Mining and Carbon Dioxide Removal

A responsible path forward for
mine operators, policymakers,
and other key stakeholders

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Glossary (1 of 4) – Mining Carbon Dioxide Removal Terminology

Section 1: Carbon Dioxide Removal Terminology

Additionality: A key principle for determining whether a specific project, or the climate benefits claimed from that project, would have occurred outside of dedicated funding or support, e.g., dedicated carbon credit purchases.

Biogenic CDR: Biogenic CDR approaches use naturally-occurring biogenic carbon fixation mechanisms to capture CO_2 from the atmosphere.

Carbon capture, utilization, and storage (CCUS): The process of capturing CO_2 either from the atmosphere or from a point-source (see *point-source emissions* below) and either using the CO_2 as feedstock, storing it temporarily or permanently in products, or storing it permanently in geological reservoirs. In some cases, this process may result in re-release of carbon to the atmosphere.

Carbon dioxide removal (CDR): Per the IPCC, CDR is any human-induced activity that removes CO_2 from the atmosphere to be stored in either geologic, terrestrial or marine reservoirs, or else in durable products, on timescales of decades to millennia.

Carbon mineralization (also known as mineral carbonation): A process where CO_2 reacts with minerals to form stable, solid carbonate compounds, effectively sequestering carbon.

Counterfactual: An alternate case in which no action, or a different action, was taken. Counterfactuals are assessed to understand the extent to which an activity may count as "Additional" (see "Additionality").

Downstream losses (in a CDR context): The reduction in the amount of CO_2 sequestered due to inefficiencies or any physical, chemical, or biological losses during the transportation or storage steps.

Durable CDR: Carbon removal that results in long-term CO_2 storage, e.g., greater than 100 years.

Enhanced rock weathering: A CDR approach that accelerates the natural weathering of rocks or minerals, to capture and store CO_2 from the atmosphere as dissolved bicarbonates.

Geochemical CDR: CDR methods that rely on chemical reactions involving alkaline mineral feedstocks to capture and store CO_2, such as mineral carbonation or enhanced weathering.

Leakage (in a carbon market context): Occurs when emissions reduction policies or activities in one jurisdiction or project cause an unintended increase in emissions elsewhere. For example, when industries relocate to areas with weaker regulations to avoid costs or when activity is simply displaced, resulting in a net rise in global emissions.

Life cycle assessment (LCA): A method to evaluate the environmental impacts of a product or process from its creation to its disposal, crucial in assessing the true effectiveness and additionality of CDR strategies.

Monitoring, reporting and verification (MRV): The process of tracking, documenting, and confirming the effectiveness of CDR activities to ensure accountability.

Ocean alkalinity enhancement: A CDR technique that involves increasing the alkalinity of seawater to enhance its capacity to absorb and store CO_2.

Point-source emissions: Point source emissions are greenhouse gas emissions released from a discrete, identifiable and stationary source.

Glossary (2 of 4) – Mining Carbon Dioxide Removal Terminology

Section 2: Mining Terminology

Acid & Metalliferous Drainage Management: Refers to strategies to prevent, control, and treat impacts resulting from acid rock drainage (see below) as well as the (subsequent) leaching of metals from carbonates and reactive silicates into soil porewaters and waterways.

Acid Rock Drainage (ARD), also known as Acid Mine Drainage (AMD): Describes the formation of acid when sulphide-bearing mine wastes are exposed to oxidizing conditions, typically in the presence of water, due to groundwater, rain and run-off. ARD can cause major long-term environmental problems at mine sites if appropriate prevention and/or management strategies are not adopted.

Life of Mine (LOM): The total expected duration of a mining operation from commencement of production through planned closure, based on current economically recoverable reserves and the approved mine plan.

Ore: Naturally occurring rock or sediment containing a high concentration of a valuable mineral that can be extracted economically.

Ore concentrate: The commercially valuable product that remains after raw, freshly mined ore has been processed (beneficiated) to remove the waste rock or gangue. Gangue minerals or ore concentrate minerals may contain alkalinity that can be used for CDR projects.

Overburden: The layer of soil and rock that lies above a mineral deposit, often removed during mining.

Spoil and waste rock: Rock that is mined but does not meet the economic cut-off grade for target commodities, and is therefore stored, unprocessed, in bulk waste facilities.

Social License to Operate (SLO): The ongoing acceptance and approval of an organization's activities by its stakeholders and the general public.

Tailings: The waste material left after extracting valuable minerals from ore.

Tailings Storage Facility (TSF): A managed structure to safely and permanently store processed tailings.

Section 3: Technical Terminology

Acid: An aqueous (water) solution rich in protons (H+) measured by pH. Dissolution of carbon dioxide in water creates acidity that can be neutralized to sequester CO_2 in the liquid or solid phase.

Alkaline materials: Substances with a high pH that can neutralize acids, often used in carbon dioxide (CO_2) removal (CDR) to increase alkalinity and enhance carbon storage.

Alkalinity: The capacity of an aqueous solution to neutralize acid. Key contributors to alkalinity include free hydroxides, bicarbonates, and carbonates, e.g., carbonate alkalinity, and phosphate species.

Amorphous: A non-crystalline solid (typically glassy) with no long-range order in its atomic structure, often leading to different reactivity compared to crystalline forms.

Bicarbonate: A soluble ion (HCO_3^-) formed when CO_2 reacts with water and an alkaline substance, playing a key role in buffering systems and carbon storage.

Buffering system: A system that resists changes in pH by neutralizing added acids or bases, crucial in maintaining environmental stability in CDR processes.

Glossary (3 of 4) – Mining Carbon Dioxide Removal Terminology

Section 3: Technical Terminology, continued

Carbonate and carbonate minerals: Compounds containing the carbonate ion (CO_3^{2-}), which are significant in CDR as they form stable carbon storage products (typically solid minerals).

Carbonation potential (C_{pot}): The theoretical potential of a material to capture and store CO_2 as solid carbonate ions, often used in evaluating the effectiveness of CDR methods.

Cation: A positively charged ion that plays a role in various chemical reactions, including those involved in CDR processes, e.g., magnesium^{2+} (Mg^{2+}), calcium^{2+} (Ca^{2+}).

Chemical composition: The identity and proportion of elements or compounds in a substance, which affects its reactivity and suitability for CDR.

Dissolution: The process by which a solid substance dissolves in a liquid, crucial in enhanced weathering and other CDR methods where minerals react with CO_2.

Dissolution rate: The speed at which a substance dissolves in a liquid, influencing the efficiency of CDR in processes like enhanced weathering. The macroscopic dissolution rate is proportional to a mineral's reactive surface area, i.e., the effective area of a mineral exposed to the reactive solution. Without active intervention, mineral dissolution rates tend to decay exponentially with time, reducing CDR efficacy.

Enhanced weathering potential (E_{pot}): The theoretical potential of a material to capture and store CO_2 as alkalinity or bicarbonate solution, often used in evaluating the effectiveness of CDR methods.

Geochemical modeling: The use of computer simulations to predict the outcomes of chemical interactions.

Hydroxide: A negatively charged ion (OH^-) that increases alkalinity and plays a role in certain CDR processes.

Mafic rock: A type of rock rich in Mg, Ca, and iron (Fe), often targeted for enhanced weathering or mineralization processes due to its potential to capture and store CO_2.

Mineral: A naturally occurring, inorganic substance with a fixed chemical formula. Rocks and sediments are composed of minerals.

Mineral carbonation (also known as carbon mineralization): A process where CO_2 reacts with minerals to form stable, solid carbonate compounds, effectively sequestering carbon.

Mineral kinetics: The study of the rates at which minerals react in processes like weathering, influencing the efficiency of CDR.

Modal mineralogy: The quantitative assessment of the mineral content of a rock, important for determining its suitability for CDR applications.

Molar volume: The volume occupied by one mole of a substance. It is usually expressed in cubic meters per mole (m^3/mol) or sometimes in liters per mole (L/mol).

Oxide: A compound of oxygen with another element, often involved in chemical reactions in CDR processes, such as those forming carbonates.

Particle size distribution (PSD): The range of sizes of particles in a material, which can affect the reactivity and efficiency in processes like enhanced weathering.

Reactive transport model: A simulation that combines chemical reactions with physical transport processes, used to predict the behavior of CDR systems.

Glossary (4 of 4) – Mining Carbon Dioxide Removal Terminology

Section 3: Technical Terminology, continued

Silicate minerals: A group of minerals containing silicon and oxygen, significant in CDR processes like enhanced weathering due to their ability to capture CO_2.

Slag: A by-product of metal smelting that can be used in CDR processes due to its potentially high reactivity with CO_2.

Solubility: The ability of a substance to dissolve in a liquid, important in understanding how minerals interact with CO_2 in CDR processes.

Ultramafic rock: A type of rock extremely rich in Mg and Fe, highly reactive for enhanced weathering and carbon mineralization in CDR applications.

Weathering (or natural weathering): The natural process of breaking down rocks and minerals, which can be accelerated in CDR to capture and store CO_2.

Section 4: Other Terminology

Mining CDR: The full set of synergies between mining activities, assets, and infrastructure and various CDR applications. (See page 20)

Verified Site Outcomes: Measurable and auditable improvements in mine-site conditions or risks, supported by baseline data, monitoring, and transparent evidence, showing that an intervention delivers real, operational, closure-related, environmental, or community-facing benefits.

SECTION 1

Executive Summary

Mining and Carbon Dioxide Removal
A responsible path forward for mine operators, policymakers, and other key stakeholders

THE OPPORTUNITY

CDR at mining sites could yield more than 1 billion tonnes of CO_2 impact per year at competitive cost versus other forms of CDR, while improving mine safety, productivity, and earnings.

Mine operators have the materials, land, equipment, expertise, and operational capabilities needed to implement many emerging CDR techniques on-site. Select important examples include:

- **Mineralizing tailings and waste rock from active nickel mines** and other mafic and ultra-mafic mine sites.
- **Providing space on closed mine sites** for biomass burial and for afforestation and reforestation.
- **Remediating legacy asbestos mines**, as is being explored in Thetford Mines and Baie Verte in Canada.
- **Sequestering carbon captured from air or from biomass in reactive minerals, in-situ or ex-situ,** while recovering critical minerals.

The overall impact opportunity for CDR on mining sites is estimated to be more than 1GtCO$_2$ per year. The potential scale, cost, and delivery rate varies by site, but indicative estimates suggest:

- Mineralizing tailings generated each year from mafic and ultra-mafic mines could theoretically support **~100-170 MtCO$_2$/year of CDR**, and use of legacy tailings could increase the potential volumes to **~520-820 MtCO$_2$/year of CDR**.[1]
- Biomass burial in sealed subsurface voids could provide a similar magnitude of CDR each year.
- Costs for these interventions could be **$80-300/tonne**—highly competitive compared to other forms of durable CDR.

Mineralization-based CDR can improve waste management, safety, productivity, and EBITDA by converting tailings and waste rock—which are a risky and costly liability to manage—into verified carbon removal, low-carbon construction materials, and industrial byproducts.

Responsible CDR activities could also help mine operators to strengthen their:

1. **Sustainability targets** and reporting
2. **Social license to operate** and overall reputation
3. **Support from communities, regulators, and other stakeholders** for specific potential projects

Notes and sources: [1] RMI analysis of the CDR potential based on annual tailings production rates from mafic-ultramafic rock types. These calculations of theoretical potential do not consider practical and regulatory constraints that could limit actual deployment potential. They also do not consider intentional mining of materials for geochemical CDR, other rock types, or additional waste materials such as waste rock and overburden, all of which may further enhance CDR potential.

THE CHALLENGE

CDR on mine sites also poses operational challenges, sits outside the conventional business model of mining companies, and relies on markets, systems, and policy that are emergent

Introducing new CDR activities onto mine sites presents challenges as well as opportunities for mine safety, production, and economics:

- **Introducing any new activity into projects that are active or being planned introduces new risks** of operational error and thus of negative impacts on safety, production, and economics.
- **Handling legacy tailings, waste rock, or slag presents additional specific challenges:** Geotechnical stability, drainage, contamination risks, and regulatory restrictions on disturbing closed or capped facilities can prevent projects that appear promising on paper from proceeding.

The markets, carbon accounting systems, and regulatory frameworks for monetizing the CDR value of these interventions are all emergent and uncertain.
There are **three viable pathways** to create value from CDR projects:

Generate **carbon credits** to be sold in carbon markets.

Embed the carbon value into **lower-carbon products** that command price premiums or address regulatory requirements that apply at the product level, such as Carbon Border Adjustment Mechanisms.

Apply CDR internally to satisfy internal carbon prices or targets, or to address regulations that apply at the corporate level, such as GHG emissions pricing, taxes, or trading schemes focused on industrial emitters.

All rely on an enabling environment that is emergent.

WHAT NEEDS TO BE DONE

Mine operators need to work with stakeholders from other sectors to build the project pipelines, market infrastructure, regulation, and policy needed for responsible CDR deployment

ACTION AGENDA FOR MINING AND CDR

Mine Operators

Evaluate and assess options for integrated CDR projects

- Increase internal awareness of CDR opportunities
- Evaluate available assets and waste streams, and match to CDR solutions
- Participate in processes to develop best practices, new market infrastructure, standards and regulation
- Screen and scope projects for feasibility and value, within the operating and/or closure context
- Use project learnings to strengthen best practice and regulation

Project Developers

Design projects that solve problems for mine operators and local communities

- Develop solutions that deliver risk mitigation and business value to mine operators, and verifiable benefits to local communities, as well as CDR
- Share data, insights, and ideas to catalyze innovation in MRV, carbon accounting, monetization, and regulation
- Co-design community engagement and benefit agreements alongside mine operators and local communities
- Prioritize safety, risk reduction, and verification in project design and delivery

Regulators & Policymakers

Create clear pathways for governed deployment

- Provide enabling regulations for CDR interventions on mine sites and clarity on regulatory pathways for pilots and demos
- Provide clarity on how carbon policies, markets, and accounting will evolve
- Define safeguards and monitoring expectations
- Clarify waste reclassification and repurposing pathways, where relevant
- Integrate mine-site CDR into carbon accounting for products, emission trading schemes, and carbon border adjustment mechanisms

Registries, Verifiers, & NGOs

Ensure pathways for high-integrity, auditable projects

- Develop and align frameworks and rules for carbon accounting, claims, MRV, and other evidence
- Develop tools and standards for comparable, auditable projects that are hard to mis-use
- Encourage and legitimize innovation and learning alongside high integrity
- Help build an open-access evidence base, tools, and infrastructure to support MRV
- Monitor system functionality and use, and ensure ongoing accountability of other actors

Community Stakeholders

Get involved early in shaping project outcomes

- Get informed on the opportunities and limitations of integrated carbon removal as a means of climate change mitigation and environmental remediation
- Contribute to shared project designs and outcomes by engaging early with mine operators and project developers and providing information on the local context and priority issues
- Outline community priorities on environmental outcomes and shared benefits

Buyers, investors, public R&D funders, and donors

- Provide funding support for regulators, policymakers, NGOs, and communities to engage with the mining industry
- Provide catalytic funding for innovation paired with technical learning, transparency, legitimacy, and scrutiny

SECTION 2

Introduction and Framing

This report is motivated by the vital role of minerals in scaling carbon dioxide removal

Carbon dioxide removal (CDR) needs to scale responsibly to limit the worst effects of climate change. We are early in proving which CDR approaches are most effective, but it is clear a portfolio of methods will be needed and that geochemical methods, which rely on alkaline minerals and thus on mining, will be a vital piece of that portfolio.

The mining industry is poised for growth in the coming decades, as the provider of critical minerals and materials for continued global economic development. In the 2025 MiningIQ Leadership Insights survey, 28% of mining companies surveyed planned to more than double output by 2030[1].

That growth will bring real climate and sustainability pressures: even with accelerating decarbonization efforts, residual emissions and legacy impacts will be hard to eliminate fully. The way in which the mining industry grows will have lasting consequences.

Gigaton-scale CDR deployment will be a massive operational and resource challenge, requiring industrial-scale expertise and infrastructure, as well as a relentless focus on the efficient management and utilization of resource inputs. We will need to maximize use of existing industrial infrastructure, wastes, processes, and value chains to address logistical and sustainability challenges and prevent the unnecessary diversion of resources, including materials, water, and energy, away from communities.

A significant volume of the mining industry’s mafic and ultramafic waste rock and tailings could be used for CDR, as could a significant amount of its land, subsurface space, and infrastructure. CDR projects could help mine operators manage a range of environmental risks, including, but not limited to, their own greenhouse gas (GHG) emissions. And carbon sequestration could be paired with in-situ and ex-situ mineral recovery to make new mines more sustainable. Mine operators are waking up to these opportunities, and there are a growing number of efforts underway as a result.

Mining urgently needs to advance responsibly. So does CDR. This is the moment to assess what could be achieved if mine operators mobilize to address CDR opportunities, what the associated risks and challenges could be, and what a responsible path forward for operators, governments, investors, communities, and other key stakeholders would entail.

Notes and sources: [1] Mining IQ. "Leadership Insights 2025: Strategies for Growth." Mining Journal, 2025.

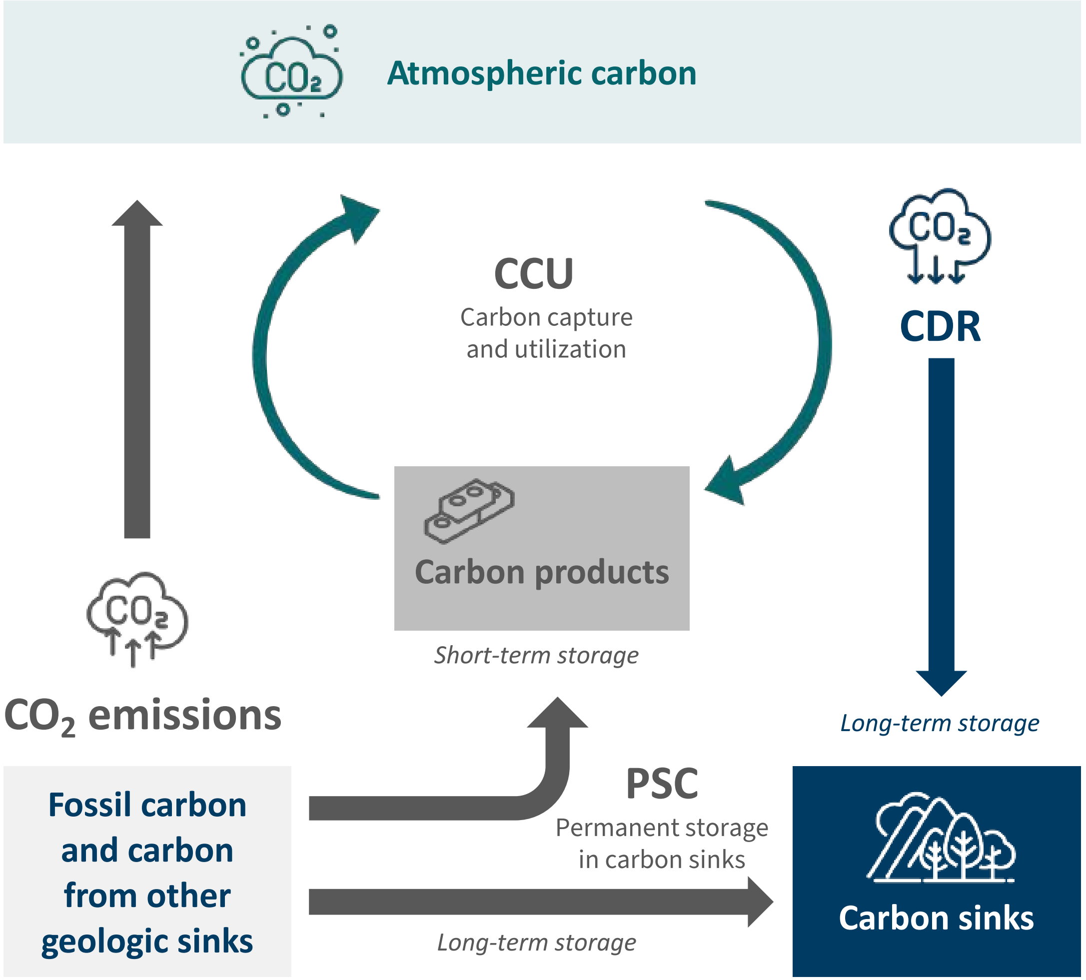
Carbon Dioxide Removal is distinct from other forms of carbon management

Carbon Dioxide Removal is defined[1] as any human-induced activity that removes CO_2 from the atmosphere to be stored in either geologic, terrestrial or marine reservoirs, or else in durable products, on timescales of decades to millennia.

CDR differs from Point Source Capture and Storage (PSC) in that the source of CO_2 is the atmosphere itself, rather than an industrial point-source. It also differs from Carbon Capture and Utilization (CCU), in that for CCU captured CO_2 is primarily intended for use in the creation of a physical product, which may or may not re-release the carbon to the atmosphere once it's used.

The storage options that exist for sequestering CO_2 removed from the atmosphere are similar to options for storing CO_2 from point sources. This can create opportunities for joint carbon management projects but can also create confusion regarding the overall climate impact and attribution of benefits. While PSC can offer meaningful and useful ways to help manage atmospheric CO_2 concentrations, it does not remove previously emitted CO_2 from the atmosphere.

This report focuses on atmospheric carbon removal opportunities, along with relevant storage options, that can be employed to durably and safely sequester CO_2.



Atmospheric carbon

CCU
Carbon capture and utilization

CDR

Carbon products
Short-term storage

CO_2 emissions

Long-term storage

PSC
Permanent storage in carbon sinks

Fossil carbon and carbon from other geologic sinks

Long-term storage

Carbon sinks

Notes and sources: [1] Definition taken from the IPCC. Further discussion on the various definitions of CDR can be found in the commentary "Clarifying what is meant by greenhouse gas 'removals' and categorising types of 'removal-related activities'". Figure adapted from Carbon Gap's Guide to Certifying Carbon Removal.

The range of carbon removal and storage opportunities is vast

Carbon removal and storage pathways can be categorized according to their primary inputs and underlying removal mechanisms

Geochemical CDR

Geochemical CDR approaches use naturally-occurring neutralization reactions between acidic forms of carbon and alkaline minerals to convert *CO_2 from the atmosphere* into solid carbonate minerals or dissolved bicarbonates.

Geochemical CO_2 Storage

Geochemical storage approaches use naturally occurring neutralization reactions between acidic forms of carbon and alkaline minerals to convert *already captured and concentrated CO_2* into solid carbonate minerals or dissolved bicarbonates.

Synthetic CDR

Synthetic CDR approaches use engineered systems, for which the key input is low-carbon energy, to capture CO_2 directly from the air or to alter water chemistry to indirectly remove CO_2 from the air.

Biogenic CDR

Biogenic CDR approaches take advantage of naturally-occurring biogenic carbon fixation mechanisms to capture CO_2 from the atmosphere, either making use of sustainable biomass wastes or creating land-based carbon sinks.

Geochemical CDR methods that rely on rocks or minerals as feedstock are especially applicable to mining operations, as they can take advantage of existing mine tailings or waste rock and involve similar engineering challenges. In addition to supporting geochemical CDR methods, mining operations and related infrastructure provide an equally compelling case for the deployment of most other methods of CDR, including those that make use of biomass and existing water processing, underground deposits or depleted caverns. **This report explores the range of CDR approaches that can be deployed either directly within mining operations or off-site using mineral outputs.**

Notes and sources: [1]Definition taken from the IPCC. Definitions of carbon dioxide removal pathways from RMI's Applied Innovation Roadmap for CDR.

This report is for mine operators, governments, and key stakeholders across sectors in the responsible development of mining and CDR

Recent pilot projects are proving that CDR is no longer theoretical or aspirational, but is happening now, and with encouraging results.

It is important for mine operators, governments, investors, communities, and key stakeholders in other sectors to understand the promise and potential of CDR technologies, and the advantages they may confer when deployed specifically within a mining context.

As CDR develops, a host of synergistic opportunities are emerging across multiple industries to remove CO_2 while also improving efficiencies, reducing industrial wastes, and delivering value in other ways.[1]

Of all industries, mining stands out as one of the most promising because of the overlaps in needs for mineral feedstocks from a CDR standpoint, and the need for safe and environmentally sustainable waste management from the mining standpoint.

Climate change is not waiting. Physical, economic, and regulatory pressures are growing. Aligning longer-term economic cycles in mining with more immediate climate imperatives is crucial.

This report is a starting point to address what we see as an urgent need for integrating CDR into the wider set of more sustainable mining practices.

For **Mine Operators:**

- *A comprehensive picture of relevant CDR approaches*
- *An assessment of the promise and potential of CDR for mining operators*
- *Key considerations for responsible and successful implementation, including decisions about which sites, materials, and commercial pathways warrant early focus*
- *An action agenda with priority actions*

For **Regulators and Policymakers:**

- *A comprehensive picture of relevant CDR approaches*
- *An assessment of the promise and potential of Mining CDR for emissions mitigation*
- *Key considerations for responsible and successful implementation*
- *An action agenda with priority actions*

For **Key Stakeholders Across Sectors:**

- *An action agenda articulating where and how CDR project developers, civil society, researchers, innovators, and companies in other sectors can engage with mine operators and with government to help Mining CDR to move forward in a responsible way*

Notes and sources: [1] Our report, Seizing the Industrial Carbon Removal Opportunity, highlights opportunities for CDR to integrate into the wider industrial landscape, including the mining industry.

