CARBON DIOXIDE REMOVAL MISSION

MISSION INNOVATION Carbon Dioxide Removal Mission

Technical Track on Enhanced Mineralization

Work Plan

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Authorship List:
Renee Birchall
Andrew Lenton
Naif Alqahtani
Abdulrahman AlQuraishi
Bader Alfarraj
Hatem Alhazmi
Khalid Alharthi
Faisal Al Qurooni

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Mission Innovation's Carbon Dioxide Removal Mission

To achieve net zero emissions, it is essential to not only decarbonize existing industries and utilize renewable energy but also permanently remove carbon dioxide (CO_2) from the atmosphere. To mitigate the impacts of climate change[1] and achieve this goal, as a global community we must urgently explore innovative technological solutions to remove billions of tonnes of CO_2 from the atmosphere each year.

The goal of the Carbon Dioxide Removal Mission (CDR Mission) is to enable CDR technologies to achieve a net reduction of 100 million tonnes (0.1 gigatons) of CO_2 per year globally by 2030. The CDR Mission plans to achieve its goal through activities informed by innovation priorities and organized around three short-term outcomes:

> **Outcome 1: Enhanced understanding of local & global CDR potential,**
> **Outcome 2: Advancement of R&D for CDR technologies,**
> **Outcome 3: Global demonstrations & pilot-scale tests.**

At present, the CDR Mission is prioritizing engineered and hybrid[2] CDR approaches and cross-cutting disciplines across four technical tracks:

- Biomass with Carbon Removal and Storage (BiCRS),
- Direct Air Capture (DAC) with storage,
- **Enhanced Mineralization (EM)**,
- Cross-Cutting: Life Cycle Analysis (LCA) and Techno-Economic Analysis (TEA), and Monitoring, Reporting, and Verification (MRV).

The CDR Mission is co-led by the United States of America (Department of Energy (DoE)), the Kingdom of Saudi Arabia (Ministry of Energy), and Canada (Natural Resources Canada (NRCan)). Core Members include Australia (Commonwealth Scientific and Industrial Research Organization (CSIRO)), the European Commission, India (Ministry of Science and Technology), Japan (National Institute of Advanced Industrial Science and Technology (AIST)), Norway (Gassnova), and the United Kingdom (Department for Business, Energy, and Industrial Strategy).

[1] IPCC Summary for Policy Makers
[2] Hybrid approaches use technology to supplement natural CDR processes. Biomass with Carbon Removal and Storage (BiCRS) and enhanced mineralization are examples of hybrid approaches.

Introduction to Enhanced Mineralization

Mineral carbonation is a naturally occurring geological process that has been crucial in removing atmospheric carbon dioxide (CO_2) as part of the global carbon cycle for millions of years[3]. During naturally occurring rock weathering processes, stable carbonates are formed by reacting dissolved CO_2 in rainwater with (divalent) alkaline earth metal cations in exposed rocks.

Recent research and development have focused on enabling these reactions to be accelerated. This acceleration is termed enhanced mineralization (EM) and describes carbon dioxide removal (CDR) through the deliberate formation of stable carbonate minerals by reacting CO_2 with CO_2-reactive feedstocks (i.e., rocks or materials that contain high amounts of magnesium and calcium ions). This acceleration is critical if EM is to deliver on its potential to play a significant role in permanently removing atmospheric CO_2. With robust and sustained policy support, EM technologies have the potential to remove 1 billion tonnes of CO_2 per year by 2035 and 10 billion tonnes of CO_2 per year by 2050[4].

Enhanced mineralization techniques typically fall into two categories: ex-situ or in-situ:

- Ex-situ applications typically include combining atmospheric CO_2[5] with crushed silicate materials (i.e., ultramafic tailings[6] or industrial wastes[7]) or applying crushed mafic silicate rock (i.e., basalt[8]) to the soil to interact passively with atmospheric CO_2.
- In-situ applications involve injecting CO_2 into onshore or offshore mafic or ultramafic rock formations[9].

In some cases, EM presents an opportunity to reduce and potentially ameliorate some environmental impacts associated with mining and industrial waste. Some co-benefits include the potential recovery of critical minerals in mine tailings and soil health improvements through increased pH, increasing agricultural productivity. The crucial challenge for enhanced mineralization CDR technologies is accelerating these approaches to achieve

[3] Fitch P, Battaglia M, Lenton A, Feron P, Gao L, Mei Y, Hortle A, Macdonald L, Pearce M, Occhipinti S, Roxburgh S, Steven A, Australia's sequestration potential, CSIRO, Canberra, Australia.
[4] https://www.icef.go.jp/pdf/summary/roadmap/icef2021_roadmap.pdf
[5] This can also include CO_2 not captured from the atmosphere.
[6] ARCA
[7] MCi Carbon
[8] UNDO
[9] Wilcox, Kolosz, and Freeman, "Carbon Dioxide Removal Primer".

fast-acting, scalable, and cost-effective as part of the development of responsible pathways to net zero[10].

Overview of the Enhanced Mineralization Technical Track

Australia and the Kingdom of Saudi Arabia are co-leading the enhanced mineralization (EM) technical track. Participant members are from the United States of America, Canada, and Japan.

