions and locking into low standards
- Risk of MRV investment revealing previously unknown carbon pathways
- Regulatory challenges in setting standards that remain flexible and responsive to new science and innovation
- Risk of MRV failing to capture unintended negative impacts
- Concerns about bio-carbon decomposition and reversal, affecting long-term carbon storage
- Potential ecosystem impacts, especially from ocean-based carbon removal
- Loss of buyer confidence due to faulty MRV
- Fragmentation in the MRV market leading to lower standards and slower capital deployment
- The risk of getting bogged down in pursuit of “perfect” MRV, hindering actual carbon removal efforts
- Project level MRV doesn’t “add up” into system level net carbon removal
- Ethics for who develops and funds standards
- Carbon verification with major health and environmental performance blindspots
- Investment in MRV/lack of implementation due to a “stuckness” in meeting a compensatory bar
- Faulty MRV leading to reduced climate impact
- MRV granularity silos knowledge sharing across projects, methods, certification/standards development schemes
- Lack of integrity to projects or MRV data
- MRV cost/complexity upends value proposition of CDR’s rank order
- It takes too long to arrive at consensus methods and impatience to see results

- MRV errors leading to breach of contract

Question 4: Enablers and Game Changers through 2050:

- Importance of regulatory guidance and enforceability for MRV
- Need for standardization through government authorization of methodologies and international data agreements
- Legislation and regulation to support breakthrough MRV technologies
- Development of new sensors and MRV capabilities
- Application of advanced computational resources for MRV modeling and estimation
- Integration of sensor systems with transport and other large industries
- Transparency and access to data
- Publicly available data sets and archives
- Field studies to provide conclusive data on adverse impacts and human health
- Sustained investment in R&D for MRV technology and frameworks
- Critical mass and economies of scale in data management and modeling
- US government focus and funding for MRV, including a national strategy for GHG MRV and information systems
- Merging of compliance and voluntary markets for broader adoption of MRV standards
- Public engagement and funding to support MRV as a public good
- Adoption of consensus MRV standards by governments and integration with existing industry practices
- Non-carbon benefits to enable access to other markets and revenue streams
- AI/ML advancements to support MRV
- CO_2 transport and storage infrastructure
- United Nations mandate through the World Meteorological Organization ('WMO')

Question 5: Open Questions and Uncertainties through 2050:

- What constitutes "good enough" quality and certainty for MRV, especially for land-based methods
- How to ensure stability of MRV systems amidst political changes
- What are the system boundaries for MRV by different approaches?
- Costs associated with MRV and who should bear these costs, especially in the context of compliance markets
- How to manage long-term monitoring requirements and reversal risks
- Ensuring comprehensive understanding of carbon cycles and earth system feedback
- Determining best practices for attribution and avoiding double counting in MRV
- Who will establish and maintain open source MRV data?
- How to coordinate global MRV efforts and subdivide responsibilities among national agencies
- The role of MRV in supporting broader climate actions beyond offsetting, including its integration into voluntary and compliance markets
- The need for temporal components in MRV credits (e.g., "ton-year")
- Potential for MRV as a public good and the implications for funding and policy
- Whether MRV can be effectively demonstrated and validated at pilot scales for emerging technologies like ocean-based carbon removal
- The required level of certainty to issue credits for different claims
- Understanding climate impact and uncertainty within baseline and counterfactual scenarios
- Establishing a baseline for ocean-based carbon removal methods

- Achieving cost-effective MRV for open systems to unlock $100 per ton CDR
- Differentiating accuracy from precision in MRV reporting

Subject Matter Experts (SME) Supporting Breakout Session Facilitation

Virtual Breakout – Day 1 & 2	
Virtual Room	Aaran Patel, The Nand & Jeet Khemka Foundation
Breakout Sessions – Day 1	
CDR - Rock	Colin McCormick, Carbon Direct
	Julio Friedmann, Carbon Direct
CDR - Ocean	Anya Waite, Ocean Frontier Institute
	David Ho, University of Hawai'i at Manoa
CDR - Land	Charlotte Levy, Carbon180
	Dave Hillyard, CTR Foundation
CDR - Air	Noah Deich, Department of Energy
	Rory Jacobson, Department of Energy
Methane & Nitrous Oxide Removal	Erika Reinhardt, Spark Climate Solutions
	Rob Jackson, Stanford University
Breakout Sessions – Day 2	
Science & Technology	Nikki Batchelor, XPRIZE
	Tim Bushman, Carbon Removal Canada
Socio-Behavioral & Communities	Cecilia Martinez, Bezos Earth Fund
	Holly Buck, University at Buffalo
Finance & Markets	Nan Ransohoff, Frontier
	Ryan Orbuch, Lowercarbon Capital
Policy & Regulatory	Jack Andreasen, Breakthrough Energy
	Michael Wara, Stanford University
Measurement, Reporting & Verification	Anu Khan, Carbon180
	Peter Minor, Icarus