This report is organized across three sections: from opportunity to action

① *The promise and potential of Mining CDR*

Sections 2-5 cover how CDR intersects with the mining industry, why these activities are compelling to mine operators from a business standpoint, and the landscape of current activity.

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2. Introduction

3. Mining Carbon Removal and Storage Pathways and their Emissions Mitigation Potential

4. The Business Case for Mining CDR

5. Landscape of Mining CDR Activity

② *Real-world considerations*

Sections 6-10 cover key considerations for developing real-world Mining CDR projects.

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6. Providing Feedstock for Geochemical CDR

7. Quantification and Measurement Considerations

8. Environmental and Social Considerations

9. Siting Considerations

10. Mining CDR Hubs

③ *A responsible path forward*

Section 11 offers recommendations to advance ining CDR responsibly, tailored to the roles that mine operators, industry, and other stakeholders each need to play.

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11. A Responsible Path Forward: Recommendations

Two appendices provide deeper technical assessments of Mining CDR pathways and an assessment of market and regulatory drivers

The **Technical Appendix** provides further detail on some of the Mining CDR pathways featured in this report.

It covers:

- *How each CDR process works*
- *What resources are required*
- *Pricing and primary cost drivers*
- *How each process integrates into mining operations*
- *Considerations for scaling this pathway in the context of mining*

The **Appendix on Market and Regulatory Drivers** highlights key policy levers and market dynamics that shape the business case for Mining CDR.

It covers:

- *The Carbon Border Adjustment Mechanism*
- *Emissions Trading Systems*
- *The Science-Based Targets Initiative*
- *Carbon Accounting Reform*
- *Differentiated Products*

SECTION 3

Mining Carbon Removal and Storage Pathways and their Emissions Mitigation Potential

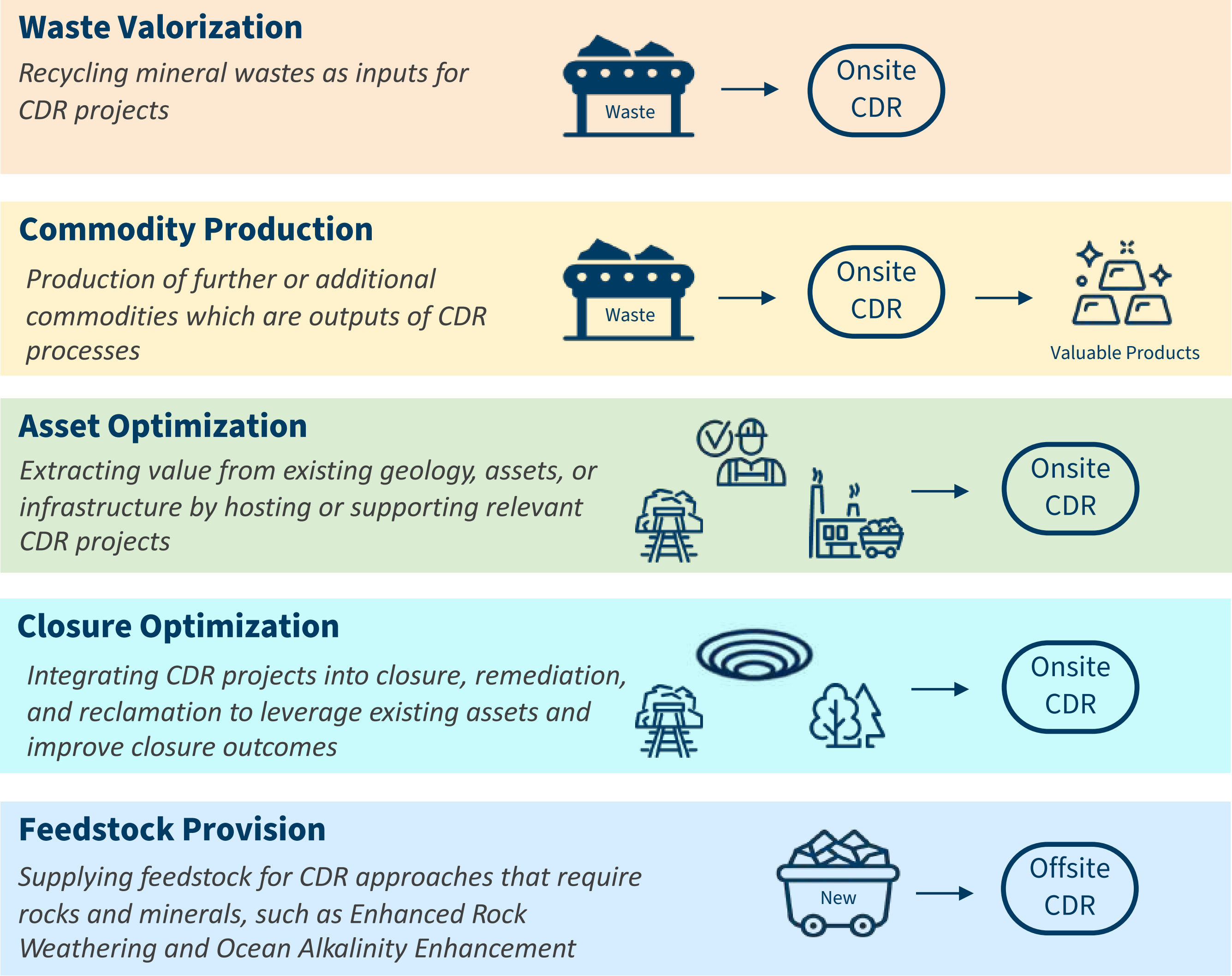
Mining and Carbon Dioxide Removal
A responsible path forward for mine operators, policymakers, and other key stakeholders

Synergies abound for Mining Carbon Removal and Storage

Integrating carbon removal into mining operations can be approached by identifying synergies between mining activities, assets, and infrastructure and various CDR applications. CDR projects can be deployed throughout various stages of the mining value chain, and various stages of the Life of Mine (LOM), either as a separate, bolt-on process, or integrated into existing process chains.

Integration possibilities are broken down here into five categories based on how they relate to mining assets, infrastructure, and processing. The relationship between mining and geochemical CDR pathways requiring mineral feedstocks is evident. Less evident are novel CDR pathways that can simultaneously perform both carbon removal and extract metals, acids, and other commodities, including from materials that have been previously processed or from ores that are otherwise uneconomical. Other wastes produced on site are also applicable as CDR inputs, including process water or brines. Mining operations also possess the logistical infrastructure and equipment to process and handle rock and water volumes at scale and are already permitted for industrial activity. Upon closure, CDR can be used to mitigate issues related to storage of wastes or rehabilitation.

We refer to these foundational elements as *Mining CDR*, which includes the possibility of multiple simultaneous approaches or variations on the use of these resources on a single site.



Waste Valorization

Recycling mineral wastes as inputs for CDR projects

Commodity Production

Production of further or additional commodities which are outputs of CDR processes

Asset Optimization

Extracting value from existing geology, assets, or infrastructure by hosting or supporting relevant CDR projects

Closure Optimization

Integrating CDR projects into closure, remediation, and reclamation to leverage existing assets and improve closure outcomes

Feedstock Provision

Supplying feedstock for CDR approaches that require rocks and minerals, such as Enhanced Rock Weathering and Ocean Alkalinity Enhancement

Multiple geochemical CDR methods are applicable to mining operations

		CDR Method	Description & Mining Rationale	On-site Opportunity Level	Area of Relevance				
					Feedstock Provision	Waste Valorization	Commodity Production	Asset Optimization	Closure Optimization
Geochemical CDR:	Carbon Mineralization	**Surficial Mineralization** **also known as Industrial Mineralization**	Surficial Mineralization accelerates natural reactions between alkaline minerals, atmospheric CO_2, and water under ambient conditions to form solid carbonate minerals. Processed or ground alkaline mine tailings, waste rock, or slags are ideal feedstocks and can be carbonated directly on site.	█		▨		▨	▨
		Surface Water Mineralization **also known as Pit Lake Restoration**	Alkaline material is added to existing pit lakes, where it increases pH in order to draw down atmospheric CO_2 and precipitate out solid carbonates that then settle on the lake floor. Pit lakes are found exclusively on mining operations, and may be rehabilitated in the process of doing CDR.	▒		▨		▨	▨
		Reactor-based Mineralization with Co-products **also known as Direct Air Capture + Mineralization**	Electrochemical or thermal processes are used to produce an acid and a base, enabling the capture of CO_2 from the atmosphere and its storage in carbonate minerals, while recovering metals from input minerals. These processes can be integrated directly into the mining value chain, using wastes and enhancing the overall recovery of metals. These reactor-based approaches may pull from ambient CO_2 sources or incorporate CO_2 captured from the air, from biomass, or from water.	▓		▨	▨	▨	
	Alkalinity Enhancement	**Enhanced Rock Weathering** **also known as Terrestrial Enhanced Weathering**	Finely ground alkaline materials are spread onto soils, or arranged in heaps, to accelerate geologic weathering. Enhanced rock weathering primarily relies on mined or quarried feedstocks. Processes can be deployed directly on mining operations for non-agricultural purposes. Some wastes, for example kimberlites, may be safe for agricultural use.	▒ *There are larger opportunities to provide feedstock for **offsite** projects*	▨	▨		▨	▨
		Phytomining + Enhanced Rock Weathering	This process employs enhanced rock weathering on fields of hyperaccumulator plants, which are then processed to extract metals. It presents opportunities for carbon-negative metal production using low-grade ores.	░	▨	▨	▨	▨	▨
		Wastewater Alkalinity Enhancement **also known as Containerized Enhanced Weathering**	A CO_2-bearing fluid, namely wastewater, is contacted with alkaline materials in a reactor to accelerate weathering reactions and store carbon as bicarbonates, which are then released with the treated wastewater stream. Wastewater Alkalinity Enhancement is similar to other water treatment activities and could be applied to domestic wastewater treatment or the processing of any wastewater with high biogenic CO_2 content.	░ *There are larger opportunities to provide feedstock for **offsite** projects*	▨			▨	

Opportunity Level for CDR Deployment specifically within Mining Operations	░ Limited Opportunities	▒ Few Opportunities	▓ Some Opportunities	█ Significant Opportunities

Notes and sources: This table aims to summarize current technological trends in Mining CDR. It is not meant to be fully exhaustive and will evolve as new approaches are developed. Some overlaps may exist between the different technologies presented. We tried to remain consistent with our previous work regarding the denomination of approaches; however, some terms and abbreviations might differ from what is used elsewhere, and different industries often use different terms to refer to the same thing, e.g., carbon mineralization vs. mineral carbonation, or enhanced weathering vs. solubility trapping.

Geochemical CO_2 storage methods are also applicable

		CDR Method	Description & Mining Rationale	On-site Opportunity Level	Area of Relevance				
					Feedstock Provision	Waste Valorization	Commodity Production	Asset Optimization	Closure Optimization
Geochemical Storage:	In situ	**In Situ Mineralized Storage**	Concentrated CO_2 is injected into geologic wells where it mixes with water to form carbonic acid, reacting with rock formations to form stable carbonates. In Situ Mineralization can take advantage of geological formations in or near mining operations to act as CO_2 storage.	█				▨	▨
		In Situ Mineralized Carbon Storage and Metal Recovery also known as CO_2-Enhanced Metal Recovery[1]	A CO_2-bearing fluid is injected into subsurface mafic or ultramafic deposits in order to leach metals, such as nickel or cobalt, while also mineralizing CO_2 as carbonate minerals. Metals are returned to the surface through the fluids that circulate through the deposit.	█			▨	▨	▨
	Ex Situ	**Reactor-based Mineralized Storage**	Concentrated CO_2 is reacted with alkaline minerals above ground in a controlled environment to form stable carbonates. Alkaline material inputs from mining operations are ideal feedstocks, and this process can be located directly on mining operations. In some cases, carbonated outputs may be used as construction materials.	▓		▨	▨	▨	▨
		Reactor-based Mineralized Storage for Metal Recovery	Supercritical CO_2 is injected at pressure with ores *pre-comminution*, and then rapidly depressurized, breaking rock as it expands. As the surface area of rocks is increased, accelerated reactions with the CO_2 form stable carbonates. This process aims to reduce the costs and energy requirements of comminution while increasing mineral liberation.	▓			▨		

Opportunity Level for CDR Deployment specifically within Mining Operations	░ Limited Opportunities	▒ Few Opportunities	▓ Some Opportunities	█ Significant Opportunities

Opportunity levels for carbon storage within geological resources associated with mines are quite significant, however many of these storage methods are at low technology readiness levels, and more information through pilot and demonstration level projects is needed to understand practical and market constraints.

Notes and sources: This table aims to summarize current technological trends in Mining CDR. It is not meant to be fully exhaustive and will evolve as new approaches are developed. Some overlaps may exist between the different technologies presented. We tried to remain consistent with our previous work regarding the denomination of approaches; however, some terms and abbreviations might differ from what is used elsewhere, and different industries often use different terms to refer to the same thing, e.g. carbon mineralization vs. mineral carbonation, or enhanced weathering vs. solubility trapping. [1]More information can be found in the articles linked here and here.

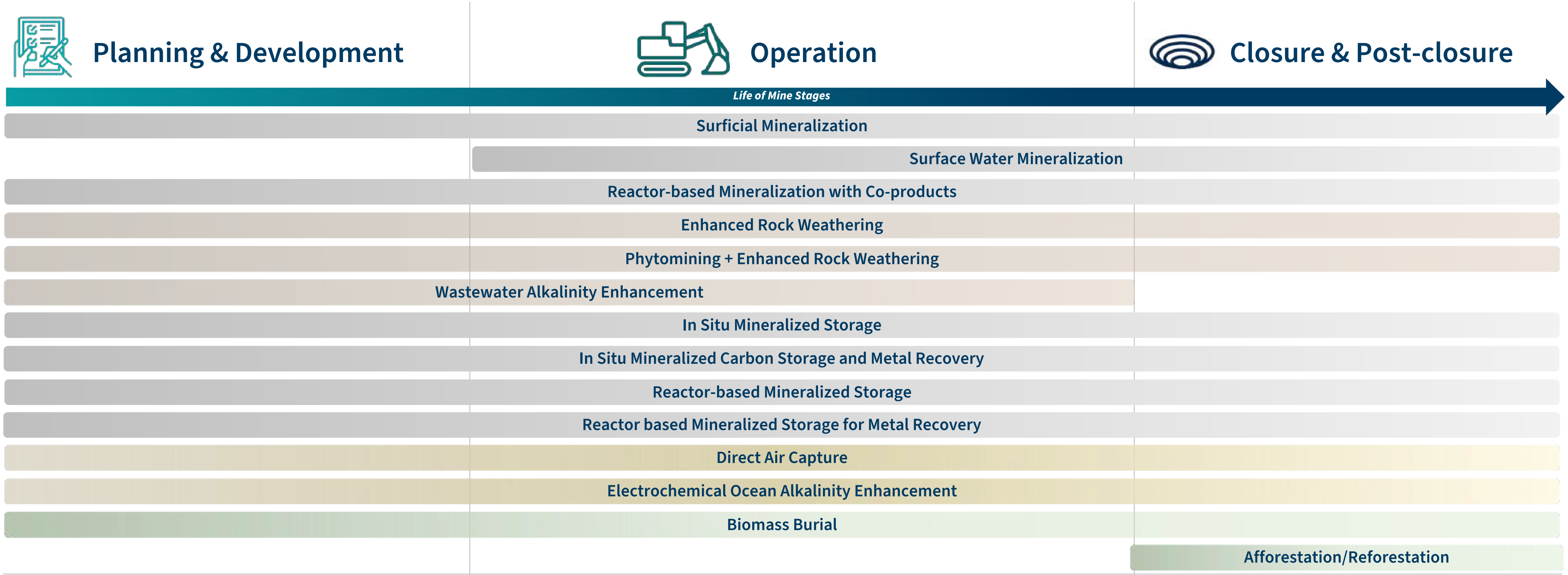
Synthetic and biogenic CDR methods offer additional Mining CDR options

	CDR Method	Description & Mining Rationale	On-site Opportunity Level	Area of Relevance				
				Feedstock Provision	**Waste Valorization**	**Commodity Production**	**Asset Optimization**	**Closure Optimization**
Synthetic CDR	***Direct Air Capture***	Using a range of technological processes and air contactors, ambient air is moved and filtered to recover atmospheric CO_2 that can then be stored permanently. Direct Air Capture technologies can be implemented on unused land areas and can co-utilize renewable / low-carbon energy sources that are increasingly deployed at mining operations. They can also be used as a source of CO_2 for operations on the mine site.	▒				▨	▨
	Electrochemical Ocean Alkalinity Enhancement	Electrochemical splitting of desalination brines to produce acids, which can then be further used, and bases, which can be mixed with seawater before returning to the ocean to draw down atmospheric CO_2. For mines relying on desalinated water, there are opportunities to reduce the overall emissions footprints and negative environmental impacts of waste brines. However, it is important to note these processes are only net negative if the acid is neutralized and not returned to the water system. Acids and bases produced may also be used for commodity processing.	░	▨			▨	
Biogenic CDR	***Afforestation/Reforestation***	Degraded ecosystems such as forests are rehabilitated through replanting and other technological means of assisted regrowth. Mine sites can be restored to prevent soil erosion or leaching, and certain tree/plant species have demonstrated the ability to absorb and remediate toxic chemicals.	█ *Opportunities are significant to reforest abandoned sites with no reclamation plans*				▨	▨
	Biomass Burial ***also known as Biomass Geological Sequestration***	Biomass products, including waste biomass, can be buried in sealed, anoxic underground areas, where they resist decay and release of greenhouse gases back into the atmosphere. Mines undergoing closure can take advantage of decommissioned underground spaces by using them as sealed locations for durable storage of dry biomass.	█				▨	▨

Opportunity Level for CDR Deployment specifically within Mining Operations	░ **Limited Opportunities**	▒ **Few Opportunities**	▓ **Some Opportunities**	█ **Significant Opportunities**

Notes and sources: This table aims to summarize current technological trends in Mining CDR. It is not meant to be fully exhaustive and will evolve as new approaches are developed. Some overlaps may exist between the different technologies presented. We tried to remain consistent with our previous work regarding the denomination of approaches; however, some terms and abbreviations might differ from what is used elsewhere, and different industries often use different terms to refer to the same thing, e.g. carbon mineralization vs mineral carbonation, or enhanced weathering vs solubility trapping.

Most CDR methods can be applied and monetized during active operations



Incorporating CDR into planning stages will ensure environmental compliance and optimize techno-economics. Most CDR pathways can be deployed as soon as operations are underway. Permitting and regulatory concerns are most efficiently addressed during the initial planning phases.

CDR can be implemented during active phases but may require retrofitting and modification of certain processes. During active operations, the focus is typically on mineralization processes, where fresh, high-reactivity tailings are treated as they are processed or deposited. Pathways leveraging processed water or desalination brines should be deployed during operational phases.

CDR can be implemented as an end-of-life approach to remediate a mine site as well as to extend commercial activity. Pathways that make use of land or assets after they are no longer needed would be deployed during closure or post-closure.

Notes and sources: [1]Precedents include these projects: ARCA deployed their pilot project with BHP during an operational phase; Canada Nickel is incorporating plans to carbonate materials from the Crawford Nickel Mine from the planning phase; Baie Minerals is leveraging vast quantities of legacy chrysotile tailings from the Baie Vert mine, post-closure. Constraints on timing of deployment will depend largely on the specific opportunity, including on permitting.

CDR can help restore post-mining landscapes and reactivate infrastructure

Several CDR processes may be suitable for implementation during the closure of mines, or as part of a remediation strategy for abandoned legacy sites. Multiple CDR methods can take advantage of remaining mine assets while contributing to the remediation of the site.

Key CDR opportunities for legacy mine sites in need of remediation

Mine Asset	CDR & CO_2 Storage Methods	End-of-Life Use
Mineral wastes	• Surficial Mineralization • Surface Water Mineralization • Reactor-based Mineralization • Enhanced Rock Weathering	Mineral wastes may be utilized through a variety of CDR approaches, including some that can generate valuable co-products, such as critical minerals.
Tailings storage facilities (TSF)	• Surficial Mineralization • Enhanced Rock Weathering	Mine tailings may be utilized after mines have closed down, provided that mineralization or weathering does not introduce hazards, e.g., negative impacts on geotechnical stability.
Subsurface voids or chambers	• Reactor-based Mineralization • Biomass Burial	Mineralized tailings or biomass can be sequestered in closed subsurface facilities (backfilling).
Pit lakes	• Surface Water Mineralization	Acidic pit lakes may be remediated through alkalinity addition and thus turned into a long-term carbon sink.
Land and rivers	• Enhanced Rock Weathering • Alkalinity Enhancement (rivers)[2] • Afforestation/Reforestation	Ecosystem restoration can potentially revive ecosystems and make land available for further uses.

CDR as a land remediation strategy

Afforestation/reforestation or other ecosystem restoration efforts can be a viable option to help transform former mine sites into carbon sinks, while harnessing a range of co-benefits such as biodiversity conservation or improved air quality. However, to be considered a valid CDR approach, the additionality and net-negativity of land restoration projects needs to be verified.

Repurposing retired coal assets

As part of efforts to reach global climate and health objectives, many countries are moving to retire coal mines and related infrastructure. Mining CDR can utilize expiring and devalued assets to create economic and environmental benefits for their operations, potentially supporting communities where coal is being retired in a transition to more sustainable forms of energy and industry.

Coal phase-out may provide opportunities to implement CDR, primarily through:

- Using coal fly ash, a combustion product in coal power plants, as a mineralization feedstock, even a few years after it is produced.
- Deploying CDR on closed coal mining operations, either by remediating land or by using subsurface assets to store biomass.

Notes and sources: [1]Popkin, 2022. [2]There is an opportunity to address some contaminated rivers through a pathway not explicitly covered here, called River Alkalinity Enhancement. More details can be found here.

The theoretical potential volume of Mining CDR is large: >1Gt per year

Determining potential volumes of carbon removal or carbon storage is challenging. Most estimates, including those below, are based on the theoretical capacity for alkaline mine wastes to sequester carbon based on volume and calcium(Ca) or magnesium(Mg) content. Practical constraints, including processing rates and material handling, low-carbon energy costs and availability, regulatory constraints, or undetermined baseline weathering rates, will limit actual deployable capacity. However, there is also significant runway for innovation in this domain, particularly in the development of novel activation technologies, and this could increase actual deployable capacity. As pilot and demonstration projects advance, we will learn more about developing more realistic CDR capacity estimates. **For now, the theoretical estimates are too compelling to ignore:**

From new and legacy tailings:

Our analysis conservatively estimates that **newly produced and historical tailings from mafic and ultra-mafic sites** could theoretically produce up to:

~ 520 $MtCO_2$/yr

via mineral carbonation

or

~ 810 $MtCO_2$/yr

via alkalinity generation[1]

From biomass burial:

Estimates on the potential scale of burying biomass within sealed subsurface voids are emerging and suggest volumes could reach:

~ 100 - 500 $MtCO_2$/yr

by 2040 using woody biomass and agricultural residue[2]

From waste rock:

While waste rock and overburden may be far less reactive than tailings, volumes are significantly higher. Including all mining waste streams increases theoretical potential significantly, though more work is needed to determine a realistic range. Current projections predict up to:

>1 $GtCO_2$/yr

from waste rock and overburden[3]

Capacity estimates are given for mineral feedstocks in general, rather than for specific Geochemical CDR pathways. At this stage, it would be unrealistic to project potential volumes for specific approaches as they are broken down in this report, given that many of the same feedstocks can be used for multiple pathways, and that technologies are still advancing. Ultimately, CDR volumes will depend on which pathways can be successfully scaled, as well as on what an optimal portfolio of approaches might look like for a given site. Details on feedstock needs for specific CDR pathways per tonne of CO_2 removed are provided in the Technical Appendix.

Notes and sources: Frontier Climate, which has unique visibility on emerging technologies, stated in June 2026 that they believe surficial mineralization has the potential to scale to 10 Gt per year. This would require purpose-built mining operations. See https://frontierclimate.com/writing/growth-amc. [1]RMI analysis of the annual tailings produced by operations in mafic-ultramafic rock types and the generalized geochemistry of each rock type. These calculations of theoretical potential do not consider limitations to reaction kinetics or practical and regulatory constraints that could limit actual deployment potential. [2]Estimates for CDR using biomass burial are based on the volumes of suitable organic wastes within economic distances to mines with subsurface voids, according to an assessment from Rewind. [3]Theoretical estimates are given in Discovery Alert's Carbon Dioxide Sequestration in Mining: Implementation Strategies and Technologies.