The Mission Innovation Carbon Dioxide Removal (MI-CDR) Mission Action Plan[11] outlines the top four innovation priorities for the EM technical track:

1. **Mineralization kinetics,**
2. **Energy use, land use, and environmental impacts,**
3. **Life-cycle analysis (LCA), techno-economic analysis (TEA), and**
4. **Monitoring, reporting, and verification (MRV).**

Further details on these innovation priorities and other key technology challenges and innovation gaps for EM technologies can be found in the MI-CDR Mission Roadmap[12]. Activities conducted in the EM technical track will be informed by the innovation priorities outlined in the Mission Roadmap and aim to advance the CDR Mission's outcomes.

Purpose of This Document

The purpose of this document is to outline the work plan of the enhanced mineralization (EM) technical track, including:

- Define an agreed scope of work and actions, with input and feedback from all participants,
- Engage with key stakeholders, attract new members, and make progress toward the goals of MI-CDR.

Roles and Responsibilities

The co-leads (Australia and the Kingdom of Saudi Arabia) will coordinate all activities for the technical track, including:

- Develop, coordinate and update the EM technical track work plan, seek feedback from members, and revise the plan as necessary,
- Initiate workshops on relevant topics within the EM technical track,

[10] Fitch P, Battaglia M, Roxburgh S, Steven A, Feron P, Gillespie M, Birchall R, Lenton A, Seyyedi M, Fawell P, Jenkins C, Evans D and S. Langley (2023) Sequestration cost reduction workshops report, CSIRO, Canberra, Australia.
[11] "Carbon Dioxide Removal Mission Action Plan 2022-26."
[12] https://explore.mission-innovation.net/wp-content/uploads/2022/09/Carbon-Dioxide-Removal-Mission-Roadmap-Sept-22.pdf

- Develop timelines and track progress towards deliverables,
- Synthesize input from members, stakeholders, and workshops for use in reports, initiatives and/or other correspondence to members,
- Provide regular updates during all-member CDR Mission meetings.

All members of the EM technical track, where possible, will:

- Actively engage in tasks and share information/data as agreed,
- Provide input and comments as requested for plans, reports, etc.,
- Engage in the organization and execution of workshops and/or other related events,
- Engage with the research community, private industry, academia, and other relevant stakeholders to encourage participation in EM technical track activities.

Interested CDR Mission members are welcome to become EM technical track members; in addition, non-member governments, academia, innovators, or other stakeholders can become members and/or contribute to technical track activities following the MI Stakeholder Engagement Plan.

If you are interested in learning more about how you can get involved, please contact Renee Birchall (renee.birchall@csiro.au) and/or Faisal Al Qurooni (faisal.qurooni@moenergy.gov.sa).

The Enhanced Mineralization Technical Track Work Plan

Accelerating international collaboration to help realize the full potential of a global enhanced mineralization (EM) industry on the pathway to net zero is a central goal of this technical track. The EM technical track will undertake activities across three phases addressing the CDR Mission's short-term outcomes to achieve this goal (the timelines are flexible and will be reviewed annually). Please note, while members are encouraged to participate in all activities, it is not mandatory.

Outcome 1: Enhanced understanding of local & global CDR potential,
Outcome 2: Advancement of R&D for CDR technologies,
Outcome 3: Global demonstrations & pilot-scale tests.

Phase 1 (June 2023 – September 2024):

Phase 1 aligns with the CDR Mission's short-term Outcome 1 and comprises activities that align with the resource mapping project. The resource mapping project aims to facilitate an enhanced understanding of local and global CDR potential through identifying and consolidating CDR-specific geospatial data[13].

Phase 1 will address these aims for EM approaches over two activities, focusing on mapping and publishing mafic and ultramafic formations:

Activity 1.1: Enhanced mineralization resource mapping

Key outcomes of Activity 1.1 include:

- Data compilation and identification of data sources, gaps, transparency, and barriers, land and resource access within member countries,
- Mapped EM feedstock, i.e., mafic and ultramafic geological formations (including characterization data where applicable), mine waste and tailings,
- Mapped CO_2 sources, location climate data, natural resources, and relevant infrastructure,
- Identification of best practices for mapping and characterization,
- Identification of potential collaborative partnerships between various stakeholders.

[13] "Carbon Dioxide Removal Mission Action Plan 2022-26."

Activity 1.2: National- and international enhanced mineralization resource map publication and related activities

Key outcomes of Activity 1.2 include:

- Publicly available national- and integrated international digital maps of EM resources, including mapped feedstocks, CO_2 sources, natural resources, and infrastructure,
- Facilitate knowledge transfer to the public and promote evidence-based decision-making for EM technology locations/projects and feedstocks,
- Formal launch of the EM Resource Map by technical track co-leads at MI-9 in Brazil, September 24th 2024.