SECTION 4

The Business Case for Mining CDR

CDR has two primary commercial value propositions for mine operators

Waste management is a significant liability and operating cost for mines. Practices that reduce and transform waste are highly valuable to mine operators, as are interventions that reduce risk and strengthen safety, production, and earnings on active project sites. CDR activities can do all of this, while presenting mine operators with opportunities to improve environmental sustainability efforts, social license to operate, support from communities, and avenues for new strategic growth. These wide-ranging benefits can be grouped into two primary value propositions:

Risk management and strategic resilience

- **Evidence is accumulating that CDR applications can reduce site-level liabilities, operating costs, and risks** in several key domains:
  - **Waste transformation** and reduction
  - Improved **geotechnical stability** of tailings
  - Improved acid and metalliferous **drainage management**
  - Improved pit lake **water quality**

- **Responsibly integrating CDR could also help mine operators to strengthen their:**
  - **Environmental sustainability targets** and reporting
  - **Social license to operate** and overall reputation
  - **Support from communities, regulators, and other stakeholders** for specific potential projects

Monetization and strategic growth

Mine operators can generate CDR on-site and monetize the resulting carbon value through one of three pathways:

- Generating **carbon credits** to be sold in carbon markets
- Embedding the carbon value into **lower-carbon products** that command price premiums or address regulatory requirements that apply at the product level
- **Applying CDR internally** to satisfy internal carbon prices or targets, or to address regulations that apply at the corporate level

Mine operators can also:

- **Monetize co-products from on-site CDR activities**, which can include critical minerals, metals, and industrial raw materials
- **Sell more minerals and rocks as feedstock for CDR projects off-site**, including for Enhanced Rock Weathering, Alkalinity Enhancement, and oxide looping Direct Air Capture projects

CDR offers multiple opportunities to better manage risk on mine sites

Mine operators manage a wide range of long-term risks, including those related to safely managing large volumes of waste, geotechnical stability, acid drainage and metal leaching, water quality, closure outcomes, and environmental restoration needs.

Mining CDR methods can help address these risks and even turn them into opportunities. Some methods are better suited for waste transformation and reduction, tailings stability, or metal leaching; others for improving water quality, closure outcomes, or environmental restoration.

CDR Method		Waste Transformation and Reduction	Improved Geotechnical Stability	Improved Acid & Metalliferous Drainage Management	Improved Pit Mine Water Quality	Closure Confidence	Environmental Restoration
Geochemical CDR and Storage	Surficial Mineralization	Medium potential	Medium potential	Low potential	Low potential	Low potential	Low potential
	Surface Water Mineralization	Medium potential	Low potential	Unlikely	High potential	High potential	High potential
	Reactor-based Mineralization with Co-products	High potential	Unlikely	High Potential	Unlikely	Medium potential	Medium potential
	Enhanced Rock Weathering	Low potential	Unlikely	Unlikely	Unlikely	Low potential	Low potential
	Phytomining + Enhanced Rock Weathering	Low potential	Unlikely	Unlikely	Unlikely	Low potential	Low potential
	Wastewater Alkalinity Enhancement	Low potential	None	Unlikely	Unlikely	None	None
	Electrochemical Ocean Alkalinity Enhancement	Low Potential	None	Unlikely	Unlikely	None	None
	Reactor-based Mineralized Storage	Medium potential	Medium potential	Medium Potential	Unlikely	Unlikely	Unlikely
	Reactor-based Mineralized Storage for Metal Recovery	Medium potential	Unlikely	Medium Potential	Unlikely	Unlikely	None
	In Situ Mineralized CO$_2$ Storage	None	Unlikely	None	None	None	None
Biogenic CDR	Afforestation/Reforestation	None	Medium potential	Low potential	Unlikely	High potential	High potential
	Biomass Burial	Medium potential	Medium potential	Low potential	Unlikely	Medium potential	Medium potential

Sources: Renforth, 2019; RMI, 2023; WSP, 2026.

CDR on mining sites could theoretically improve safety and environmental impact metrics

CDR could potentially enhance existing mine safety efforts because:

1. Reduced waste means reduced safety issues associated with waste
2. Evidence suggests tailings stability can be improved
3. Metal leaching in water may be reduced
4. Closure could receive additional investment

Reporting area	Relevant metrics	Potential enhancements through CDR
Waste management	Hazardous waste, mineral waste / tailings volumes[4]	• Waste repurposing reduces tailings management and waste-rock management burdens
Tailings risk	TSF stability, consequence classification, GISTM / independent review, risk ratings[2]	• Surficial mineralization may improve tailings stability through carbon mineralization and cementation • Reactor-based mineralization creates carbonated materials that can be used for more stable backfill
Metal leaching and water quality	Water withdrawals, discharges, water quality, water-stressed-area exposure[3]	• Mineralization can immobilize metals, reducing contaminant mobility • Surface water mineralization can neutralize acidic pit lakes and improve pit water quality • Wastewater alkalinity enhancement improves pH and treatment performance in water systems
Closure & stewardship	Closure progress, landform stability, long-term liability indicators	• Closure-aligned CDR helps improve landform stability, closure confidence, and long-term monitoring outcomes • Pit lake mineralization converts problematic pit lakes into a managed closure asset • Biomass burial can help to backfill voids or pits where conditions are suitable

See Section 8, Environmental and Social Considerations, for more detail on environmental considerations related to Mining CDR

Sources: [1]BHP, 2026a; Rio Tinto, 2026a. [2]BHP, 2026b; Rio Tinto, 2026b. [3]BHP, 2026c. [4]Rio Tinto, 2026c.

Carbon mineralization may strengthen the stability of mine tailings

Early evidence

Peer-reviewed laboratory anchor – Power et al. (2021)[1]

In brucite-bearing ultramafic tailings, in situ carbon mineralization produced cemented specimens with brucite consumption of 64-84% and unconfined compressive strengths that would be sufficient in most scenarios to adequately stabilize tailings.

Operator pilot/test – WSP/BHP Mt. Keith (2025)[2]

On Mt. Keith, increased undrained peak shear strength was observed in nickel tailings through carbon mineralization through direct aqueous CO_2 exposure. Measurable strength gains appeared within weeks in real tailings. The results demonstrate that carbon mineralization has the potential to enhance the strength of nickel tailings.

More research is needed, especially over sustained periods of time in operational settings, for nickel tailings and for other tailings types.

What still needs to be tested

- Longevity of strength gains under operating and closure conditions
- Brittleness, permeability, and post-peak or liquefied strength behavior
- Performance across heterogeneous tailings in operational settings
- Risks associated with disturbance, exposure, or changes to drainage and water balance
- Measurement thresholds and monitoring requirements that can support safety, liability and carbon claims

Implications for operators

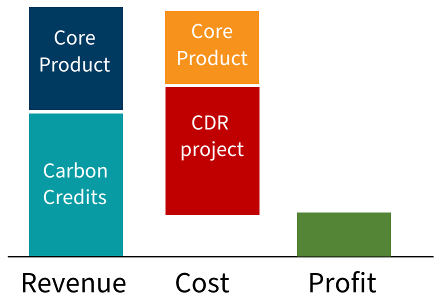
Gains in tailings stability from carbon mineralization interventions could deliver valuable improvements in safety, continuity, closure, and liability, alongside CDR.

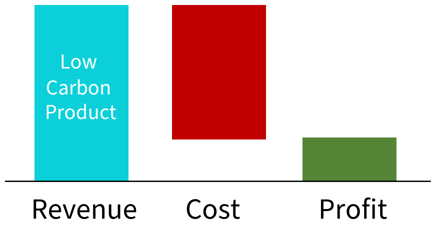
Investment committees will likely require site-specific geotechnical evidence to validate safety benefits and should budget for ongoing monitoring and contributions to the scientific evidence base.

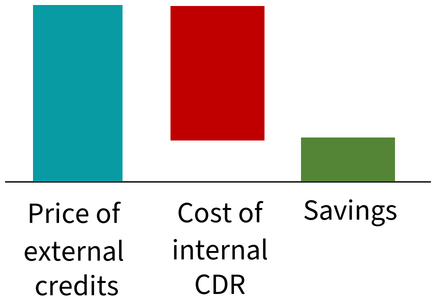
Sources: [1]Power et al., 2021. [2]Jimenez et al., 2025.

Mine operators can monetize CDR through three different pathways

	What it looks like in practice	Value driver	Challenges
1 **Generate carbon credits** to be sold in carbon markets	- For credit eligibility, **CDR projects on mine sites must require external carbon credit revenue streams to be economically viable**—and thus additional - in the eyes of credit registries - Mine operators and/or project developers should **engage with third-party registries and verifiers** to seek the issuance and verification of credits, to be sold to external buyers that are purchasing voluntarily or to comply with regulations or participate in other programs - **Double counting must be avoided**, e.g., CDR values must not be applied to issuers' emissions reporting or the Core Product (though undifferentiated products can be sold and contribute to revenue)	- **Market value of high-quality CDR** carbon credits	- **Demand** volume / certainty - **MRV** (additionality, baselines, permanence)
2 **Embed carbon value into low-carbon products** that command price premiums or address emissions regulations that apply at the product level	- **Products derived from Mining CDR, e.g., construction aggregates and binders** from mineralization, are sold with associated low- or net-zero claims - The carbon attribute is **monetized through product premiums** or by addressing emissions regulations that apply at the product level, such as **Carbon Border Adjustment Mechanisms (CBAMs)** - The carbon claim is **typically governed via Environmental Product Declarations** or other product standards, with credit generation occurring (if at all) downstream	- **Premium for Low Carbon Products** versus undifferentiated products - Emissions regulations on products, e.g., **CBAMs**	- **Market formation** for differentiated products - **Regulatory uncertainty**
3 **Apply CDR internally** to satisfy internal carbon prices or targets, or to address emissions regulations that apply at the corporate level	- CDR is **used to abate internal corporate emissions**, e.g., Scope 1 or 3, with no on-product claims, **or to address emissions regulations that apply at the corporate level**, such as emissions trading schemes or taxes focused on industrial emitters - **Value is realized via avoided procurement of credits** from third parties or crediting against internal carbon pricing	- Internal **carbon price** - Value of **savings** and risk diversification vs. reliance on external credits	- Lack of clear **guidelines on insetting CDR** - **Regulatory uncertainty**





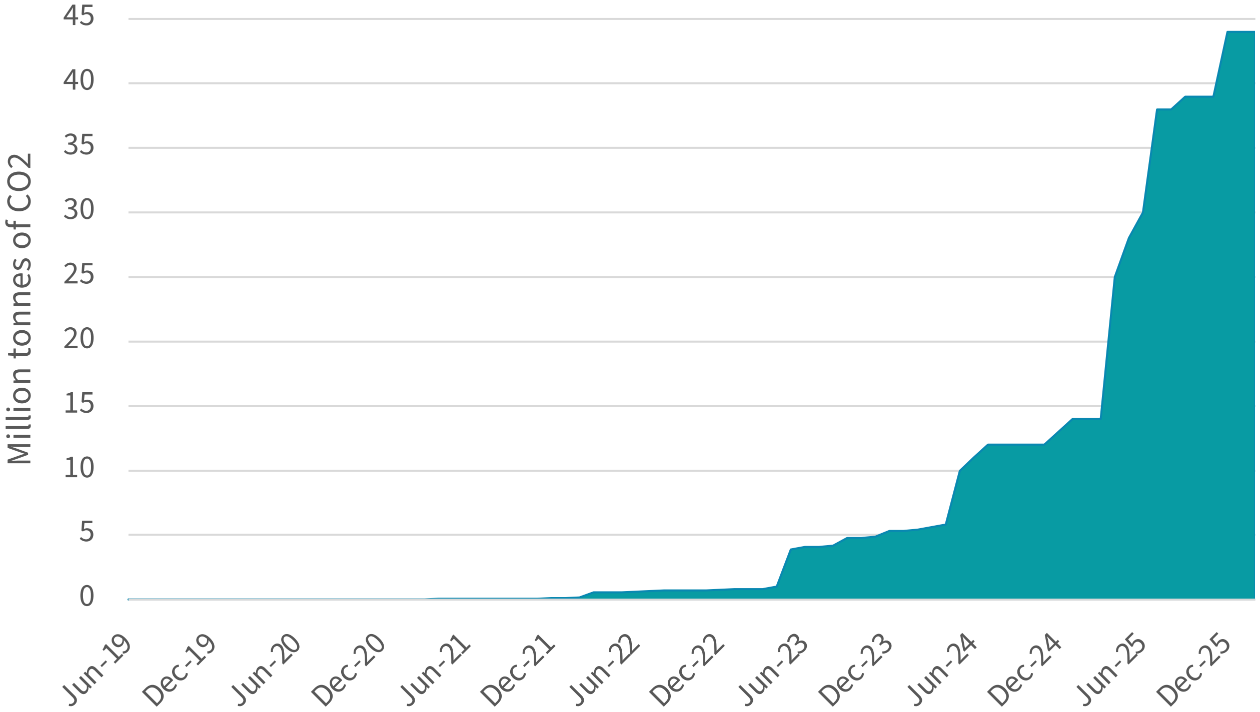


The market for durable CDR credits is early, but growing

Purchasing is currently driven by voluntary corporate credit purchases. Big tech companies dominate high volume purchases, accounting for roughly 80% of purchases in 2024, with Microsoft alone representing ~79% of contracted durable CDR tonnes[1].

The number of participating buyers is expanding. Market reviews report that more than 100 new buyers entered the durable CDR market in 2025, with growing engagement from sectors such as finance, professional services, and early movers in aviation and industry. However, their purchases have been modest in size thus far, relative to tech leaders.[2]

Cumulative CDR credit sales



Over 30 million tonnes of durable CDR was sold in 2025, more than double the volume of all prior years combined.

Notes and sources: [1]CDR.fyi [2]Climeworks, 2025; Carbon Credits, 2025. Graph displays cumulative sales of CDR from cdr.fyi (accessed February 26, 2026).

Governments are beginning to engage with, and shape, CDR markets

The international landscape for carbon removal is evolving, with steadily increasing government interest, funding, and rulemaking on selective topics

1. **Direct procurement and sectoral demand signals** are emerging—with limited funding
2. **Standards and certification infrastructure** is hardening—but narrowly
3. **Integration into regulatory systems** is becoming more tangible—but remains selective and pathway-specific

Canada is advancing: the Advanced Carbon Removal Coalition to mobilize CA$100 million in demand and investment into CDR by 2030, a CDR protocol under its Greenhouse Gas Offset Credit System[1], and, at the provincial level, Carbon Management Frameworks that include CDR.

The European Union proposed in July 2026 the purchase of up to 250 Mt of permanent CDR from 2031-2040, using funds from auctioned Emissions Trading Scheme allowances. The EU's Carbon Removal and Carbon Farming framework informs which projects are allowed - currently BioCCS and DACCS.[5] (***See also Appendix 2***.)

Through Article 6.4 of the Paris Agreement, the **United Nations** is facilitating trade in CDR credits and defining quality standards; however, fully approved mechanism methodologies are limited.[3]

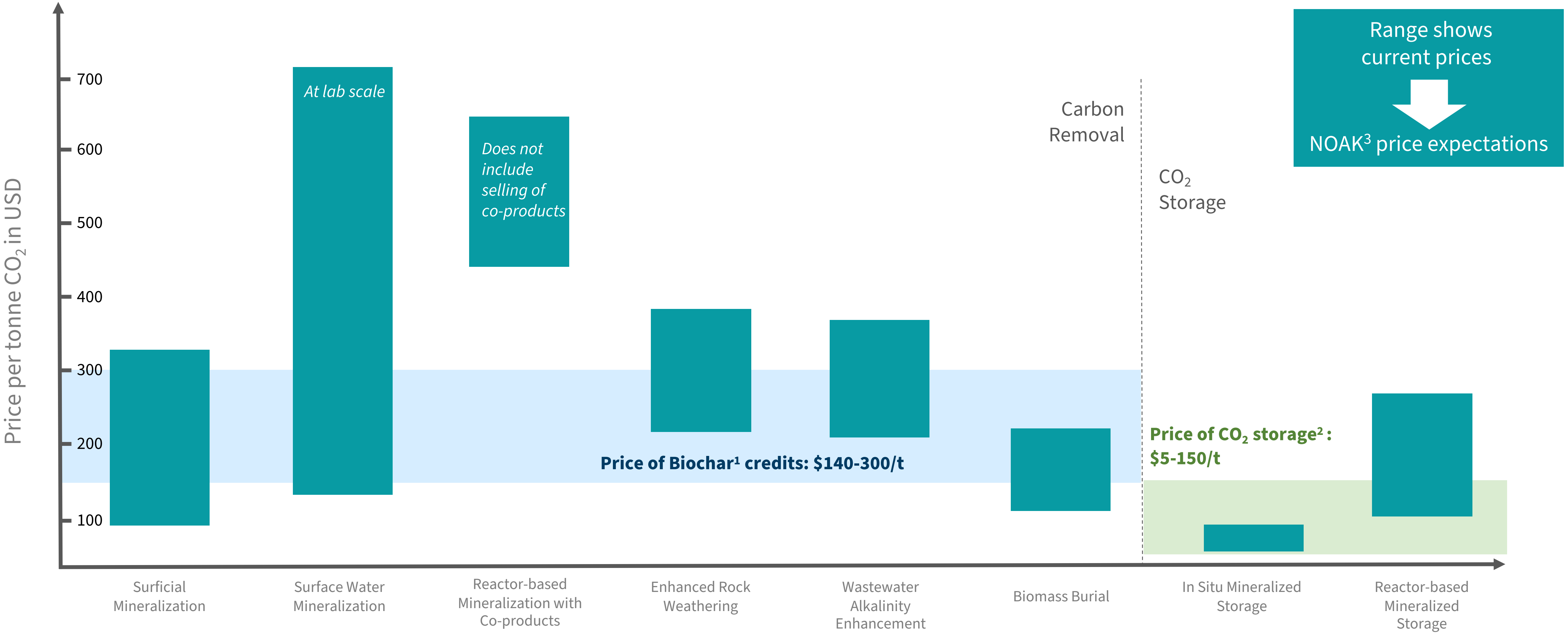
The Carbon Offsetting and Reduction Scheme for International Aviation (**CORSIA)** allows the aviation industry to purchase CDR credits to offset emissions.[6]

California regulators are working on integration of CDR under the Cap-and-Invest program. Direct Air Capture is included in the state's Low Carbon Fuel Standard.[2]

Japan allows CDR to cover up to 5% of a company's total greenhouse gas emissions under its Green Transformation Emissions Trading Scheme (GX-ETS), including from projects outside Japan.[4]

Notes and sources: This list is not exhaustive. In addition to directly supporting demand, many countries support research, development, and deployment (e.g., for pilot projects) through grants and tax credits. [1]Canada Low Carbon Fuel Procurement Program; Canada Greenhouse Gas Offset Credit System [2]US CDR Pilot Purchase Prize appropriations [3]Article 6.4 Overview; California LCFS; California SB 905 [4]Japan GX-ETS and CDR [5]EU ETS CDR integration; UK ETS CDR integration; UK and EU ETS linkage; EU CRCF [6]CORSIA Isometric approval.

Mining CDR is expected to be highly price-competitive in CDR markets



Notes and sources: [1]Biochar is a form of CDR that pyrolyzes waste biomass, burning it without oxygen, in order to reduce the biomass content to its carbon component. Carbon removal credits produced from biochar are among the most purchased forms of CDR, and biochar itself has a host of applications. Prices are highly competitive in a range between $140 - 300/tCO$_2$. [2]CO$_2$ Storage costs can range from $5-147/tonne depending on whether storage is located onshore or offshore. More on CO$_2$ storage costs can be found in the Cost of CO$_2$ Storage. [3]NOAK = Next of a Kind Projects

In a developed CDR market, Mining CDR could earn billions of dollars annually

Demand for durable CDR will vary depending on policy pressure but is projected to range from $20 – 135 billion per year in 2040[1] , and $100 - 500 billion in 2050.[2] Projects conducted in partnership with experienced mine operators can reduce the financing, development, and operational risks[3] that are still common across early CDR deployments.

Method	Annual site-level revenue	x	Number of viable sites (example)	=	Annual potential revenue across all sites	vs.	Estimates of the total addressable market for durable CDR
Carbon mineralization at nickel, chromium, or titanium mines, legacy asbestos mines, or other mines that become viable over time as technology evolves	**$40 – 200M** ***Key assumptions***: *(1) 2-4 Mt of reactive tailings per site per year* *(2) 0.25 tCO$_2$ removed per tonne of tailings feedstock* *(3) Prices at $80-200 per tCO$_2$ removed*		**100 sites** ***Key reference points:*** *(4) ~127 nickel, chromium, titanium mines exist worldwide* *(5) There are ~142 legacy asbestos mines in the US alone*		**$4-20B** **50-100 Mt of CDR** *This equates to 4-20% of BCG's low-end estimate for CDR demand in 2050 of $100B.* *The volume estimate also equates to ~10-20% of the estimated total annual physical potential estimated by RMI (520 Mt per year).*		**By 2040[1]**: • 80-870 Mt CO$_2$ per year • $20-135B **By 2050[2]**: • 0.5-2.5Gt CO$_2$ per year • $100-500B
Biomass burial at retired coal mines and other sites in need of backfill material for sealed caverns	**$0.5-5M** ***Key assumptions***: *(6) Between 5,000-50,000 tCO$_2$/y stored at a single site* *(7) Prices at $100 per tCO$_2$ removed*		**1,000** ***Key assumptions:*** *(8) A fraction of the ~6,900 coal mines around the world could be at least partially backfilled using biomass*		**$0.5-5B** *This equates to 0.5-5% of BCG's low-end estimate for CDR demand in 2050 of $100B.* *The volume estimate equates to ~1-10% of the estimated total annual physical potential estimated by RMI (500 Mt per year).*		

Key assumptions are explained further on the following page.

Notes and sources: [1]The Time for Carbon Removal Has Come (BCG 2023), [2]Scaling CDR: Demand Drivers for Durable Carbon Removal (BCG 2024), [3]Supercritical's report Delivered or Delayed has more context on delivery risks within the CDR market. [4]Global Energy Monitor, 2026, [5]Ram Amar, 2025; Rewind, 2026.

In a developed CDR market, Mining CDR could yield billions of dollars annually:

Backup for key assumptions and reference points

#	Key assumption / reference point	How values were determined
(1)	2-4 Mt reactive tailings per site per year	Rough estimates for tailings volumes per site were estimated from data provided for nickel operations in *Rock-to-Metal Ratio: A Foundational Metric for Understanding Mine Wastes*[1] using data in Table S4 [(Attributable Ore Mined – Commodity Contained in Processed Ore)/Number of Operations]. For nickel this comes to 3.3 Mt tailings/site.
(2)	0.25 tCO$_2$ removed per tonne of tailings feedstock	This report documents ranges for reactivity of ~0.2 - 0.75 (see section 6 for more on mineral feedstocks). A conservative estimate of 0.25 was chosen here. For mineral inputs which are more reactive, or which could undergo economically efficient thermal preprocessing, project revenue should increase.
(3)	Prices at \$80-200 per tCO$_2$ removed	Frontier Climate has estimated costs for surficial mineralization will drop to under \$80/tCO$_2$ through their diligence behind the Quebec Surficial Mineralization Hub.[2] This report estimates current prices are \$330/tCO2 and that prices will drop to ~\$100/tCO$_2$ for Next Of A Kind (NOAK) projects (see Technical Appendix). The value of \$200/tCO$_2$ was chosen as a representative average as prices drop.
(4)	~127 nickel, chromium, titanium mines exist worldwide	Values for nickel, chromium and titanium operations were given in *Rock-to-Metal Ratio: A Foundational Metric for Understanding Mine Wastes.*[1]
(5)	There are ~142 legacy asbestos mines in the US alone	The United States Geological Survey reports 142 legacy asbestos mine sites.[3]
(6)	Between 5,000-50,000 tCO$_2$/y stored at a single site	The company Rewind is anticipating storage capacities of up to 50,000 tonnes per year by 2028.[4]
(7)	Prices at \$100 per tCO$_2$ removed	This report assumes prices will decrease to \$100-150/tCO$_2$ (see Technical Appendix).
(8)	A fraction of the ~6,900 coal mines around the world could be at least partially backfilled using biomass.	The Global Energy Monitor tracks 6,900 coal mines globally[5]; its May 2025 dataset counts 1,485 closures from 2015–2024, including 1,173 in the U.S. alone.[6]

Notes and sources:[1]Rock-to-Metal Ratio: A Foundational Metric for Understanding Mine Wastes, Supplementary Data found here. [2]Launching the Quebec Surficial Mineralization Hub [3]Reported Historic Asbestos Mines in the United States, [4]Mines are Carbon Infrastructure; [5]Global Energy Monitor, 2026. [6]United States Environmental Protection Agency, 2026.

Mining CDR activities could also generate monetizable byproducts

Some Mining CDR activities may create additional monetizable byproducts, in addition to carbon removal.

In particular, carbonation-assisted leaching and In Situ Mineralized Carbon Storage and Mineral Recovery can help mobilize and recover critical minerals, while some electrochemical carbon mineralization pathways can also produce low-carbon industrial raw materials such as sulfuric acid, phosphoric acid, calcium carbonate, and alkaline materials. In certain in situ systems, these same reactive conditions may also stimulate geological hydrogen generation.[1,2,3]

Mining CDR process	Byproducts		
	Critical Minerals	**Industrial Raw Materials**	**Geologic Hydrogen**
Reactor-based Mineralization with Co-products: *Acid leaching / hydrometallurgical pathways*	Cobalt, copper, nickel (pathway-dependent)	Phosphoric acid; sulfuric acid; MgO / low-carbon MgO; alkaline oxides; silicates	NA
Reactor-based Mineralization with Co-products: *Electrochemical extraction pathways*	Copper, nickel, rare earth elements	Sulfuric acid; phosphoric acid; calcium carbonate / limestone; calcium hydroxide / slaked lime; low-carbon cement materials	NA
In Situ Mineralized Carbon Storage and Mineral Recovery	Cobalt, copper, nickel	NA	Yes

Notes and sources: [1]Yan et al., 2026. [2]WSP, 2026. [3]Lammers et al., 2023.

In a developed CDR market, mine operators could also generate billions of dollars per year by supplying feedstock for CDR off-site

Enhanced Rock Weathering projects on croplands and coasts, such as those being deployed by Mati Carbon and Project Vesta, Mineral Alkalinity Enhancement methods, such as those being piloted by Planetary, CREW, and Carbon Run, and Direct Air Capture methods that rely on mineral oxide looping, as Heirloom does, all require alkaline mineral feedstock as their primary input.

If these CDR methods scale, the demand for feedstock from mines and quarries will be significant.

The table on the right estimates the tonnes of mineral feedstock required to deliver on outstanding delivery commitments for these three emergent CDR pathways and estimates potential feedstock market growth through 2050 assuming a compound annual growth rate for Enhanced Rock Weathering and Mineral Alkalinity Enhancement of 10-20% per year.

BCG projects the overall durable CDR market could be $100 – 500 billion in size in 2050; the implied feedstock market values in 2050 of $297 million – 8.1 billion for Enhanced Rock Weathering and Mineral Alkalinity Enhancement feedstock sales could be accommodated comfortably within such a market.

Illustrative and indicative estimates

Pathway	Enhanced Rock Weathering	Mineral Alkalinity Enhancement	Direct Air Capture	Total
Outstanding delivery commitments[1] (tonnes of CO_2)	742,347	263,828	2.44M	
Assumed average delivery timeline (years)	10	10	10	
Feedstock needed per tonne of CO_2 delivered (tonnes)	3-5[2]	1-3.5[3]	TBD	
Implied volume of feedstock needed to meet current commitments (tonnes)	2.2 – 3.7M	263,828 – 923,398		
Type of feedstock*	Basalt	Limestone		
Market price per tonne ($)	$10[5]	$30-70[6]		
Implied market value today ($ per year)	**$22.3 – 37.1M**	**$7.9 – 64.6M**	**TBD**	**$30.1 - 102M**
Projected CAGR through 2050	*10-20%*			
Implied market value in 2050 ($ per year)	**$219M - 2.9B**	**$78M – 5.1B**	**TBD**	**$297M – 8.1B**

Depends on penetration achieved by oxide-looping approaches to DAC

Notes and sources: *Basalt and limestone were chosen here as a simplifying assumption to support indicative estimates; they are the feedstocks most commonly used but many ERW and MAE suppliers use other feedstocks that have other price-points. [1]CDR.fyi Leaderboards; CDR.fyi refers to "Mineral Alkalinity Enhancement" as "Alkalinity Enhancement". [2]Beerling et al., 2020 https://www.lithoscarbon.com/ and https://www.bbc.com/news/science-environment-65648361. [3]RMI, 2023 and Renforth et al., 2017. [5]Breunig et al., 2024 and Between a Rock and a Hard Cost: The Economics of Enhanced Weathering. [6]https://aggregatemarkets.com/en/products/limestone (accessed 6/1/26).

CDR on mine sites also poses risks, the cost of which should be budgeted for

Additional risks that arise through new CDR activities may impact operational controls, as well as health, safety, and environmental management. Costs to address these risks are uncertain, given the novelty of CDR activities on mine sites, but could be significant. For now, we provide some context on some expected costs that should be budgeted for. More details on environmental and safety considerations are given for each of the CDR approaches in Section 8.

Area	Potential risks due to CDR interventions	Cost considerations
Critical Control Management[1]	CDR can challenge existing controls previously identified through Critical Control Management (CCM) practices, especially concerning health and safety measures already in place.	• Additional scoping and identification of controls, alongside plans for addressing risks and verification activities
Waste management and tailings risk	Disturbing tailings can affect geotechnical stability, drainage, pore pressure, seepage, dusting, or contaminant mobility. Legacy TSFs are especially sensitive because disturbance can reopen previously stabilized risks.	• Engineering review, updated stability studies, and assessments for safety measures • Additional monitoring for tailings that are disturbed
Water management	Weathering, alkalinity addition, or CO_2 injection can mobilize metals, change pH too quickly, affect groundwater or aquifers, alter pit-lake ecology, or increase water demand in stressed basins.	• Increasing water treatment capacity • Additional monitoring of wells • Compliance costs to address changes in water chemistry
Air quality	Dust and fine particles may be suspended through active handling and processing of rock and mineral feedstocks.	• Increased need for water and dust suppression • Increased monitoring
Workforce safety	Added material handling, grinding, spreading, or transport can increase worker exposure to dust, mobile equipment, reagents, or unstable surfaces. Some feedstocks may contain asbestiform minerals, trace metals, sulfides, or radioactive materials.	• Additional workforce training • Additional Personal Protective Equipment (PPE)
Closure & stewardship	Poorly designed CDR can complicate closure plans, extend monitoring obligations, create unclear long-term carbon or site liability, or introduce uncertainty around post-closure landforms, underground voids, pit lakes, or biomass storage.	• Revision of closure plans for CDR integrated into mines already in operation • Extended monitoring obligations • Additional insurance
Consumer protection scrutiny	Carbon crediting projects are subject to scrutiny from the media and, in some jurisdictions, consumer protection agencies and regulators regarding false or misleading claims.	• Robust science and MRV for carbon outcomes and claims • Legal and media risk management diligence and review • Additional evidence demonstrating any environmental benefits

Notes and sources: [1] See ICMM's Good Practice Guide on Critical Control Management for more information.

To justify costs projects will need to demonstrate value in key investment criteria below

The table below summarizes how additional value can be generated through overall safety improvements, increased production, and increased revenue.

Criteria	① Safety	② Production	③ ROIC / EBITDA
Definition	Protect people, assets, communities, and the environment by reducing operational, geotechnical, geochemical, water, or closure risk.	Increase production through the potential acceleration of pre-production processes, such as permitting and community approval, repurposing wastes into valuable products, or expanding production to provide feedstock for off-site CDR.	Improve returns on invested capital by reducing costs, liabilities, or capital burdens, or by creating significant additional revenue without significant additional capital expenditure.
How Mining CDR could potentially deliver value[1]	• Mineralization may improve the geotechnical stability of tailings piles. • Mineralization immobilizes metals to reduce leaching risk. • Pit lake mineralization helps reduce water quality risks. • Closure-aligned CDR helps reduce long-term safety and liability risk.	• The carbon removal value and other environmental benefits of CDR interventions can strengthen regulator and community trust and help secure approval pre-production. • During active projects, more material can be transformed into valuable products, thereby reducing waste. • Mines and quarries can expand production to provide feedstock, such as basalt, limestone, or magnesite, for off-site CDR activities.	• Waste management liabilities and costs can be reduced, as more material is converted to physical products and/or monetized removal credits. • Increased production from existing land, waste, equipment, and infrastructure increases returns on committed capital.

Notes and sources: [1]This list is illustrative and non-exhaustive.

The operators that can screen, prove, and replicate projects will shape the Mining CDR opportunity

In-house projects can create a strategic moat

- Operators can develop and deliver Mining CDR internally, using their own assets, processes, and governance systems
- They can then directly control feedstock, siting, operations, research and development, monitoring plans, and claims strategies
- They will be able to build early advantages by executing and governing projects well, while developing technical and commercial expertise

Learning compounds across an asset portfolio

- Early projects build practical capability in site screening, permitting, safeguards, data collection, MRV, valorization, and closure integration
- Replication across additional sites could reduce future diligence costs and shorten decision cycles
- Eventually, operators could build reusable playbooks for evidence generation, internal diligence and decision-making, and deployment

Successful projects will shape norms, markets, and standards

- Projects with strong verified outcomes will shape MRV protocols, industry standards and norms, the expectations of third-party registries, buyers, and financiers, and regulation
- Commercial terms, contracts, and practices established during early projects, for example on intellectual property, economics, and liability, are likely to become common practice

Frontrunners can set a high bar for responsible, high-integrity deployment and equip others

- Frontrunners that visibly demonstrate what good looks like can become a widely referenced example for communities, regulators, the media, and third-party financiers and off-takers
- Frontrunners that share useful learnings and tools from their experience can encourage peers and competitors to engage, and reduce the cost for them to start

The Business Case for Mining CDR: mine operators that move early to develop strong projects can gain valuable strategic capabilities and advantage

1 Two key value drivers

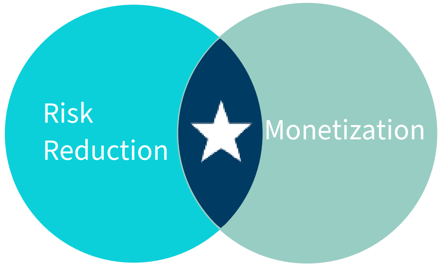
Risk management and strategic resilience

Less waste, safer sites, stronger sustainability, SLO, and support from communities and regulators for new projects

Monetization and strategic growth

CDR on-site monetized as credits, products, or at the corporate level; sales of byproducts and feedstock for CDR off-site

2 Best sites and projects stack both



Priority sites and projects

Projects that transform waste management liabilities into monetizable products are prime candidates.

3 Early capability compounds

Companies that build strategic capabilities early will be better positioned to compete and win

- Screening and prioritization
- Deployment and operations
- MRV and audit-ready claims
- Product offerings (CDR, low-carbon products)

Sustained competitive advantage from:

- Economies of scale, scope, and learning
- Shaping markets, standards, and rules

SECTION 5

Landscape of Mining CDR Activity

Many emerging CDR developers rely on mineral feedstocks, mining infrastructure, or both

The emergence of companies actively pursuing Mining CDR project development is a recent phenomenon.

Catalyzed by a myriad of factors, including the development of SBTi in 2021, the proliferation of corporate net-zero commitments, and the completion of the first offtake agreements, Mining CDR is expected to undergo additional growth this decade as more companies recognize the economic and environmental benefits of integration.

RMI has identified multiple emerging innovators in CDR whose activities are either directly or indirectly related to the mining industry. Here, these innovators are grouped by their primary CDR activity, but overlaps exist, and there may be cases in which projects or companies deploy more than one CDR method at a time.

Surficial Mineralization

- ANVIL
- ARCA
- Karbonetiq

In Situ Mineralization & Storage

- 44.01
- cella
- DEEP SKY
- ROCKBURST TECHNOLOGIES
- CO2LOCK
- Carbfix

Enhanced Rock Weathering

- Mati
- InPlanet
- alt carbon
- LITHOS
- ZeroEx
- CARBONAUGHT
- Terradot
- TAMBORA CARBON REMOVAL
- UNDO
- FLUX
- CARBON NEUTRAL INITIATIVE
- silica
- GREEN SEQUEST
- Silicate
- Metalplant
- VESTA

Reactor-based Mineralization & Storage

- Paebbl
- CET Cambrian Environmental Technologies
- travertine
- GREENORE
- EXTERRA carbon solutions
- MCi CARBON
- ECO2 MAGNESIA
- Aspiring Materials
- Yuanchu Technology
- REVORA MATERIALS
- SKYRENU
- neustark Removing CO2 permanently
- CARBON CURE
- ATLAS
- Blue Planet Systems
- carbon8
- Auxilium
- CARBONYX
- COreactive
- Alithic Carbon Solutions
- BAIE Minerals Inc.

Biogenic CDR

- Rewind
- Living Carbon

Surface Water Mineralization

- Aquarry

Alkalinity Enhancement

- CREW
- PLANETEERS
- VYCARB
- FV
- Limenet
- CAPTURE6
- PRONOE
- CarbonRun
- PLANETARY
- ALKAMY CARBON
- Ebb

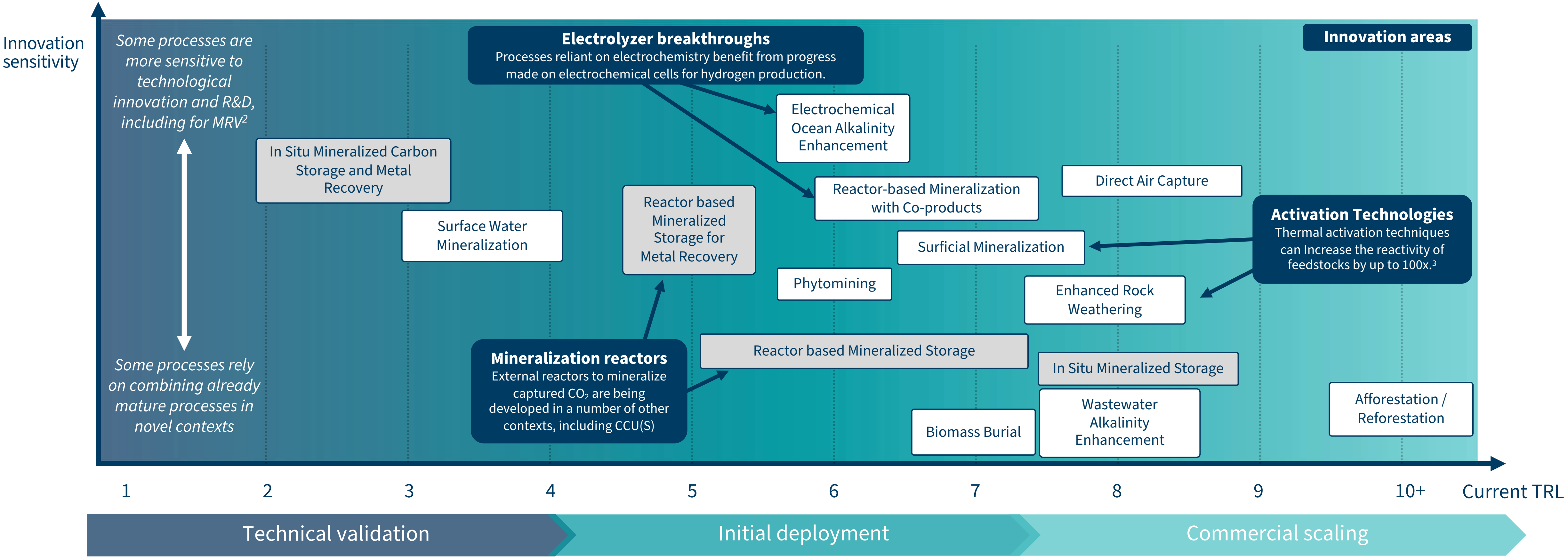
Note: This representation provides a non-exhaustive overview of the landscape of Mining CDR developers and will evolve in the future. Companies were categorized based on their main activity, but it should be noted that some activities may overlap or correspond to several of the CDR processes presented here.

Innovation is advancing across Mining CDR Pathways

Technology Readiness Levels (TRLs) of Mining CDR processes and their responsiveness to technical innovation[1] are shown below, based on where existing pilot and demonstration scale projects are as of publication of this report. TRLs are explained further in the Technical Appendix.

End-to-End CDR

CO_2 Storage Options



Innovation sensitivity

Some processes are more sensitive to technological innovation and R&D, including for MRV[2]

Some processes rely on combining already mature processes in novel contexts

Innovation areas

Electrolyzer breakthroughs
Processes reliant on electrochemistry benefit from progress made on electrochemical cells for hydrogen production.

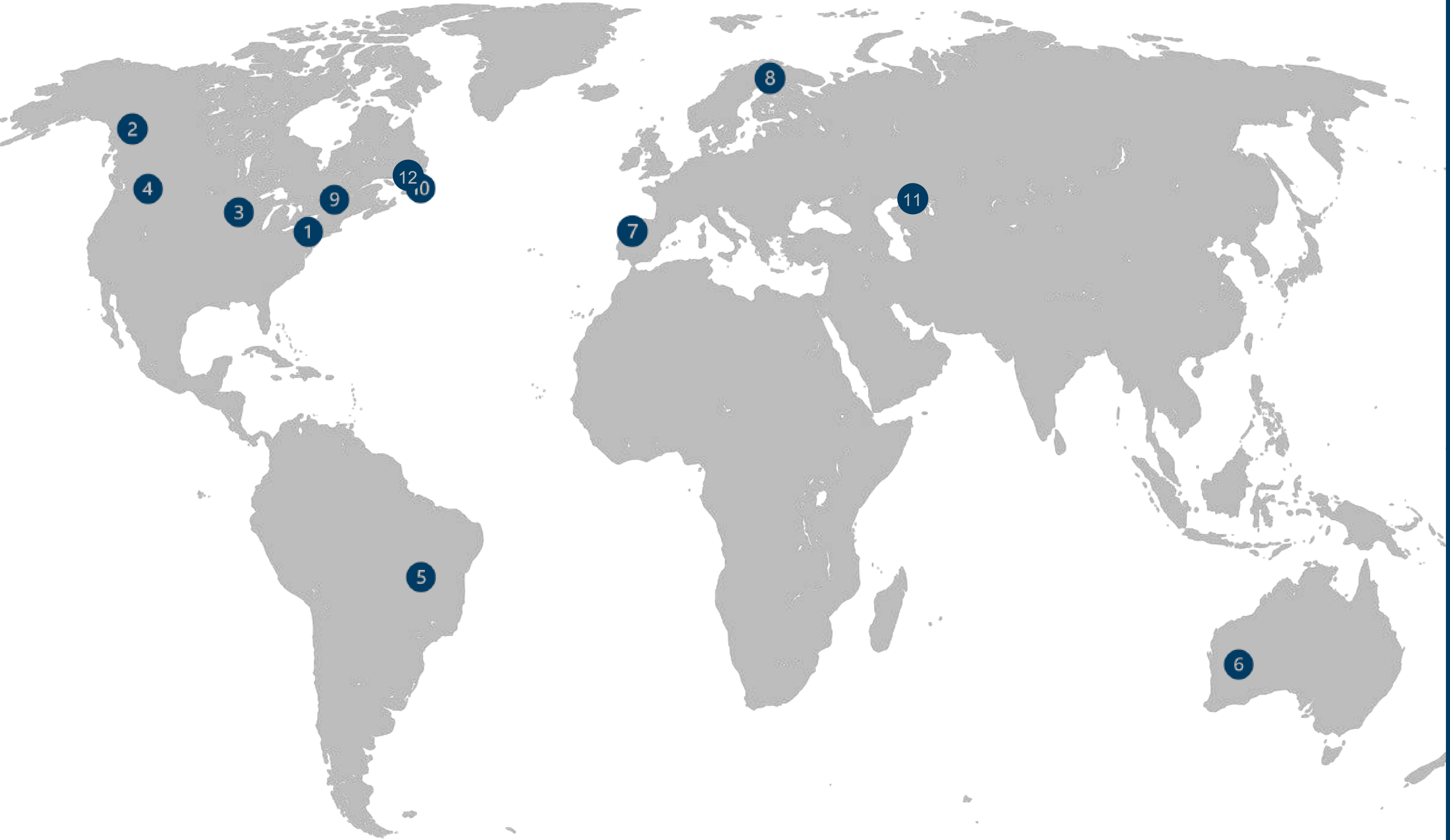
Mineralization reactors
External reactors to mineralize captured CO_2 are being developed in a number of other contexts, including CCU(S)

Activation Technologies
Thermal activation techniques can Increase the reactivity of feedstocks by up to 100x.[3]

Technical validation	Initial deployment	Commercial scaling
Basic science and RD&D, health and ecosystem impacts, measurability	GHG accounting, infrastructure, offtake, FOAK financing, permitting	Scaled incentives, standards, public will, supporting narratives

Notes and sources: [1]The TRLs shown here refer to the overall maturity of the processes but do not depict maturity levels in a mining context specifically. For instance, although In Situ Mineralization is at TRL 9, it has not yet been implemented in a mining context. Although TRLs are a useful indicator, they only provide a partial view of the overall maturity and development of technologies. More details on how TRL levels are determined are found in the Technical Appendix. [2]MRV, or Monitoring, Reporting and Verification, is described further in Section 6. [3]ARCA's Mineral Activation technology uses microwave radiation to break down mineral structures for faster and more efficient weathering and mineralization.

Research and pilot projects span the globe



Project Developer & Location

1 - Travertine & Sabin Metals **2024 - present**
Reactor-based Mineralization with Co-products
Rochester, New York, United States

2 - ARCA & GigaMetals **2026 - 2036**
Surficial Mineralization | N. British Columbia, Canada

3 - RioTinto, Talon Metals, Carbfix, & Advantek **2022 - 2025**
In Situ Mineralization | Tamarack, Minnesota, United States

4 - Teck Resources **2022 - 2024**
CCUS Point Source Capture | Trail, British Columbia, Canada

5 - Anglo American & ZeroEx **2025 - present**
Enhanced Rock Weathering | Barro Alto, Brazil

6 - BHP & ARCA **2023 - present**
Surface Mineralization | Mount Keith, Western Australia

7 - Pasek & EU-funded C-Sink Project **2024 - present**
Enhanced Rock Weathering | David Mine, Spain

8 - Boliden & EU-funded C-Sink Project **2024 - present**
Passive Carbon Mineralization | Kevitsa Mine, Finland

9 – Karbonetiq & Harsco Environmental **2025 - present**
Surficial Mineralization | Contrecoeur, Quebec, Canada

10 - BAIE Minerals **2025 - present**
Reactor-based Mineralization with Co-products
Baie Verte, Newfoundland, Canada

11 – Rewind & Saknakhshiri **2025 - present**
Biomass Burial | Tkibuli, Georgia

12 – Quebec Surficial Mineralization Hub **2026 - present**
Surficial Mineralization | Thetford, Quebec, Canada

Notes and sources: The above projects and their accompanying info were sourced from company publication, press releases, and news publications.

SECTION 6

Providing Feedstock for Geochemical CDR

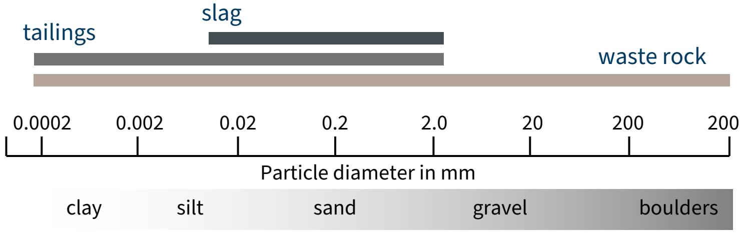
Many mining waste streams are ideal feedstocks for geochemical CDR

Mineralization and weathering-based CDR approaches depend on minerals characterized by high alkalinity and elevated concentrations of calcium (Ca) and magnesium (Mg), which are widely present in alkaline waste streams generated by large-scale metal and diamond mining operations. Different feedstocks will be more or less suitable for different CDR methods, a topic that is discussed further in the Technical Appendix.