The foundational information made available from Phase 1 of the EM technical track work plan can contribute to:

- An emerging understanding of potential sites for future EM technology deployment through the identification of existing and potential feedstocks,
- Providing data that may act to connect and/or identify potential stakeholders and partnerships,
- Emerging understanding of TEA inputs, i.e., data required to calculate CDR potential, including annual CO_2 removal capacity and the impact of a changing climate,
- Emerging understanding of LCA considerations for different EM approaches,
- Emerging understanding of monitoring, reporting, and verification (MRV) constraints and future challenges.

Phase 2 (January 2024 – December 2025):

This phase aligns with the CDR Mission's short-term Outcome 2 and comprises activities to facilitate the development of CDR industries in member countries and address critical technology challenges and innovation gaps through collaborative Research Development and Demonstration (RD&D). Collaborative RD&D between critical stakeholders to facilitate knowledge transfer and sharing ideas to promote evidence-based decision-making is a primary focus of this phase.

The following activities will be targeted in this phase:

Activity 2.1: Identify and support national CDR enablers

Scaling EM technologies is fundamental to achieving the goal of MI-CDR and realizing global activities and industries. Successful scaling requires significant investment, research, policy, and regulatory support to ensure widespread adoption and meaningful contribution towards net zero; CDR enablers (e.g., CDR industry roadmap development) within member countries will promote industry growth and development.

Other CDR enablers may include:

- Establishment of an RD&D project/case study database to identify overlaps and opportunities to collaborate,
- Generation of platforms that facilitate networking, collaboration and knowledge sharing among various stakeholders (e.g., scientific and industry conferences and workshops, scientific or community forums).

Anticipated key outcomes of Activity 2.1 include:

- New collaborative partnerships between industry, universities, and research organizations that will enable EM technologies to advance from pilot to large field scale,
- Explore new case studies and understand the opportunities and challenges of attracting significant public- and private-sector investment that can potentially move demonstrations from laboratory to commercial scale.

Activity 2.2: Collaborative RD&D projects/case studies

EM RD&D is critical to drive innovation, improve efficiency, and address technical challenges to lay the groundwork for scalable and cost-effective technologies with potential uptake by industry. Leveraging outcomes of Activity 2.1, it is anticipated that new collaborative RD&D projects/case studies will be initiated. These RD&D projects/case studies will ideally focus on the

CDR Mission's innovation priorities and other key technology challenges and gaps identified for EM technologies, all subject to change at any point.

Anticipated key outcomes of Activity 2.2 include:

- Technology-driven and scalable laboratory or small-scale demonstrations of EM technologies,
- Determine the most amenable materials/reactive feedstocks for EM (i.e., improved understanding of mineralization kinetics, rates, and acceleration),
- Development of quantification, remote-sensing, modelling, and/or data characterization technologies for MRV,
- Explore and identify positive and negative environmental impacts associated with EM approaches,
- Identification of any potentially marketable and sustainable, durable, low-emission products.

Phase 3 (January 2025 – December 2026):

Phase 3 aligns with the CDR Mission's short-term Outcome 3 related to demonstration and pilot-scale testing. Pilot-scale testing is crucial in developing and implementing new technologies, processes, and systems. In addition, risk management, concept validation, and performance optimization efforts during pilot testing will increase the likelihood of the successful transition of EM technologies to commercial operations.

The following are the activities targeted in this phase:

Activity 3.1: Assessing the benefits and potential of combining enhanced mineralization with non-mineral carbon dioxide capture technologies

Assessing the combination of non-mineral carbon capture methods, e.g., direct air capture (DAC) with EM technologies, potentially offers more effective and efficient CDR solutions. This assessment will be completed through expert elucidation in targeted workshops and communicated through a publication.

Potential key outcomes of Activity 3.1 include:

By publicizing an assessment of integrating chemical or biological DAC with enhanced mineralization technologies, the technical track can contribute to:

- Raising awareness of sustainable innovation and RD&D approaches,
- Increasing awareness of EM technological approaches that can reduce environmental impact, land use, and enhance environmental co-benefits,
- Improving understanding of optimization options, which can help projects to increase CDR capacity,
- If possible, identify pilot testing opportunities and collaborators.

Activity 3.2: Enabling collaborative pilot-scale testing

Leveraging on the outcomes of Phase 2 and Activity 3.1, it is anticipated that collaborative pilot-scale testing will be initiated within and between member countries. Where appropriate, the EM technical track will work closely with the pilot tests to achieve outcomes determined by their respective nations.

Anticipated key outcomes of Activity 3.2 may include:

- Understanding of risks and risk mitigation strategies,
- Concept validation of EM technologies taken to pilot-scale testing,

- Data collection and analysis for informed decision-making (i.e., optimization and improvement),
- Develop common metrics and methodologies across potential sites and EM approaches (LCA/TEA), including transportation and dispersion of crushed rock for enhanced rock weathering projects,
- National and international standardization of MRV,
- Preliminary engagement with credible third-party independent accreditors for regulated and unregulated carbon markets.
- Sharing where appropriate knowledge from pilot-scale tests.

If you are interested in learning more about how you can be part of the EM technical track or MI-CDR, please contact Renee Birchall (renee.birchall@csiro.au) and/or Faisal Al Qurooni (faisal.qurooni@moenergy.gov.sa).