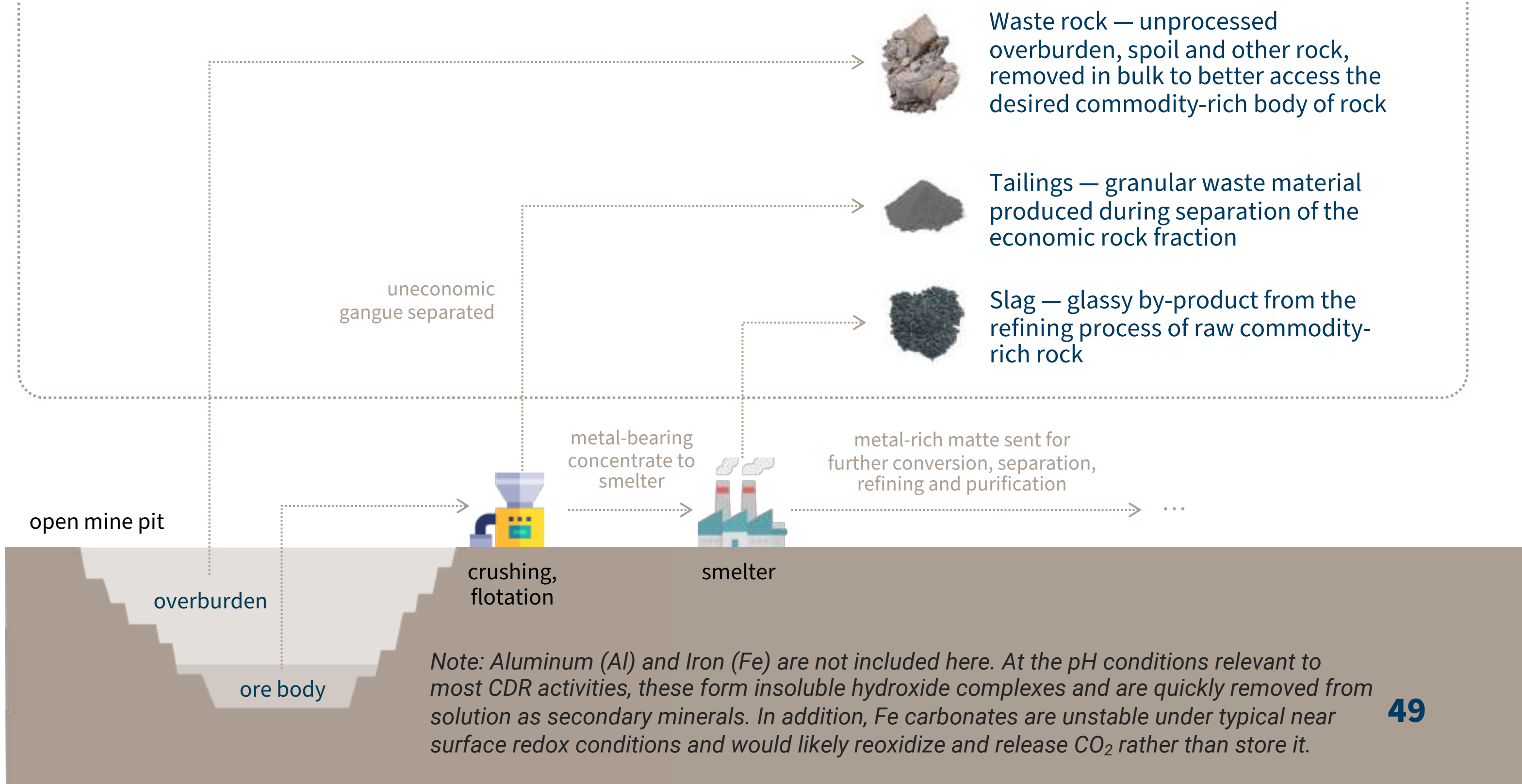
Why mineral wastes are ideal:

- **Abundance of available material.** The mining industry generates billions of tonnes of applicable mine wastes across the globe.
- **Favorable grain sizes.** Feedstocks with smaller than sand-size grains reduce the need for energy- and cost-intensive pretreatment steps.
- **Available infrastructure.** Mining operations readily process solid materials daily at kiloton-scale with adequate infrastructure.
- **Land availability.** Mining operations may be able to process and deploy material on site, reducing the need to transport heavy feedstock at scale.
- **Industry interest + in-house expertise**. Mine operators are actively working on decarbonizing their activities and investigating CDR opportunities.

Geochemical CDR can make use of multiple waste materials as inputs, taking advantage of their various physical, chemical and geochemical characteristics. Waste rock, tailings, and slag are all applicable to multiple methods of CDR.



▲ Different types of solid mine waste have varying particle sizes, ranging from very fine-grained, clay-sized tailings to large boulders of waste rocks.



Waste rock — unprocessed overburden, spoil and other rock, removed in bulk to better access the desired commodity-rich body of rock

Tailings — granular waste material produced during separation of the economic rock fraction

Slag — glassy by-product from the refining process of raw commodity-rich rock

Note: Aluminum (Al) and Iron (Fe) are not included here. At the pH conditions relevant to most CDR activities, these form insoluble hydroxide complexes and are quickly removed from solution as secondary minerals. In addition, Fe carbonates are unstable under typical near surface redox conditions and would likely reoxidize and release CO_2 *rather than store it.*

Geochemical feedstock suitability depends on host rock mineralogy

Geochemical CDR pathways accelerate reactions between minerals and CO_2 (and water) to produce either:

- **dissolved bicarbonate ions** (alkalinity) through mineral dissolution
- **solid carbonate minerals** through precipitation of carbonate with magnesium or calcium[1]

Materials containing Mg- and Ca-bearing silicate minerals, as well as (hydr)oxides, are typically targeted as feedstocks for geochemical CDR due to their reactivity with CO_2, but these materials are also of interest because of their global volumetric availability. For mine wastes, the chemical and mineralogical suitability is dependent on the mined commodity, and ultimately on the host rock. Identifying appropriate wastes can therefore be approached either by targeting specific commodities or specific host rocks.

Although common rock-forming silicate minerals such as plagioclase, pyroxene and mica host cations required for CO_2 reactions, they are intrinsically slow-reacting phases. Achieving meaningful dissolution of these minerals likely requires substantial intervention, either through fine comminution and controlled hydrology in the field, or through engineered systems (e.g., reactors) that maintain strong weathering conditions such as low pH and elevated CO_2.

Deployment should initially focus on more readily reactive materials such as asbestos residues or serpentinites, while research progresses on methods that should eventually accelerate the dissolution of slower reacting cation bearing silicates.

Mafic and ultramafic rocks are igneous rocks composed of silicate minerals and characterized by high cation content and very low silica content (below 55% and 45% SiO_2 respectively). The high magnesium content of these rocks allows for natural reactions with CO_2.

Examples of mafic rocks

basalt gabbro

Examples of ultramafic rocks

serpentinite dunite hornblendite

Examples of suitable minerals

plagioclase talc olivine pyroxene serpentine chlinochlore hornblende wollastonite

Choosing the right feedstock for a given CDR strategy involves

- Maximizing rates of the targeted chemical reactions to produce either bicarbonates or carbonates
- Determining heavy metal content, which may be desirable or undesirable based on the CDR method
- Minimizing associated costs, transport and energy requirements, environmental impacts
- Avoiding displacement of feedstocks with alternate economic use cases
- Ensuring formation of secondary alkaline minerals (e.g., magnesium clays) does not reduce anticipated removals

Notes and sources: [1]Harrington et al., 2024.

Sites can be targeted based on commodity type

Identifying suitable wastes as desirable feedstocks can be done by targeting specific commodities, though this should only be considered as a rule-of-thumb approach. Many minerals and metals, can be mined in a variety of geological contexts that are not always suitable for CDR (see examples given in the table to the right[1]). It is thus crucial to conduct site-specific studies to better characterize host rocks before engaging in projects.

Primary Commodities include:
Ni, Cr, Ti, PGMs, diamonds, Cu, Pb-Zn

Primary bulk rocks include:
basalt, gabbro, amphibolite, olivine, wollastonite, asbestos

Although nickel can be extracted both from sulphide and laterite deposits, the former can be a useful CDR feedstock, while the latter is an ultramafic rock that is already heavily weathered, limiting its potential[2]. Attention must be given to the potential for acid-generating reactions (e.g., sulfide oxidation) which could ultimately release CO_2 through carbonate buffering.

- 🔴 Unlikely to be suitable
- 🟠 Limited use
- 🟡 Some possible use
- 🟢 Suitable (with considerations)

Relevant Commodities	General host rock deposit type	Mineralogic characteristics	
Aluminium	Bauxite red mud	Al-hydroxide mineral-rich	🟧
Asbestos	Serpentinite	Mg-rich serpentine minerals	🟩
Chromium	Mafic igneous complex	Ca- and Mg-bearing silicates	🟩
	Podiform	Ca- and Mg-bearing silicates	🟩
Copper-gold-silver	Carlin-type	Sediment (typically calcareous)-hosted	🟥
	Orogenic	Metamorphosed volcanic and sedimentary rocks	🟧
	Hydrothermal	Precipitates of variable mineralogy	🟥
	Porphyry	Igneous intrusion-related	🟨
	VMS	Volcanic activity-related	🟨
	Sediment-hosted	Sedimentary rocks	🟥
	Iron oxide copper gold	Igneous intrusion- and hydrothermal-related	🟧
Diamond	Alluvial	Eroded and transported sediments	🟥
	Kimberlite	Ca- and Mg-bearing silicates	🟩
Iron	Banded iron formation	Sedimentary rock	🟥
	Ironstone	Sedimentary rock	🟥
	Kiruna-type	Magmatic and hydrothermal origin	🟨
Nickel	Laterite	Red, clay-rich soil formed from intense weathering	🟧
	Sulphide	Ca- and Mg-bearing silicates	🟩
Olivine	Dunite	Mg-rich olivine minerals	🟩
Lead-zinc	Sedimentary exhalative	Hydrothermal origin	🟥
	Skam	Calc-silicate minerals in metamorphic rock	🟨
Phosphorus	Sedimentary phosphrite, igneous	Ca- and Mg- bearing phosphates and carbonates, Ca-phosphate and igneous silicate gangue	🟩
PGMs	Layered mafic intrusion	Ca- and Mg-bearing silicates	🟩
Talc	Serpentinite	Mg-rich serpentine minerals	🟩
Tin	Granite-related	Silica-rich with minor Ca-silicates	🟥
	Secondary	Chemical-mechanical/redeposition origin	🟥
Titanium	Anorthosite	Ilmenite-bearing anorthosite with titaniferous Fe oxides	🟩
Uranium	Hematite breccia complex	Iron oxides in granitic rock	🟥
	Metasomatic	Chemical alteration in metamorphic rocks	🟥
	Quartz pebble conglomerates	Sedimentary rock	🟥
Tungsten	Shale	Sedimentary rock	🟥
	Wolframite vein	Alteration, replacement of intrusive rocks	🟥

Notes and sources: [1]Table and analysis adapted from Bullock et al., 2023 and Bullock et al., 2021. [2]An exception to this can be found in the example of Anglo American's Project Earthstone, where processed slags react even faster than most tailings.

Sites can also be targeted based on host rock

Host rock composition is the primary driver of geochemical CDR capacity. At least 18 different, highly common rock types (see table) show suitable CDR applicability, and often these minerals are mixed within a single site. Note that mineralogy and petrology of the host rock can be vastly different from the ore body, and waste rocks may or may not be suitable as feedstocks, even if tailings are ideal.

Geographic considerations

Geochemistry of rocks and rock wastes can be wide ranging across geographical regions, or even within the boundaries of a mine site, therefore CDR assessments should be conducted on a site-by-site basis.

Regions of the western and eastern United States, eastern Canada, eastern Brazil, Chile, Argentina, South Africa, Zimbabwe, Australia and central Russia show multiple sites of favorable host rocks, as well as sporadic areas of northern and southern Europe, Central America, northern Canada and Alaska, Philippines and Indonesia.

These sites generally straddle large (ultra)mafic rock formations, including the following remarkable examples:

Ophiolitic terranes and coastal mountain ranges of California, Oregon, Washington (United States) — dominated by dunite, serpentinite and harzburgite

Bushveld Complex in South Africa — including pyroxenite, norite and kimberlite formations

Semi-quantitative assessment of geochemical CDR feedstock suitability for different host rocks

Host rock	Examples of contained commodities	CDR capacity[1] (kgCO_2/t rock)	
Amphibolite	W, Mn, Au, Ni, Fe, Cu, Ag, Hg, Pb, Zn, Al, aggregates	~150-400	▒
Anorthite	Ti, Fe, Cu, clay, feldspar, aggregates	~140-250	░
Basalt	Aggregates, Cu, Fe, Si, Al, Au, Ag, Mn, Pb, Zn, Hg, stone	~190-450	▒
Diabase	Hg, Cu, Au, Ag, U, W, Ba, V, Mo, Pb, Zn, talc, stone	~170-330	░
Dunite	Aggregates, stone, Cr, olivine, PGMs, asbestos, Fe, Ni	~720-750	▓
Gabbro	Cr, Cu, Au, Ti, Ag, Pb, Zn, PGMs, aggregates	~220-480	▒
Harzburgite	Cr, PGMs, aggregates	~350-580	▒
Hornblendite	Zn, Au, U, Cu, Ag, Fe, Sn, Li, Mn, W, stone	~330-490	▒
Kimberlite	Diamonds	~460-760	▓
Lamprophyre	Diamonds	~210-570	▒
Lherzolite	Cu, Au, Cr	~530-610	▓
Metabasalt	Cu, Au, Ag	~190-390	░
Norite	PGMs, Ni, Cr, Au, Fe, Te, Se	~280-390	░
Peridotite	Cr, Ni, asbestos, talc, Au, Hg, PGMs, Co, Fe	~710-800	▓
Pyroxenite	PGMs, Cr, V, Fe, Au, Mn, Cu, Pb, Zn, Ag, Ti	~390-600	▒
Serpentinite	Asbestos, talc, PGMs, Cr, Ni, Co, Cu, Au, B, Hg, Sn	~550-750	▓
Tholeiite	Cu, aggregates, stone	~190-370	░
Wehrlite	Cr, Ni, PGMs, aggregates, stone	~440-800	▓

░ Promising (200-400 kgCO_2/t) ▒ Notably high (400-600 kgCO_2/t) ▓ Very high (> 600 kgCO_2/t)

Notes and sources: [1] Values shown in this table are for CDR via alkalinity generation. For CDR capacity via carbonate precipitation, the values shown here would be essentially halved. Minimum and maximum values were taken from literature studies, and the CO_2 capacity calculated based on those studies. It should be stressed that the calculations in the table are specific literature examples (selected without bias), and that for each host rock type, the chemistry and mineralogy (as well as commodity content) may vary beyond these individual cases.

Geochemical, physical, and safety factors impact the CDR potential of a given feedstock

A number of measuring and evaluation methods can be applied to characterize the properties highlighted here, including:

- Kinetic testing
- Gravimetric sieving
- Granulometry
- Gas flux measurements
- Leaching tests
- XRD, XRF
- SEM-EDS/EDX
- Dry combustion

The suitability and characterization of feedstock should be updated regularly to account for changes in reactivity. Various factors that may alter the initial characteristics of feedstocks over the lifetime of a mine include:

- Evolving exposure to the atmosphere
- Passive carbonation, weathering, and exposure to environmental conditions
- Secondary mineralization
- Evolution in particle size distribution due to mechanical or chemical stress

Feedstock properties that influence CDR potential

Feedstock Property	Description	Impacted Parameters
Particle size	Average grain size and distribution can influence reaction rates. Generally speaking, smaller particles have higher surface areas, resulting in higher reactivity to CO_2.	Removal potential
Mineralogy	Higher proportions of reactive minerals, such as brucite, result in higher removal capacities. Assessing mineralogical characteristics can also help identify hazardous components, including trace metal content or asbestiform minerals. In addition to the crystalline minerals present, any amorphous material could markedly enhance overall reactivity, as these phases can weather more rapidly than their crystalline counterparts.	Removal potential Safety
Depth from surface	For carbon mineralization conducted directly In storage facilities, the continuous burying by fresh material must be taken into account. Given the limited diffusion depth of CO_2 into the tailings, significant portions of stored materials may only be exposed to the atmosphere temporarily and are unlikely to become fully carbonated.	Removal potential
Elemental composition	Carbon, sulfur and trace metals may be present in the feedstock, leading to sulfide oxidation and subsequent acid rock drainage and further metalliferous drainage.	Safety
Exposure to Climate conditions	Temperature and pressure conditions, alongside previous CO_2 exposure, can have a significant impact on reactivity rates.	Removal potential
Radiation levels	Some feedstocks can be radioactive – appropriate testing and measurements is required to assess radioactivity levels and determine if and how the feedstock could be used safely for CDR.	Safety

Activation methods can enhance reactivity

Weathering and mineralization are natural, exothermic reactions, but reaction rates for some materials may be too low to economically justify their use. Increasing the reactivity of some materials is possible through various activation methods, some as simple as crushing and grinding to increase surface area, exposing more magnesium or calcium. More costly, novel methods apply thermal energy to alter mineral structures and allow increase access to reactive ions. Given the recognized exponential decay in mineral weathering rates with exposure time, active intervention would be required to maintain the fast reaction rates typically measured in laboratory settings.

Activation method[1]	Description	Performance & Challenges
Mechanical activation	Feedstock can be crushed and ground and/or mixed with abrasive particles to increase freshly exposed reactive surface area and thus overall weathering rates.[2]	• Relatively low cost • Energy intensive • Low efficiency
Thermal activation	Applied to serpentine group minerals in particular, heat can improve the conversion of magnesium to carbonates. Microwaves, X-rays and lasers can theoretically be used to generate the necessary heat.	• Energy intensive • Cost intensive • Low TRL for through-put processing
Chemical activation	Chemical compounds can enhance dissolution and carbonate precipitation. Chemical approaches include pH swing methods, acid leaching, or the addition of a variety of compounds, such as $NaHCO_3$ or NaCl.	• High efficiency • High cost • Potential leakage of trace metals
Ultrasound	Ultrasonic waves can disrupt material structures, expose reactive cations, and thus enhance reaction rates.[3]	• Energy intensive • Cost intensive • Low TRL
Microbiological approaches	Living organisms, such as cyanobacteria, can increase reaction rates by altering the host environment or acting directly upon the minerals. Biochemical approaches include use of enzymes (e.g., carbohydrase)[4].	• Relatively low cost • Microbes need specific climatic conditions and nutrients • Low TRL

Detailed examples:

The optimal conditions for serpentine heat treatment are obtained at high temperatures, where increased efficiency is observed following heat treatment.[5]

Zirconia beads were found to be a highly performant abrasive to increase reaction rates.

Researchers have investigated the potential of cyanobacteria to enhance the mineral carbonation of asbestiform chrysotile tailings.[6]

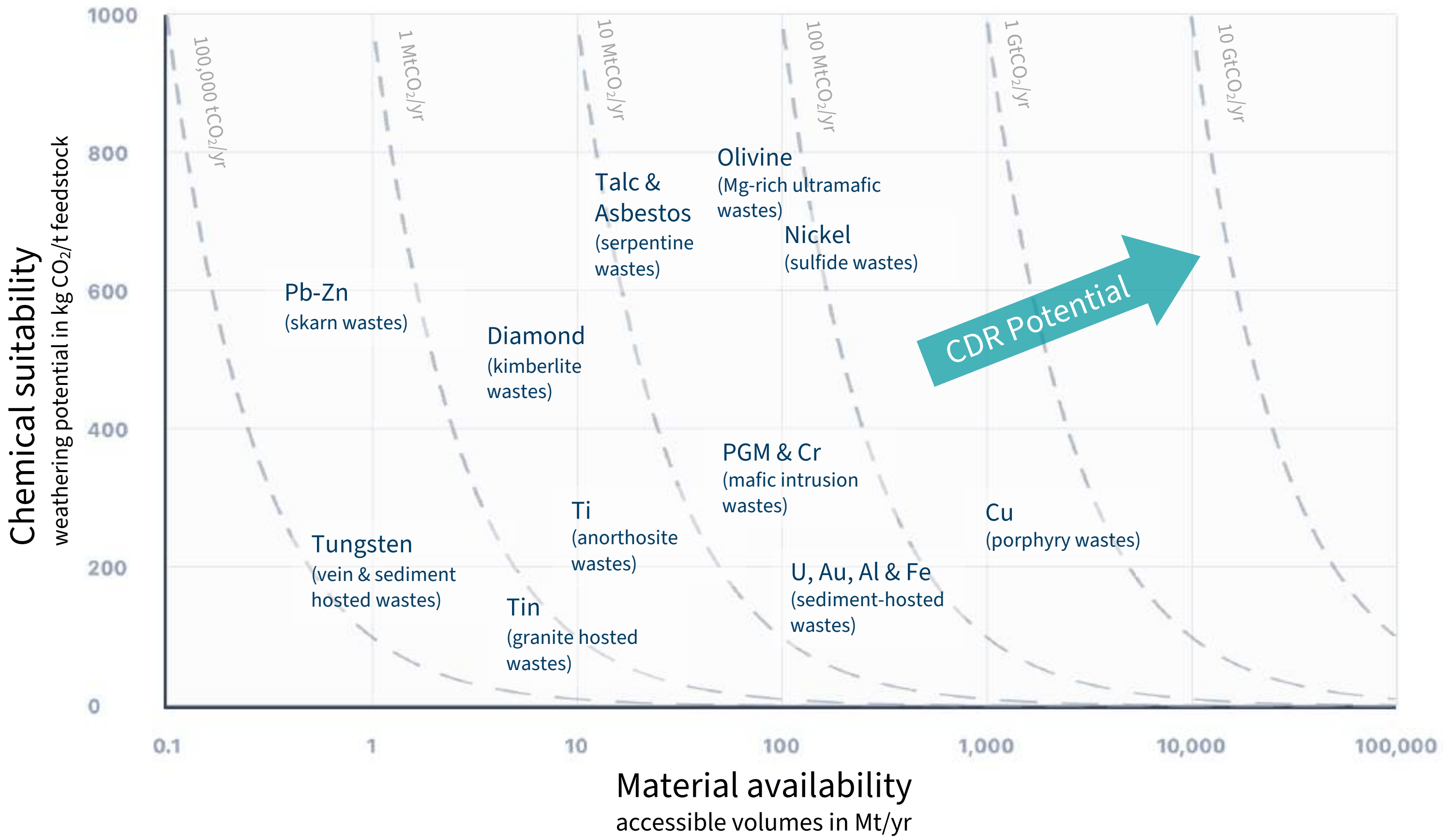
Activation methods can be energy-and/or emissions intensive, introducing trade-offs between performance and energy efficiency, impacting the overall LCA. However, deliberately activating minerals can establish additional carbonation and weathering compared to passive weathering in counterfactual scenarios. Some slow reacting materials only remain net CO_2 sinks when activated with low carbon energy, though site specific conditions such as waste heat, microbial processes or concentrated CO_2 gases could further enhance reaction rates where available.

Notes and sources: [1] Table adapted from Stokreef et al., 2022. [2] According to Stillings et al., 2023, even rocks such as granites with low reactivity can trap CO_2 through chemical adsorption. [3] For more on ultrasonic treatments, see Radfarnia et al., 2024. [5] Homeworld Collective has created a resource for biological approaches to mining from the perspective of climate-focused technology solutions. [5] Stokreef et al., 2022. [6] McCutcheon et al., 2017.

Towards global capacity estimates

We estimate the theoretical global CDR capacity from new and historical mine tailings at mafic and ultra-mafic rock sites could range from **520-820 million tonnes/year**.[1] These estimates are based primarily on volumetric data for given rock types or mined commodities assuming minerals fully react. They do not consider material processing or handling rates, which would reduce these estimates.

Carbon Removal Capacity of Mining Waste by Commodity



Carbonation or weathering potential is dependent on mineral content, reactivity, climatic conditions (temperature, pressure, humidity), as well as other parameters, such as porosity and surface area.

For a given tonne of unreacted feedstock, a maximum of 0.2 – 0.75[2] tonnes of carbon removal is theoretically possible under perfect conditions, though unlikely to be achieved without significant intervention. These values suggest that newly generated tailings could produce removals at a rate of approximately ~100 Mt/yr.[3] Including legacy tailings could significantly increase the total available material volume, while activation methods can be applied to increase dissolution rates.

Limitations & challenges to estimating capacity

- The actual CDR potential of a given feedstock is highly context-specific, and geochemical characterizations must be made to understand the current state of any material.
- Global data inventories are sparse and should be updated and built out with available geochemical information.
- Counterfactual baselining must be done to understand the passive weathering rates of untouched wastes.
- Limitations to scaling will be dictated primarily by dynamics of material handling and realistic processing rates.

Notes and sources: Graph adapted from Bullock et al., 2021. [1] Internal RMI analysis. [2] Schmidt et al., 2022. [3] Bullock et al., 2021.

SECTION 7

Quantification and Measurement Considerations

Validating carbon claims can be complex, but is essential

Validating how much carbon was removed and its expected storage duration is essential to ensure defensible claims, meet national and international standards, and to build stakeholder confidence. This is particularly critical in contexts where carbon removal generates credits, demanding the highest standards of accounting to avoid missteps and ensure true climate benefit.

The process of Monitoring, Reporting and Verification (MRV) transforms the capture and storage of CO_2 into measurable and fungible units that can be accounted for and potentially traded through carbon markets or emissions trading schemes. Standards must be set for quality in terms of project implementation, environmental impacts, quantification of gas fluxes, proxies, and other relevant parameters, as well as for reporting and transparency requirements and how projects should be verified and credited. Such standards, for example ISO[1] on the international level, or BSI[2] on the national level, are continually updated as science and innovation evolves. For CDR projects that carry an increased emphasis on long-term, or "permanent" carbon storage as a means of compensating for fossil carbon that was previously securely stored, standards may look different to those used to generate other types of carbon credits representing reduced or avoided emissions.

While many CDR technologies are new, the measurement tools required to properly measure and quantify relevant parameters are not and may be already commonly in use in the mining sector. The protocols and methodologies necessary for establishing net CO_2 drawdown, are however, new, and are currently being piloted across the pathways discussed in this report. Many have already been used to certify credits in the voluntary carbon market[3].

This section focuses on the quantification of novel CDR projects for the purposes of generating credits. It does not cover requirements for industry-specific decarbonization policies or differentiated product markets, which may have different boundaries and accounting standards. The measurement, modeling, and monitoring processes involved for understanding whether a removal actually took place is expected to look similar across the various use cases for CDR – for example applying CDR towards a reduction of net Scope 1 emissions should use the same quantification tools to determine how much carbon has been removed and stored as using CDR to generate carbon credits. However, any differences in reporting or verification between use cases are not included here.

M **Monitoring**
(also: Measurement, Modeling)
Parameters indicating CO_2 removal from the atmosphere must be quantified and tracked over time

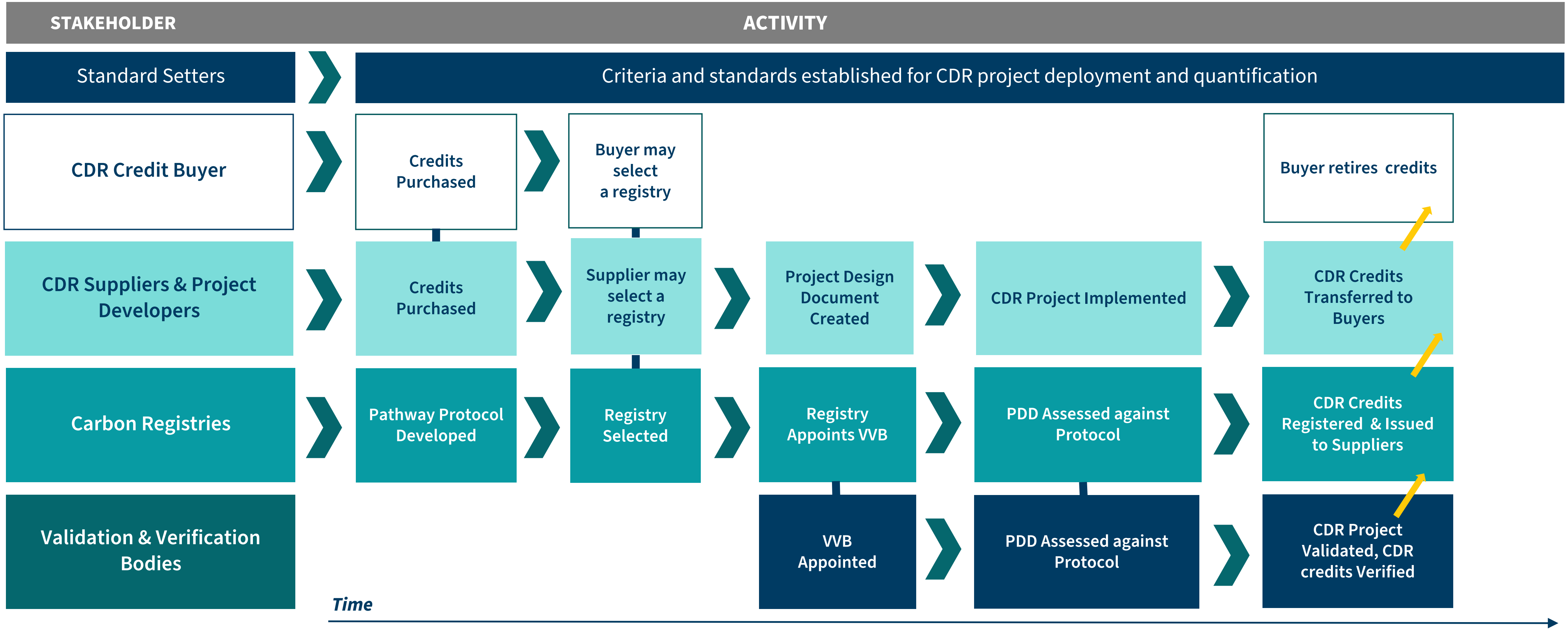
R **Reporting**
Information must be communicated transparently and remain accessible to stakeholders

V **Verification**
Independent validation is required to affirm robustness and certify a climate benefit

Notes and sources: More information about the MRV process for CDR can be found in this Mission Innovation Report. 1More information about ISO can be found here. 2 More information on BSI can be found here. 3Isometric's Registry is easy to navigate and shows verified tons for many of the pathways listed in this report. More information on protocols and methodologies is given later in this section.

The crediting process in the VCM involves many stakeholders

Generating fungible credits for CDR projects involves rigorous checks across multiple stakeholders to demonstrate evidence of net negativity. This process may look different from the generation of carbon credits representing forestation, or emissions avoidance. Here we lay out an example process for generating CDR credits including the various roles and responsibilities for key stakeholders.



STAKEHOLDER | **ACTIVITY**

Standard Setters: Criteria and standards established for CDR project deployment and quantification

CDR Credit Buyer: Credits Purchased › Buyer may select a registry › Buyer retires credits

CDR Suppliers & Project Developers: Credits Purchased › Supplier may select a registry › Project Design Document Created › CDR Project Implemented › CDR Credits Transferred to Buyers

Carbon Registries: Pathway Protocol Developed › Registry Selected › Registry Appoints VVB › PDD Assessed against Protocol › CDR Credits Registered & Issued to Suppliers

Validation & Verification Bodies: VVB Appointed › PDD Assessed against Protocol › CDR Project Validated, CDR credits Verified

Time

Notes and sources: More information about the MRV process for CDR can be found in this Mission Innovation Report.

Multiple MRV parameters determine the integrity of CDR interventions

The integrity of carbon dioxide removal interventions is defined by multiple parameters, including full lifecycle impacts and the long-term durability of the stored carbon. Parameters including additionality, durability, and social impact help to define MRV protocols and ensure that the project has made a beneficial contribution towards climate goals in a socially responsible manner with minimal adverse impacts. These parameters, outlined below, serve to establish trust that each tonne of removal is real, verifiable and results in a traceable climate impact.

Additionality confirms that the carbon removal is a direct result of the project's specific intervention and would not have occurred under a business-as-usual scenario or due to existing regulatory requirements. To demonstrate additionality, determining baseline removal under a counterfactual scenario is crucial, and can be done through pre-project measurements, control plots, models or other means.

When using alkaline feedstocks, it is especially critical to calculate any CO_2 uptake that would have occurred passively in the absence of any CDR project activities.

Lifecycle Assessment (LCA) provides cradle-to-grave accounting of all emissions generated from the implementation of a CDR project. Project developers need to assess and quantify CO_2 emissions in excess of what would have been emitted in the absence of the project and prove net negativity. This includes robust assessments of counterfactual baselines.

Wastes are generally considered emissions-free and can be utilized without including the emissions associated with the production of those wastes. This makes them especially appealing as inputs to CDR processes which are sensitive to net emissions.

Durability describes the expected timeframe that carbon will remain stored. Because the primary goal of CDR crediting is to counteract the emissions of carbon that was once securely stored (i.e., fossil carbon), durability serves as the primary differentiator for high-quality carbon credits. The variety of CDR methods that can be implemented within mining operations present a wide range of CO_2 storage durations.

Geochemical CDR processes provide a means for CO_2 to be stored over longer timeframes (>1,000 years) providing a higher level of certainty compared to other CDR options, including most biological sinks.

Risk of Reversal evaluates the potential for sequestered CO_2 to be re-released into the atmosphere due to physical, chemical, or geological disturbances. Credits are adjusted accordingly. Further mitigation methods such as buffer pools can be used as "insurance" measures to compensate.

A primary advantage of carbon mineralization is its low reversal risk, as the carbon is chemically bound into solid, inert minerals – few of which decompose with a risk of CO_2 release. For weathering and alkalinity approaches where bicarbonate is the main storage mechanism, downstream losses are a key consideration and a topic of ongoing research.

Social & Environmental Impacts are accounted for in different ways according to the type of project and governing standards, but all require adherence to local laws and regulations. Differences in requirements may appear across different protocols and methodologies.

High-quality MRV will consider impacts beyond carbon, including local water quality or biodiversity. Demonstrating a "net positive" impact on both the environment and the local community is essential for maintaining the social license to operate and meeting stringent environmental and community standards.

Registry standards for Mining CDR are advancing across pathways

As mining-relevant CDR technologies advance, so too do frameworks for quantifying and verifying removal volumes.

This table shows where pathway-specific protocols for registries active in the CDR space are directly applicable to that pathway deployed in the context of mining.

Some protocols have been developed specifically with mining operations in mind, such as Isometric's Open System Ex Situ Mineralization Protocol[1] or their Biomass Storage in Subsurface Mines[2]. Others were developed independently of mines but are still applicable under most circumstances when relevant criteria have been met because they are general to the technology itself, and not the deployment site.

Many CDR Methods are currently being piloted and testing these protocols. Updates are conducted regularly as the field evolves.

Pathway-specific MRV protocols					
	Registries				
CDR Method	Isometric	Puro	Gold Standard	Verra	Other
In Situ Mineralized CO_2 Storage	In Use	In Use			C-Capsule
Surficial Mineralization	In Use[1]	In Use	In Use	In Development	Rainbow
Surface Water Mineralization					
Reactor-based Mineralized Storage		In Use	In Use	In Development	Rainbow
Reactor-based Mineralized Storage for Metal Recovery					
Reactor-based Mineralization with Co-products	In Development			In Development	
Enhanced Rock Weathering	In Use	In Use		On Hold	Rainbow, C-Capsule
Phytomining + Enhanced Rock Weathering					
Wastewater Alkalinity Enhancement	In Use				
Electrochemical Ocean Alkalinity Enhancement	In Use				
Direct Air Capture	In Use	In Use		In Use	Absolute, C-Capsule
Afforestation/Reforestation	In Use		In Use	In Use	
Biomass Burial	In Use[2]	In Use			

Notes and sources: [1]Isometric's Open System Ex Situ Mineralization Protocol has been developed in part to certify credits generated by mineralizing mine tailings. [2]Isometric's Biomass Storage in Subsurface Mines has been recently certified at the time of writing and is now generating credits.. More generally, information can be found for each of the registries directly on their websites: Isometric, Puro, Gold Standard, Verra, Rainbow, Absolute, C-Capsule.

Quantifying CDR relies on a combined approach of measurement & modeling

The heterogeneous nature of rocks and minerals, coupled with environmental complexities, mean that complementary measurement and modeling are needed to obtain estimates of baseline CO_2 removal under a counterfactual scenario, alongside the intended CO_2 removal. Empirical evidence of weathering and mineralization is ideal, however at meaningful project sizes (e.g. annual processing of ~100k -500k tonnes of feedstock), direct measurements are neither practical, nor economical. Models should be based on empirical data and will improve over time as more data is collected.

Combining measurements and modeling to generate CDR credits

Prioritize direct measurements using various tools and measurement techniques, including those common to geochemical testing of materials commonly conducted in mining.

Model what cannot be measured, ensuring that models are based on empirical evidence and that they can be stress-tested for reliability. Models are only as good as their inputs.

Crediting of CDR can only take place when there is substantial measurement data and models have been validated.

Many relevant parameters are already being measured within mining operations, including mineralogy, particle size distribution, trace elements and metal content of feedstocks, as well as pH for liquid wastes. Examples of specific measurements necessary for quantifying carbon removal are given below:

Solution / Aqueous Measurements

- **pH**
- **Alkalinity**
- **Electrical conductivity**
- **Dissolved inorganic carbon**
- **pCO_2**
- **Major & trace elements**
- **Major anions**

Gaseous Phase Measurements

- **CO_2 fluxes via, e.g. eddy-covariance or chamber**

Solid Phase Measurements

- **Total inorganic carbon**
- **Major & trace elements**
- **Particle size distribution**
- **Surface area** (Geometric & BET)
- **Porosity**
- **Mineralogy**
- **Gas permeability**
- **Liquid permeability**

Notes and sources: [1]More specifics on best practices and options for quantification can be found in Measurements in Geochemical Carbon Dioxide Removal. For an example of what kind of quantification is expected for projects to qualify for crediting, see Isometric's Open System Ex-Situ Mineralization protocol.

Baseline determination using alkaline materials is difficult, but feasible

All CDR projects require proper accounting for any baseline carbon removal that would take place had the project not occurred. This baseline is then subtracted off any quantified CO_2 removal before credits are issued. For Direct Air Capture projects, the counterfactual is straightforward, in that there is zero baseline removal. Biogenic CDR projects must account for any growth or decay that might occur in a counterfactual setting. For subsurface biomass burial specifically, measuring baselines and net carbon removed involves quantification of mass, moisture and carbon content, but is generally straightforward. As such, this section focuses on quantification of baselines for geochemical CDR projects using mineral feedstocks. Baselines are determined by assessing the alternate fate of feedstocks and their natural reactivity rates.

Key parameters in determining baselines for mineral feedstocks include:

Passive Reactivity Rates	For materials that carbonate naturally, passive weathering and mineralization for the same feedstock must be determined for the situation in which the feedstock would be left undisturbed.
Environmental Conditions	Site-specific environmental and climate variables, such as humidity, ambient temperature, and precipitation, must be accounted for, as well as seasonal fluctuations.
Surface Area to Volume Ratios	Changes in surface area to volume ratios of both the feedstock pile, as well as the feedstock grains, will affect passive mineralization that would take place without deliberate intervention.
Exposure Time	The amount of time feedstocks would be exposed to atmospheric CO_2 in a counterfactual scenario, including as it might be moved or buried, must be considered.
Alternate Use Cases	For materials that may have been destined for other use cases, the weathering or carbonation potential for that use case must be accounted for to qualify the additional CO_2 drawdown.

Calculating Baselines

Baseline measurements should be carried out both prior to project implementation and throughout the project lifetime. Options for calculating baseline removals for geochemical CDR techniques include:

- Control plots in larger tailings piles or ponds to measure and compare carbon uptake rates over the same time period
- Direct measurement of the inorganic carbon content of feedstock prior to project implementation
- Geochemical models developed specifically for a given project
- 3D Reactive transport modeling

MRV faces risks and challenges that are being overcome as frameworks evolve

MRV frameworks for Mining CDR are evolving rapidly as measurement technologies and crediting mechanisms reach maturity. Challenges in quantifying removals stem from both inherent physical uncertainties, as well as external operational contexts. These risks and challenges are broken down here into three categories based on how they can be addressed, offering a structured approach to risk mitigation for MRV in a mining context.

Market and Technological Challenges

- **Measurement uncertainties due to heterogeneity in feedstock composition, as well as costs for geochemical assessments** should decrease as measurement techniques improve and project-specific modeling becomes easier. Lab capacity for testing is expected to increase.

- **Baseline measurements** will also become easier and more straightforward to conduct through increased experience and learning alongside improved measurement and modeling.

- **Market maturity** will evolve as more projects are deployed, with verified and delivered carbon credits.

Physical Challenges

- **Temporal lags in weathering and mineralization** present measurement challenges with low signal-to-noise given that the reactions take place over weeks to decades. This is not an issue for projects that use containers or reactors, where reactions can take place within minutes to seconds.

- **Scaling processes** will be limited based on material handling and logistical constraints.

Regulatory Challenges

- **Measurement availability** will depend on repeated access to the mine site by third parties.

- **Verification latency** can occur when there are significant time delays between carbonation events and third-party verification.

- **Inclusion in closure plans** will determine how closely both stored carbon or continued geochemical CDR processes can be monitored.

- **Future Liability** for stored carbon will depend on site ownership post-closure.

Notes and sources: More information on MRV risks and challenges can be found in Measurements in Geochemical Carbon Dioxide Removal

SECTION 8

Environmental and Social Considerations

Mining and Carbon Dioxide Removal
A responsible path forward for mine operators, policymakers,
and other key stakeholders

CDR will only be effective if it is environmentally and socially sustainable

With an emphasis on waste utilization and restoration, Mining CDR projects can avoid dedicated extraction of resources while helping operators achieve their environmental and sustainability goals. Careful examination of environmental frameworks and ecological co-benefits is required for long-term sustainability and net-positive outcomes for any project. Primary concerns for ensuring environmental health and safety requirements for CDR projects are similar to those mine operators already manage and involve:

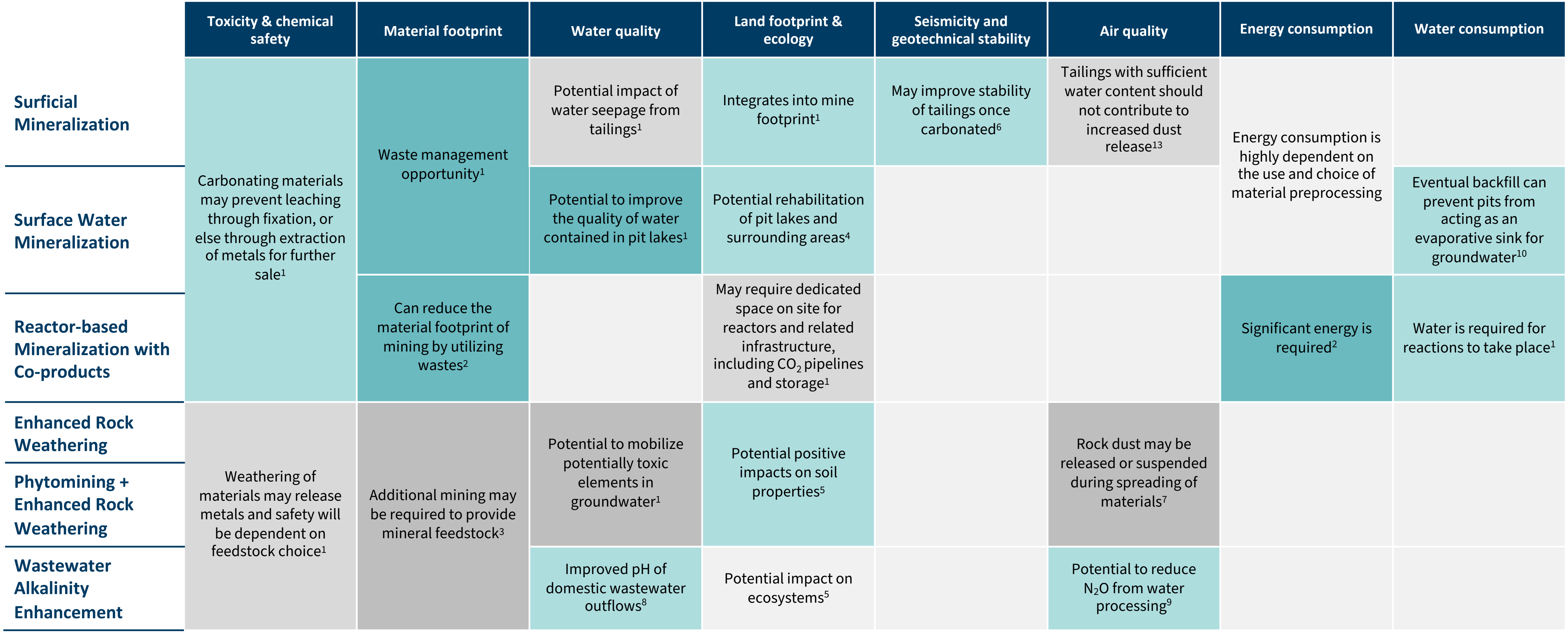
- **Toxicity and chemical safety,** and whether potentially toxic elements can be further immobilized, or will be released into the environment
- **Waste and commodity management**, including structural safety where materials are collected and stored
- **Water usage and contamination,** and potential impacts to water tables and ecosystems
- **Air quality impacts** from increased handling of crushed feedstocks and increased traffic
- **Seismicity and geochemical stability** in the case of In Situ Mineralized CO_2 Storage

It should be widely understood that all CDR projects, including Mining CDR projects, seek to improve environmental conditions and are not expected to take place when that is not possible. In all cases, community support is vital to pursuing projects and maximizing net ecological benefits. This section covers the environmental and social considerations expected to be most relevant for CDR deployment.

Notes and sources: [1]Cesar et al., 2021.

Environmental considerations can vary across geochemical CDR methods

There are multiple interactions between Mining CDR methods and environmental challenges related to mining activities. Note that existing standards addressing these concerns were likely not written with CDR processes in mind and as a result, may not currently support CDR projects.



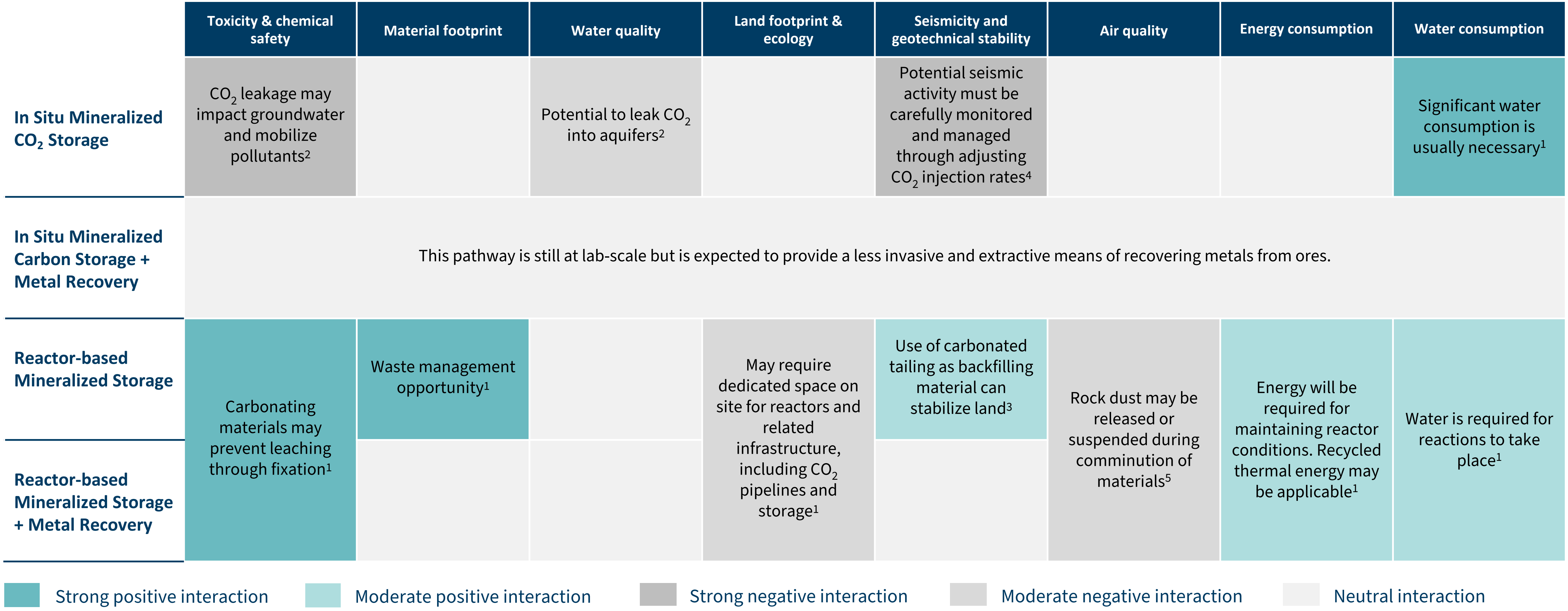
	Toxicity & chemical safety	Material footprint	Water quality	Land footprint & ecology	Seismicity and geotechnical stability	Air quality	Energy consumption	Water consumption
Surficial Mineralization	Carbonating materials may prevent leaching through fixation, or else through extraction of metals for further sale[1]	Waste management opportunity[1]	Potential impact of water seepage from tailings[1]	Integrates into mine footprint[1]	May improve stability of tailings once carbonated[6]	Tailings with sufficient water content should not contribute to increased dust release[13]	Energy consumption is highly dependent on the use and choice of material preprocessing	
Surface Water Mineralization			Potential to improve the quality of water contained in pit lakes[1]	Potential rehabilitation of pit lakes and surrounding areas[4]				Eventual backfill can prevent pits from acting as an evaporative sink for groundwater[10]
Reactor-based Mineralization with Co-products		Can reduce the material footprint of mining by utilizing wastes[2]		May require dedicated space on site for reactors and related infrastructure, including CO_2 pipelines and storage[1]			Significant energy is required[2]	Water is required for reactions to take place[1]
Enhanced Rock Weathering	Weathering of materials may release metals and safety will be dependent on feedstock choice[1]	Additional mining may be required to provide mineral feedstock[3]	Potential to mobilize potentially toxic elements in groundwater[1]	Potential positive impacts on soil properties[5]		Rock dust may be released or suspended during spreading of materials[7]		
Phytomining + Enhanced Rock Weathering								
Wastewater Alkalinity Enhancement			Improved pH of domestic wastewater outflows[8]	Potential impact on ecosystems[5]		Potential to reduce N_2O from water processing[9]		

Strong positive interaction Moderate positive interaction Strong negative interaction Moderate negative interaction Neutral interaction

Sources: [1]Back et al., 2022; Bullock, 2024. [2]Campbell et al., 2022. [3]National Academies of Sciences, Engineering, and Medicine, 2021. [4]Punia et al., 2025. [5]Levy et al., 2024 ; Buckingham et al., 2024. [6]Jayakodi et al., 2024. [7]Foteinis et al., 2023; Yu et al., 2023. [8]Kitidis et al., 2024. [9]Carbon Gap, et al, 2026. [10]McCullough et al., 2024.

Environmental considerations vary across geochemical CO_2 storage methods

There are multiple interactions between Mining CDR methods and environmental challenges related to mining activities. Note that existing standards addressing these concerns were likely not written with CDR processes in mind and as a result, may not currently support CDR projects.



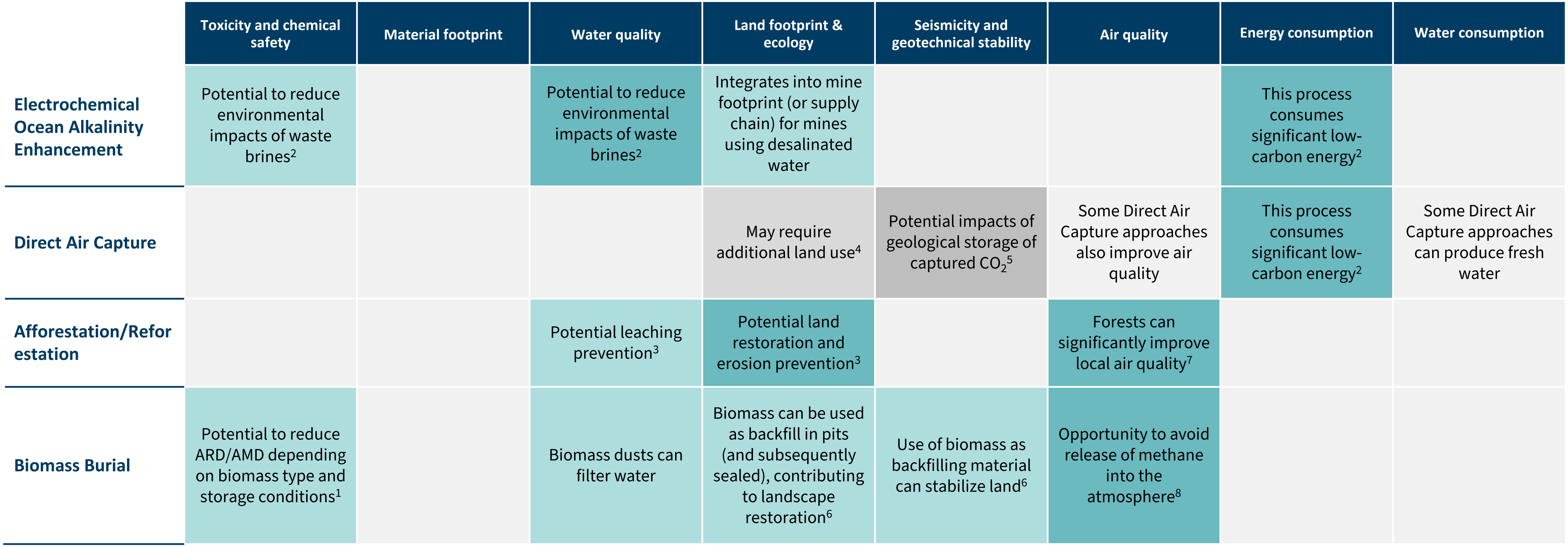
	Toxicity & chemical safety	Material footprint	Water quality	Land footprint & ecology	Seismicity and geotechnical stability	Air quality	Energy consumption	Water consumption
In Situ Mineralized CO_2 Storage	CO_2 leakage may impact groundwater and mobilize pollutants[2]		Potential to leak CO_2 into aquifers[2]		Potential seismic activity must be carefully monitored and managed through adjusting CO_2 injection rates[4]			Significant water consumption is usually necessary[1]
In Situ Mineralized Carbon Storage + Metal Recovery	This pathway is still at lab-scale but is expected to provide a less invasive and extractive means of recovering metals from ores.							
Reactor-based Mineralized Storage	Carbonating materials may prevent leaching through fixation[1]	Waste management opportunity[1]		May require dedicated space on site for reactors and related infrastructure, including CO_2 pipelines and storage[1]	Use of carbonated tailing as backfilling material can stabilize land[3]	Rock dust may be released or suspended during comminution of materials[5]	Energy will be required for maintaining reactor conditions. Recycled thermal energy may be applicable[1]	Water is required for reactions to take place[1]
Reactor-based Mineralized Storage + Metal Recovery								

Strong positive interaction | Moderate positive interaction | Strong negative interaction | Moderate negative interaction | Neutral interaction

Sources: [1]Back et al., 2022; Bullock, 2024. [2]Sun et al., 2025. [3]Jayakodi et al., 2024. [4]Snæbjörnsdóttir et al., 2020. [5]Yu et al., 2023.

Environmental considerations can vary across other CDR methods

There are multiple interactions between Mining CDR methods and environmental challenges related to mining activities. Note that existing standards addressing these concerns were likely not written with CDR processes in mind and as a result, may not currently support CDR projects.



	Toxicity and chemical safety	Material footprint	Water quality	Land footprint & ecology	Seismicity and geotechnical stability	Air quality	Energy consumption	Water consumption
Electrochemical Ocean Alkalinity Enhancement	Potential to reduce environmental impacts of waste brines[2]		Potential to reduce environmental impacts of waste brines[2]	Integrates into mine footprint (or supply chain) for mines using desalinated water			This process consumes significant low-carbon energy[2]	
Direct Air Capture				May require additional land use[4]	Potential impacts of geological storage of captured CO_2[5]	Some Direct Air Capture approaches also improve air quality	This process consumes significant low-carbon energy[2]	Some Direct Air Capture approaches can produce fresh water
Afforestation/Reforestation			Potential leaching prevention[3]	Potential land restoration and erosion prevention[3]		Forests can significantly improve local air quality[7]		
Biomass Burial	Potential to reduce ARD/AMD depending on biomass type and storage conditions[1]		Biomass dusts can filter water	Biomass can be used as backfill in pits (and subsequently sealed), contributing to landscape restoration[6]	Use of biomass as backfilling material can stabilize land[6]	Opportunity to avoid release of methane into the atmosphere[8]		

■ Strong positive interaction ▨ Moderate positive interaction ■ Strong negative interaction ▨ Moderate negative interaction □ Neutral interaction

Sources: [1]Arca et al., 2026; Back et al., 2022; Bullock, 2024. [2]Campbell et al., 2022. [3]Enescu et al., 2025 . [4]Realmonte et al., 2019. [5]Snæbjörnsdóttir et al., 2020. [6]Zhu et al., 2025. [7]Mishra et al., 2024. [8]Amelse, 2025.

There are many viable ways to manage potential environmental risks

Risk category	Description	Potential guardrails to mitigate and manage risks
Air quality	**Impacts from handling minerals:** CDR pathways that involve finely crushed minerals can disperse them into the air, degrading local air quality and endangering health.[11]	**Increased pollution monitoring,** including ground-based monitors and remote sensing technologies can be used to alert the public of increased air pollution.[12] **Increased dust suppression** via wetting or misting may be necessary. **Ecosystem restoration** pathways, such as afforestation, can contribute to enhance local air quality.[12]
Land footprint and ecology	**Additional mining activity:** This may be required to provide mineral feedstock for CDR pathways that do not make use of existing wastes. **Additional on-site infrastructure:** Some CDR projects may take space on site for infrastructure such as reactors, CO_2 pipelines, and CO_2 storage.	While additional mining is indeed a risk of conducting geochemical CDR, this report advocates that **wastes should be prioritized** as feedstocks before any new extraction is considered. **Environmental Impact Assessments** should be done to understand potential risks of including new CDR projects on site.[5] Some CDR pathways have the potential to **restore land, improve soil properties, and reduce erosion**.[6]
Water quality	**Weathering of materials can release metals:** Additional weathering of material can lead to additional metal release into the environment[13]. **Impact on drinking water sources**: CO_2 storage leakage can impact aquifers[14] and CDR pathways utilizing mine tailings can mobilize potentially toxic elements into groundwater.[6]	**Additional efforts to prevent heavy metal mobilization**, in addition to that which is already conducted, may be necessary.[6, 10] **Carbon mineralization approaches that immobilize metals can prevent leaching into waterways.** **Environmental Impact Assessments** should be done to understand potential risks of including new carbon removal or storage projects on site.[5]
Seismic activity	Geological storage of CO_2 could increase seismic activity.[10]	**Regional seismicity studies** should be conducted before any CO_2 injection occurs to inform protocols to prevent risk.[10] **Continual monitoring and pressure adjustment** has shown to be successful in managing seismic concerns when injecting CO_2 underground.[15]

Notes and sources: [1] National Academies of Sciences, Engineering, and Medicine, 2021. [2] Kashefi et al., 2020. [3] Araya et al., 2021. [4] Circular Mine; Oberle et al., 2020. [5] Realmonte et al., 2019; Levy et al., 2024. [6] Back et al., 2022; Bullock, 2024. [7] Enescu et al., 2025. [8] Punia et al., 2025, [9] Jayakodi et al., 2024; Zhu et al., 2025. [10] Snæbjörnsdóttir et al., 2020. [11] Yu et al., 2023. [12] Mishra et al., 2024. [13] Cacciuttolo et al., 2022; Araujo et al., 2022. [14] Sun et al., 2025. [15] Hjörleifsdóttir et al., 2021

For weathering approaches, heavy metal release is an issue that requires careful management

- **Assessment of heavy metals** — The concentration of metals largely depends on the composition of the original host rocks. Ultramafic rocks such as dunite usually contain larger amounts of heavy metals than mafic rocks. Environmental assessments should be conducted regularly to evaluate hazards and be integrated into decision-making (see figure to right).[2]
- **Active use of mine tailings** — In cases where stored tailings are reprocessed, additional management of toxic compounds will be needed as tailings are exposed to new conditions.[1]
- **Mineralization versus weathering** — Mineralization techniques can stabilize metals, preventing them from leaching or interacting further. Weathering techniques may liberate these metals, releasing them into water (e.g., groundwater).
- **Reducing mining waste toxicity** — In general, carbonated tailings are less prone to releasing contaminants into the environment, which could be a major co-benefit of mineralization-based CDR. Tailings from asbestos production, or red muds resulting from bauxite refining for aluminium production, are good candidates for concurrent carbon mineralization and toxicity reduction.[3]

Amounts of heavy metals (Ni/Cr)

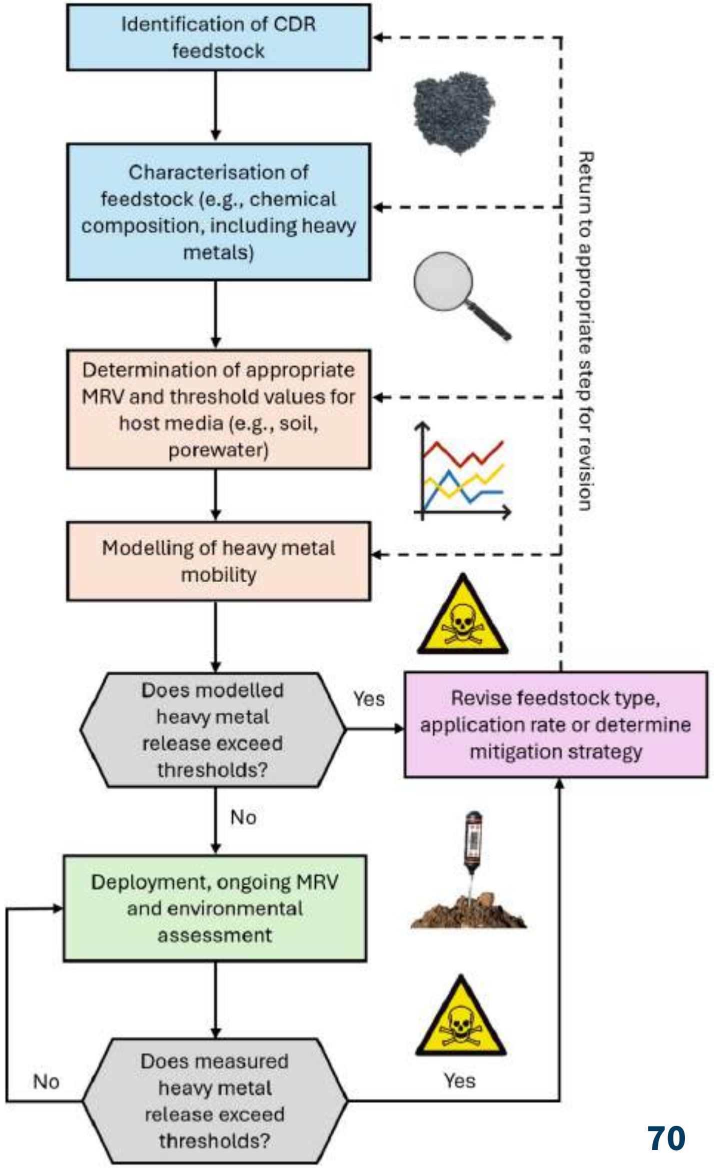
Dunite (ultramafic)
2000 mg/kg

Basalt (mafic)
200 mg/kg

Asbestos tailings stockpile at Thetford Mines (Canada)

Ni nickel
Cr chromium
Cd cadmium
Hg mercury
Pb lead
As arsenic
Cu copper
Zn zinc

A simplified decision-tree for mitigating heavy metal release during weathering applications, adapted from Liam Bullock.



Identification of CDR feedstock

Characterisation of feedstock (e.g., chemical composition, including heavy metals)

Determination of appropriate MRV and threshold values for host media (e.g., soil, porewater)

Modelling of heavy metal mobility

Does modelled heavy metal release exceed thresholds?

Yes

Revise feedstock type, application rate or determine mitigation strategy

No

Deployment, ongoing MRV and environmental assessment

Does measured heavy metal release exceed thresholds?

No

Yes

Return to appropriate step for revision

Sources: [1]Cacciuttolo et al., 2022; Arujo et al., 2022. [2]Bullock, Liam. Geochemical CDR approaches in Mining: Feedstocks and strategies, Spanish National Research Council and Carbon Neutral Initiative, 2024. [3]Back et al., 2022; Kashefi et al., 2020. [4]Punia et al., 2025

CDR activities can have a range of economic and health implications for local communities

Both mining activities and CDR can have a range of implications for local populations, both positive and negative. CDR should only take place when projects meet strict criteria and adhere to social and health standards. As many of these approaches are new and are only recently being piloted, additional care must be taken to address known challenges ahead of time. Even where CDR can improve conditions for communities, these improvements must be explored with local populations using Community Engagement[1] and Environmental Justice[2] strategies consistent with best practices. This table presents expectations for any CDR project going forward.

Addressing Sustainability Development Goals[5]

Mining CDR can directly advance SDG 13 (Climate Action) by creating massive carbon sinks from wastes and other assets. It can advance SDG 12 (Responsible Production) by repurposing wastes to recover additional metals, industrial acid inputs, and construction materials. When safely used to remediate orphaned sites, Mining CDR can address SDG 15 (Life on Land). Transforming these sites into innovative carbon removal hubs advances SDG 9 (Industry, Innovation, & Infrastructure), while diversifying local economies and creating green jobs (SDG 8, Decent Work & Economic Growth).

Economic and Health Implications of deploying CDR projects on mine sites

	Implications
Human Health	⊕ CDR has the potential to mitigate health impacts due to toxic metal release ⊕ Pathways that restore ecosystems have a net benefit on local public health ⊖ Increased material handling on site could increase air pollution associated with dust
Resource use	⊕ CDR pathways with co-products can reduce the need for the extraction or production of those materials elsewhere ⊖ CDR may cannibalize local resources, including renewable power capacity or water supply, if demand and supply are not dimensioned properly
Land Use & Infrastructure	⊕ For areas where legacy wastes impose on local communities, there is a possibility to reclaim land by transforming and utilizing those wastes[4] ⊖ Depending on the local context, implementing Mining CDR may require additional infrastructure buildout (e.g., roads, facilities, CO$_2$ pipelines) which may impact populations
Economic Activity	⊕ CDR projects may extend the life of processing and transport infrastructure ⊕ Additional jobs may be created for local communities, requiring diverse skill sets ⊕ CDR can create industrial opportunities and increase the attractiveness of a region for further activity
Acceptability	⊕ CDR may improve relationships with communities who prioritize sustainability ● Where CDR pathways might be perceived negatively, early engagement in the planning and deployment is essential

⊕ Positive impact ⊖ Negative impact ● Neutral

Sources: [1]Scott-Buechler et al., 2024; Low et al., 2024. [2]Amoah et al., 2024; Owen et al., 2023; Teevan et al., 2024. [3]Cesar et al., 2021; Prno et al., 2012 , [4]Lévesque et al., 2020
[5]The UN Sustainability Development Goals can be found here.

Taking steps to safeguard the wellness of communities and ecosystems ensures CDR is conducted in a beneficial way

CDR developers have planned or implemented action to prevent a range of negative outcomes. The examples given here provide an overview of early action[1] that can be taken.

Action	Rationale	Example
Early engagement	Engaging with local communities from the initiation and planning phase of projects should minimize potential negative impacts and conflicts with the needs of local populations and give communities a voice in determining desired project outcomes, thus increasing overall acceptability.	Several sites envisioned for Mining CDR projects in the US and in Canada are on traditional territories of First Nations. Players including CO_2 Lock[2] and Dumont Nickel have established strategies to run continuous discussions with local populations (the L'hedli Tenneh and Abitibiwinni, respectively).
Impact and benefits agreements	Assessments of potential impacts and benefits can help facilitate negotiations and establish collectively-designed plans between project developers and local populations, which can lead to legally-binding agreements.[3]	Dumont Nickel[3] has developed an Impact and Benefit Agreement with its First Nations partners.
Infrastructure consultation	CDR projects may require the buildout of additional infrastructure, which should be designed in consultation with local populations to minimize impacts.	First Nation communities are leading the development of a regional infrastructure corridor to provide all-season road access to Wyloo's[4] Eagle's Nest mine deposit.
Local job creation	A CDR project can generate additional demand for both skilled and unskilled workers.	Carbon to Stone[5] has established a partnership with Nucor, a steel producer, and plans to be part of a local decarbonization hub that would create new job opportunities.
Ecosystem protection	Environmental assessments should help identify ecosystems that should be protected from any new projects and ensure their integrity.	Ring of Fire[6] has identified peatlands as a key ecosystem to be preserved near its Mining CDR project.
Community buy-in	In case no mutual agreement with local populations can be found, the project developer may be required to find another location to implement the CDR project.	Talon Metals[7] ended up moving its minerals processing facility, initially planned to be built next to Tamarack nickel mine in Minnesota, to a new location in North Dakota, based on feedback from local communities.

Notes and sources: [1]Kapetaki et al., 2020; Calhoun et al., 2021; The Nature Conservancy, 2025. [2]George, 2024. [3]Sabin Center for Climate Change Law, Community Benefits Agreements Database. [3]BusinessWire, 2024. [4]Wyloo. [5]Carbon to Stone. [6]Raman, 2022. [7]Talon Metals, 2022.

SECTION 9

Siting Considerations

Overview of key considerations for on-site deployment of CDR

Context-specific factors are decisive in informing the feasibility of a CDR project within a given mining operation. These include the geological characteristics of the site, as well as the intended Life of Mine. Aside from access to reactive feedstocks for mineralization or weathering-based approaches, access to energy, or to capital to increase renewable energy production, can be constraining. Additionally, access to water can be similarly constraining, given available resources and the needs of local communities.

Geologic characteristics

Feedstock type and availability are the primary siting factors to consider before implementing CDR (see Section 6). Further parameters such as the presence of suitable subsurface deposits for carbon storage, or local microbial communities that may accelerate CDR reactions, should also be considered.

Water

Availability of local water resources or suitable process wastewaters, the existence of water management infrastructure, and potential conflicts with local usages of water are key considerations for CDR processes requiring water inputs.

Energy and infrastructure

Certain CDR methods have substantial energy requirements. Additional infrastructure, such as mineral processing and handling equipment, is also key in determining the relevance of a given site to implement CDR.

Land use

Available land area may vary depending on various characteristics, including mine type (open pit or underground), mined feedstock, etc. Conflicting uses may appear when mines close and land becomes available for remediation.

Local environment

CDR projects may require significant modifications that can impact local ecosystems. Careful consideration of biodiversity and involvement of local communities is necessary.

Social License, Community & Indigenous Engagement

Local community buy-in and support is crucial to executing safe and beneficial projects, and for maintaining environmental integrity.

Different CDR pathways require different infrastructure and inputs

While many mineral feedstocks may be applicable to both weathering and mineralization, optimizing for reaction rates and limiting environmental impacts requires choosing a pathway based on mineralogy, grain size, and other factors. Access to low-carbon energy and sufficient water can be constraining for deployments on site.

Mine Site Infrastructure & Assets		In Situ Mineralized CO_2 Storage	Surficial Mineralization	Surface Water Mineralization	Reactor-based CO_2 Storage	Reactor-based Mineralization with Co-products	Reactor-based CO_2 Storage for Metal Recovery	In Situ Mineralized Carbon Storage and Metal Recovery	Enhanced Rock Weathering	Wastewater Alkalinity Enhancement	Phytomining + Enhanced Rock Weathering	Electrochemical Ocean Alkalinity Enhancement	Direct Air Capture	Afforestation/ Reforestation	Biomass Burial
Feedstock Assets	Fresh Tailings	□	■ ●	▨	■ ●	■ ●	□	□	▨ ●	▨	■ ●	▨	▨	□	▨
	Legacy Tailings	▨	■ ●	▨	■ ●	■ ●	□	□	▨ ●	▨	■ ●	▨	▨	□	▨
	Coarse Waste Rock	▨	■ ●	▨	■ ●	■ ●	▨ Pre-ground Ores	□	▨ ●	▨	■ ●	▨	□	□	□
	Process Water/Effluent	▨	□	□	▨	▨	▨	▨	□	■ ●	□	■ Brines	▨	□	□
	Concentrated CO_2[1]	■ ●	□	▨	■ ●	□	■ ●	■ ●	□	▨	□	□	CO_2 is the Product	□	□
Energy & Utility Assets	High-Grade Waste Heat	□	□	□	▨	▨	□	□	□	□	□	□	▨	□	□
	Low-Grade Waste Heat	□	□	□	▨	▨	▨	▨	□	□	□	□	▨	□	□
	Available Renewable Power	▨	▨	▨	■	■ ●	▨	▨	□	□	□	■ ●	■ ●	□	□
	HVAC Systems	□	□	□	□	□	□	□	□	□	□	□	▨	□	□
	Water Processing Infrastructure	▨	□	□	▨	▨	▨	▨	□	■ ●	□	■ ●	▨	□	▨

■ Necessary for deployment ▨ Potentially useful □ Not necessary for deployment ● Key enabler

Notes and sources: Most tailings will not be suitable for enhanced weathering on land used for food production. [1]Generally speaking, "Point Source" CO_2 refers to emissions captured from industrial processes, rather than from the air. Here we refer to 'Concentrated CO_2 to represent both point source and DAC-sourced CO_2, as either will work for the listed pathways. Using Point Sourced CO_2 would count as 'avoided' emissions, rather than CDR, and while not the focus of this report, is still important.

Different CDR pathways require different infrastructure and inputs

Physical assets pertaining to the mine site, such as tailings storage facilities, or underground voids, or subsurface geology, will have an impact on which types of CDR pathways are most relevant. Community support and a relevant workforce will be critical across all pathways.

Mine Site Infrastructure & Assets		In Situ Mineralized CO_2 Storage	Surficial Mineralization	Surface Water Mineralization	Reactor-based CO_2 Storage	Reactor-based Mineralization with Co-products	Reactor-based CO_2 Storage for Metal Recovery	In Situ Mineralized Carbon Storage and Metal Recovery	Enhanced Rock Weathering	Wastewater Alkalinity Enhancement	Phytomining + Enhanced Rock Weathering	Electrochemical Ocean Alkalinity Enhancement	Direct Air Capture	Afforestation/ Reforestation	Biomass Burial
Physical & Geological Assets	TSF Surface Area	▨	■ ●	□	□	□	□	□	▨ See Note[1]	□	▨	□	□	□	□
	Depleted Open Pits	□	□	▨	▨	▨	□	□	□	□	□	□	□	□	▨
	Unused Pit Lakes	□	□	■ ●	□	□	□	□	□	□	□	□	□	□	□
	Underground Voids	□	□	□	▨	▨	□	□	□	□	□	□	□	□	■ ●
	Buffer Zone Land	□	□	□	□	□	□	□	■	□	■	□	□	■ ●	■
	Subsurface Mafic or Ultramafic Geology	■ ●	□	□	□	□	□	■	□	□	□	□	▨	□	□
Regional infrastructure and social context	Internal logistics & material handling	■	▨	■	■	■	■	■	▨	■	■	▨	CO_2 transport	□	▨
	Rail/Port Access	□	□	▨	▨	▨	▨	▨	▨	□	□	□	□	□	■
	Technical Workforce	■	▨	▨	▨	■	■	■	▨	■	■	▨	▨	▨	■
	Community Support / Social License	■	■	■	■	■	■	■	■	■	■	■	■	■	■

■ Necessary for deployment ▨ Potentially useful □ Not necessary for deployment ● Key enabler

Notes and sources: [1]In some cases, Enhanced Rock Weathering can be deployed directly in tailings storage facilities as a remediation strategy.

SECTION 10

Mining CDR Hubs

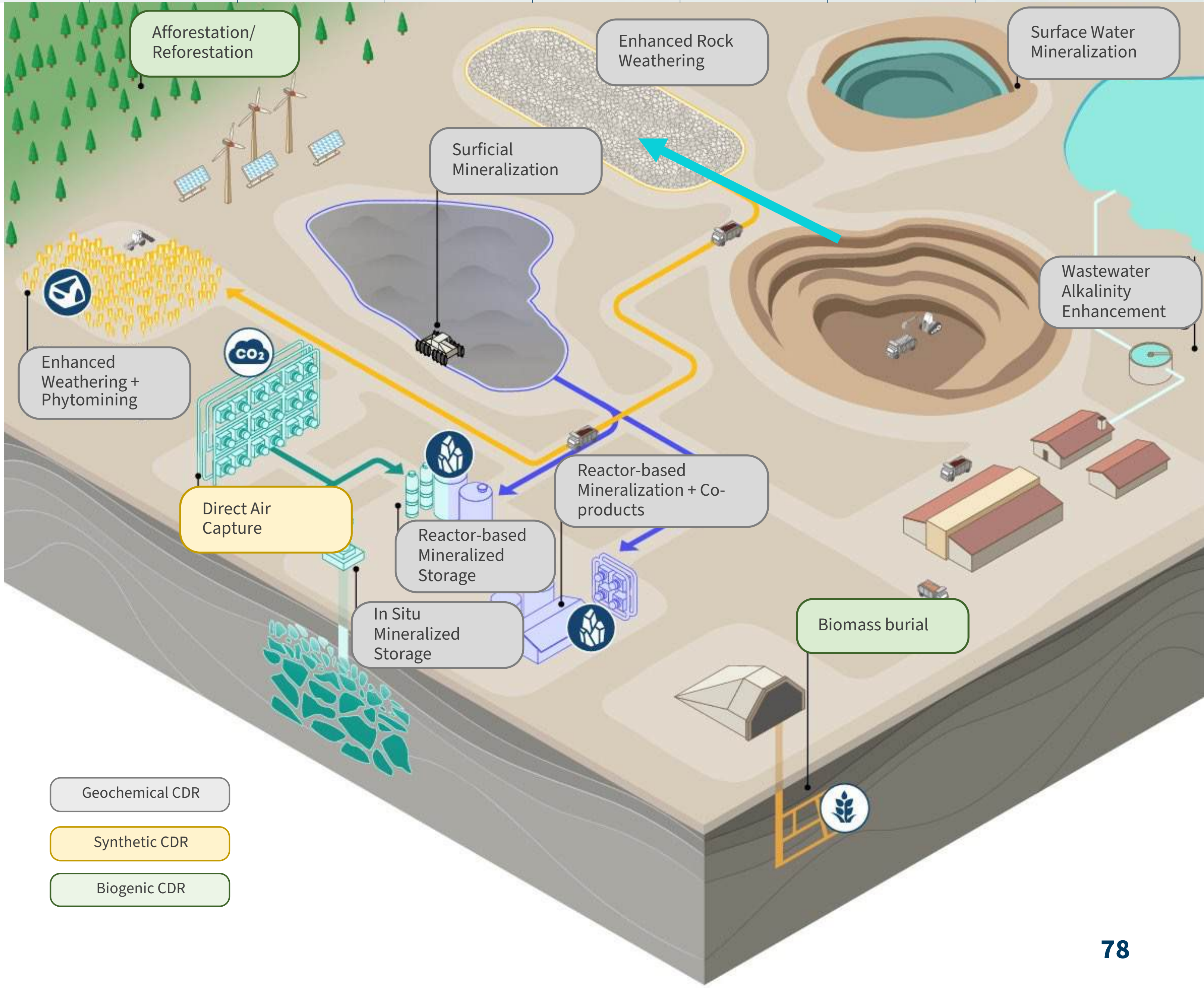
Mining and Carbon Dioxide Removal
A responsible path forward for mine operators, policymakers, and other key stakeholders

Co-locating multiple projects on mine sites could enable faster scaling

Mining operations offer a rare combination of industrial infrastructure and geological diversity that makes them well-suited to provide low-risk opportunities to test novel CDR innovations in real world settings, accelerating solutions to sustainability and circular resource use. Concentrating multiple CDR pathways on a single site – even pathways at early stages – allows practitioners, operators and regulators to maximize learning, and determine potential for wider deployment.

The near-term value as an R&D accelerator is distinct from the longer-term possibility to create massive carbon sinks from both operating and legacy mine sites. Deploying multiple CDR methods as a synchronized industrial system rather than separate, isolated projects, should reduce overall costs and maximize net carbon removal.

Realizing that potential will depend on advances in technology readiness, determination of net environmental impacts, as well as on business models that align operator incentives with climate imperatives — all of which the hub model is well positioned to help develop.



Hubs accelerate learning and reduce costs and environmental impacts

There may be substantial benefits to co-locating more than one CDR projects on existing industrial sites. The most significant of these is a reduction in both costs and environmental impacts, as compared to deploying projects individually. In terms of overall resource use, it is advantageous for CDR projects to use wastes and shared infrastructure to ensure that they are not drawing from new resource pools that are necessary for other societal activities[1]. Creating industrial hubs may also realize other benefits as well, as outlined below.

Lower Environmental Impacts

- Minimized total land disturbance and biodiversity loss compared to greenfield projects
- Lower cumulative carbon intensity of projects
- Reduction or avoidance of air pollution impacts and off-site environmental contamination that would result from transporting feedstocks off-site
- Lower environmental liability through shared responsibility

Shared Resources and Infrastructure

- Lowered CAPEX requirements for each project, especially when leveraging sunk costs of existing relevant equipment and infrastructure
- Maximized resource use, including post-closure assets and stranded assets
- Repurposed waste streams

Diversified Revenue

- Increased options for valorizing CDR and net emissions reductions
- Improved competitiveness through exposure to new markets

Shared MRV Costs

- Common baselining
- Shared measurement platforms and sensor networks
- Aggregated auditing fees
- Reduced administrative and technical overhead

Operational De-risking

- Reduced uncertainties in credit delivery and improved consistency in net carbon sequestration across the entire site
- Hedged approach to individual technological inefficiencies or fluctuations
- Increased efficiency in training and safety measures

Improved Workforce Stability

- Creation of green jobs
- Longer-term, stable employment environments, independent of fluctuations in commodity markets
- Retention of technical talent

Streamlined Permitting & Stakeholder Engagement

- Simplified environmental impact assessments and regulatory filings
- Unified and strengthened social license strategy

Notes and sources: [1] The report "Seizing the Industrial Carbon Removal Opportunity" highlights that "Competition for feedstocks, including biomass, low-carbon energy, minerals, and water may create societal strains, and is likely to disfavor carbon removal. This could impede its development completely. It is especially pertinent then to optimize resource use by harnessing relevant wastes and byproducts, existing material processing, and energy flows."

Establishing Mining CDR Hubs requires distributed ownership

The creation of Mining CDR Hubs, either as a means of advancing innovation or maximizing the CDR potential of a given site, requires public support. Initially, research funding and advances in regulation may be necessary from local and national governments. Partnerships between communities, mine operators and CDR developers are crucial from the earliest stages. As business models and market opportunities become clearer, operator-led investment, debt-financing or other innovative financing structures become more viable.

Mining Operations & CDR Hub

Financiers, Investors & Offtakers can provide upfront capital and long-term purchase agreements to de-risk projects.

Industrial Neighbors can benefit from options to store CO_2 or offload waste heat without the need for large transport networks.

Global Markets can provide guarantees for green products, and carbon credits through regulation and emphasis on reducing Scope 3 emissions.

Local Landowners, Citizens, and Communities can be partners, stakeholders, and beneficiaries in Hub projects.

Construction Industry Leaders can act as buyers of carbonated materials and long-term partners.

Regulators & Local Governments can help define legal opportunities and imperatives for maximizing resource use while maintaining rigorous environmental standards.

NGO & Research Communities can independently evaluate progress in meeting climate and environmental goals and identify opportunities for future improvements and collaboration.

Technology Providers can act as partners to supply novel technologies, carry out deployments, improve and innovate to optimize processes.

SECTION 11

A Responsible Path Forward: Recommendations

Mining and Carbon Dioxide Removal
A responsible path forward for mine operators, policymakers, and other key stakeholders

Mine operators can execute CDR pilots and demos that deliver value today and unlock durable monetization pathways and business models

Effective pilots and demos satisfy all three criteria below:

Technologies and projects fit with the operating context

Prioritize projects that match technologies and solutions to operational, regulatory, and community contexts

- **Engage with CDR suppliers and innovators** to understand the latest technologies and solutions
- **Match solutions to the right sites**: Consider feedstock, infrastructure, available assets, local context
- **Respect realities on-the-ground:** Operational, regulatory, SLO, community

The business case is real and strong

Ensure that projects improve actual site outcomes, not just carbon narratives

- **Safety:** Less waste, improved tailings stability, less risk, better outcomes
- **Production**: Increased production and asset use; stronger community / regulator support for new projects
- **Profit**: Lower costs for waste management; monetization of CDR, byproducts, and off-site CDR feedstock sales

Verification and claims withstand scrutiny

Design and resource projects such that evidence and claims can hold up under regulatory, market, and public scrutiny

- **Build strong foundations:** Establish baselines, monitoring plans, and robust evidence packages from the start
- **Produce auditable outputs** that regulators, buyers, and communities can interrogate

CDR in mining can scale when pilots unlock repeatable, well-governed deployments

The path from pilots to responsible scaling:

1 Raise the evidence bar as projects scale

Pilot success is not commercial readiness, but well-crafted field trials and pilots address key technical and operational issues and risks.

- Move from pilot to demonstration to scale only as evidence strengthens
- Validate models with measured data and reduce uncertainty at each stage
- Keep claims conservative as projects expand

2 Replicate first where fit is suitable

Scale across suitable sites and operator portfolios where deployment can become operationally repeatable and commercially durable.

- Expand across sites with similar feedstocks, constraints, and operating contexts
- Carry forward reusable evidence, playbooks, and decision rules into bankable deployment models

3 Ensure sustained stewardship at scale

Develop governance practices, policy, and regulation that pertain across geographies and across the Life of the Mine.

- Preserve monitoring and verification through closure and ownership transitions
- Share data and learnings from projects with regulators and industry bodies
- Keep claims current as site conditions, regulatory environments, and the site's operating status change

Pilot → Demonstration → Replication → Governed Scale

It is valuable and vital to share data, knowledge, and learning from early projects with the wider industry and regulators

The responsible path forward for CDR in mining

Mine operators need to work with other stakeholders to build the project pipelines, market infrastructure, and policy needed for responsible CDR deployment

ACTION AGENDA FOR MINING AND CDR

Mine Operators

Evaluate and assess options for integrated CDR projects

- Increase internal awareness of CDR opportunities
- Evaluate available assets and waste streams, and match to CDR solutions
- Participate in processes to develop best practices, new market infrastructure, standards and regulation
- Screen and scope projects for feasibility and value, within the operating and/or closure context
- Use project learnings to strengthen best practice and regulation

Project Developers

Design projects that solve problems for mine operators and local communities

- Develop solutions that deliver risk mitigation and business value to mine operators, and verifiable benefits to local communities, as well as CDR
- Share data, insights, and ideas to catalyze innovation in MRV, carbon accounting, monetization, and regulation
- Co-design community engagement and benefit agreements alongside mine operators and local communities
- Prioritize safety, risk reduction, and verification in project design and delivery

Regulators & Policymakers

Create clear pathways for governed deployment

- Provide enabling regulations for CDR interventions on mine sites and clarity on regulatory pathways for pilots and demos
- Provide clarity on how carbon policies, markets, and accounting will evolve
- Define safeguards and monitoring expectations
- Clarify waste reclassification and repurposing pathways, where relevant
- Integrate mine-site CDR into carbon accounting for products, emission trading schemes, and carbon border adjustment mechanisms

Registries, Verifiers, & NGOs

Ensure pathways for high-integrity, auditable projects

- Develop and align frameworks and rules for carbon accounting, claims, MRV, and other evidence
- Develop tools and standards for comparable, auditable projects that are hard to mis-use
- Encourage and legitimize innovation and learning alongside high integrity
- Help build an open-access evidence base, tools, and infrastructure to support MRV
- Monitor system functionality and use, and ensure ongoing accountability of other actors

Community Stakeholders

Get involved early in shaping project outcomes

- Get informed on the opportunities and limitations of integrated carbon removal as a means of climate change mitigation and environmental remediation
- Contribute to shared project designs and outcomes by engaging early with mine operators and project developers and providing information on the local context and priority issues
- Outline community priorities on environmental outcomes and shared benefits

Buyers, investors, public R&D funders, and donors

- Provide funding support for regulators, policymakers, NGOs, and communities to engage with the mining industry
- Provide catalytic funding for innovation paired with technical learning, transparency, legitimacy, and scrutiny

SECTION 12

Appendix 1: Technical Appendix

Technical Appendix

Summary

Technical assessments

The landscape of CDR technologies is rapidly maturing. The range of these technologies applicable to the mining industry is vast and ranges beyond those described previously in Section 3. For the purposes of this Technical Appendix, we have narrowed our focus even further to cover seven geochemical CDR pathways and one biogenic CDR pathway.

Geochemical CDR pathways are dependent on mineral feedstocks, slags, or other alkaline industrial wastes. These materials are continually produced through mining and metal processing, presenting environmental and safety liabilities. Applying these feedstocks towards an environmentally positive practice such as CDR presents an enormous opportunity. We primarily focus here on geochemical pathways as they are most closely tied with the core competencies of the mining industry and integrate most directly with existing mining workflows, material handling, and mineralogical expertise.

We also include a technical assessment on the opportunity to include Biomass Burial on sites in need of backfilling and sealing subsurface voids or pits. This pathway is included in part due to the potential for economic and environmental co-benefits, and in part due to the quick adoption and piloting of this novel approach, suggesting a quicker path towards near-term Mt-scale Mining CDR alongside complementary and promising geochemical pathways.

The following technical assessments are designed to serve as a starting point for mining engineering and innovation teams, providing the foundational context needed to begin exploring options for integrating CDR projects on site.

Finally, it should be noted that these assessments are tailored towards on-site deployment within a mining environment, with the exceptions of Enhanced Rock Weathering and Wastewater Alkalinity Enhancement. These two pathways may be interesting within the context of mining operations, but potential of on-site deployment is limited to sites with sufficient land area or domestic wastewater processing. They are included here in part because these pathways have significant potential outside of a mining context and are highly dependent on mineral inputs. It should be noted that all technologies described here can have broader applications in other industrial sectors, however the focus here is on the unique operational constraints and opportunities found within mining operations.

The technical assessments are organized as follows

On-site Only CDR Options

These methods are expected to take place within mining operations in order to minimize off-site transport of materials or to leverage existing on-site assets, especially mineral wastes as feedstocks for CDR.

Enhanced Mineralization:

1. Surficial Mineralization
2. Surface Water Mineralization
3. Reactor-based Mineralization with Co-products

Biogenic CDR:

4. Biomass Burial

On- and Off-site CDR Options

These methods may be deployed within mining operations under certain circumstances but are also likely to be deployed in regions surrounding mines or quarries.

Alkalinity Enhancement:

5. Enhanced Rock Weathering
6. Wastewater Alkalinity Enhancement

On-site CO_2 Storage Options

These storage options are intended for deployment on-site where applicable.

Mineralized CO2 Storage:

7. Reactor-based Mineralized Storage
8. In Situ Mineralized Storage

Structure of the Technical Assessments

Each of the technologies covered is assessed across five lenses: process, resources, costs, integration into mining, and scaling. These are meant to give a cursory understanding of what is involved in deploying within mining operations.

Process Overview — This section includes a diagram showing a generic version of the process in a mining context, accompanied with a brief explanation of the different steps describing the key inputs, outputs, and components of the process.

Resource Requirements — This section presents primary resource-related challenges, specifically for mineral feedstocks, water, energy, and land. It also highlights key constraints for the technology to scale up.

A special focus on suitable feedstocks highlights either the different applicable host rocks or minerals that can be used for each geochemical process, or the applicable sources of waste biomass for biomass burial.

Key Economic Drivers — This section highlights the primary CapEx and OpEx drivers and key cost-related insights based on cost analysis by RMI and publicly available data. A potential pathway to drive costs down by activating key levers is highlighted.

Integration Assessment — This section provides a high-level evaluation of compatibility with mining operations and any implications of integrating this technology.

Scaling Up — This section highlights key challenges that need to be tackled for the technology to scale up in a sustainable manner: knowledge gaps, technical improvements, evolutions, and conditions for integrating into mining operations.

Resource Requirement Ratings

Ratings for resource requirements are provided at a high level and are meant to give an overall sense for the general consumption of resources needed for each pathway. These ratings can be qualitative as well as quantitative but are not meant to suggest that requirements are ever too high to proceed, though it is true that carbon removal processes can be resource-intensive in general. These ratings are also not meant to be indicative of cost. In many cases, where pathways are resource intensive, integrating into mining activities is a means to deploy in way that optimizes resource use while minimizing the impacts of using that resource.

Rating	**Feedstocks** *This includes feedstocks that are either sourced expressly for use in CDR, or feedstocks derived from wastes with little to no economic value.*	**Water** *Water requirements are defined as additional water needs that could impact local water supply and are not based on the amount of water needed to facilitate geochemical reactions or grow biomass.*	**Energy** *Energy requirements refer to additional energy inputs, both thermal and electrical, that are needed to carry out CDR activities.*	**Land** *Land requirements refer to additional land beyond mining operations. Context is given for the operational footprint of CDR activities within a given site.*
Low	This process uses little to no mineral or biomass feedstocks.	This process uses little to no water under normal operating conditions. Values are below 2000L/tCO_2.	This process uses little to no energy to process materials, and energy needs may refer to transport only. Values are below 0.5 MWh/tCO_2.	This process is meant to be contained within existing mine operations but may need some space in order to process or store materials.
Medium	This process might use mineral feedstocks, for example as a sorbent, but they are not used as a continual input. Values might be less than 0.5 t/tCO_2.	This process relies on water and uses between 2000-10,000 L/tCO_2.	This process relies on continual and significant energy inputs beyond transportation of materials. Values range from 0.5 - 1 MWh/tCO_2.	This process may either require additional land within operations, or else be deployed off-site with a significant footprint.
High	This process is dependent on significant and continual access to mineral or biomass feedstocks as inputs and typically use more than 0.5t/tCO_2.	This process is heavily dependent on water and uses more than 10,000 L/tCO_2.	This process relies on continual and significant energy inputs beyond transportation of materials, with energy requirements greater than 1 MWh/tCO_2.	This process requires vast amounts of surface area and would displace existing uses of land.

Technology readiness levels

Using company deployment information and well-established technology readiness level (TRL) scales, we determined our own TRL scale unique to CDR and rated each approach based on it

CATEGORY	TRL/MRL	DEFINITION[1]	DEPLOYMENT LEVEL ACHIEVED
Market scaling	MRL 10+	**NOAK facilities** deployed commercially under **different conditions** and **geographies**	Commercial[2]
First deployment	9	Project is **fully operational** under real conditions and **first commercial activities** occur[3]	Commercial
Technology demonstration	8	**Commercial scale** project undergoes **final stages** of testing and evaluation	Demo[2]
	7	FOAK project occurs at **commercial scale** and under **relevant environmental conditions**	Demo
Pilot validation	6	Project occurs at **pilot scale** and under **relevant environmental conditions;** FOAK commercial scale facility not completed	Pilot[2]
Technology development	5	Project occurs at **lab scale** and under **relevant environmental conditions**	Lab
	4	**Components** of a project are **integrated** and tested at **lab scale**	Lab
Basic research	3	**Experimentation** occurs to test **proof of concept**	Concept
	2	**Conceptual research** applied to **practical applications**	Concept
	1	**Basic principles** and **concepts** of a project researched	Concept

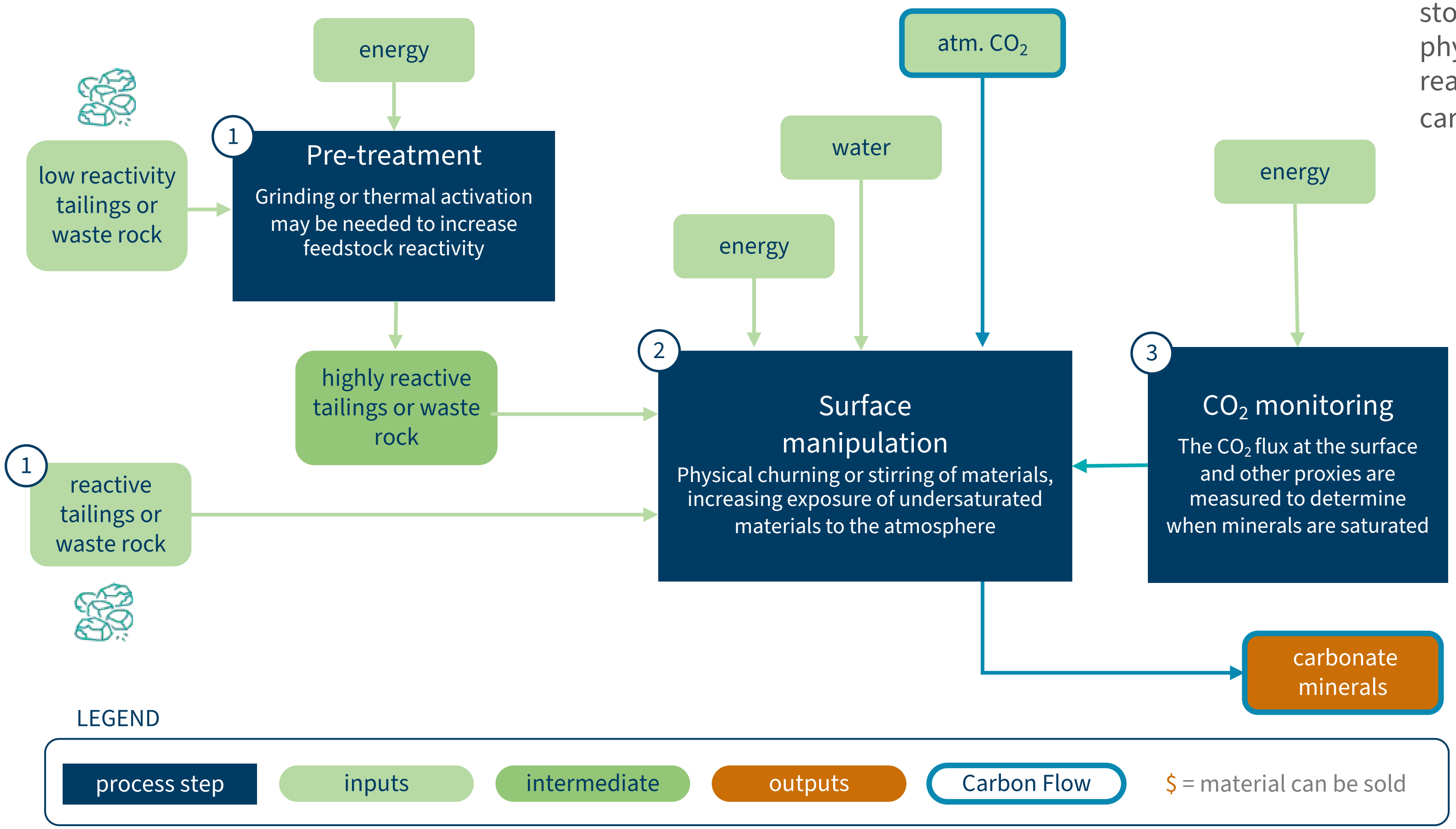
Notes and Sources: Adapted from RMI's Applied Innovation Roadmap. [1]We based our TRLs on two well-established scales. The DOE's Technology Readiness Level Scale which ranges from 1-9 and the DOE's technology risk scale which includes both technology readiness levels and market readiness levels. The scale shown above was designed to broadly cover all 32 of the CDR approaches mentioned in the AIR. For TRL scales pertaining to a specific technology, experts in the field may argue these definitions should shift slightly. [2]The main distinction between demo and pilot deployment is that the former occurs at commercial (or full) scale whereas the latter occurs at much smaller scale. The main distinction between demo and commercial deployment is that the former has not yet participated in commercial activities whereas the latter is commercially operating. [3]Commercial activities can be defined as selling either a product (i.e., biochar) or carbon removal credits, not including pre-purchases.

Technical Appendix

Surficial Mineralization

Surficial Mineralization, also known as Industrial Mineralization, integrates into existing mining operations by accelerating natural reactions between tailings or waste rock, CO_2, and water. Feedstocks are manipulated by chemical or physical means to optimize surface reactions with CO_2 from the air under ambient conditions to form carbonate minerals.

Surficial Mineralization



energy

① **Pre-treatment**
Grinding or thermal activation may be needed to increase feedstock reactivity

low reactivity tailings or waste rock

highly reactive tailings or waste rock

① reactive tailings or waste rock

atm. CO_2

water

energy

② **Surface manipulation**
Physical churning or stirring of materials, increasing exposure of undersaturated materials to the atmosphere

energy

③ **CO_2 monitoring**
The CO_2 flux at the surface and other proxies are measured to determine when minerals are saturated

carbonate minerals

LEGEND

process step	inputs	intermediate	outputs	Carbon Flow	$ = material can be sold

TRL ● ● ● ● ● 6 7 ● ●

PROCESS DESCRIPTION

Surficial Mineralization can be integrated on site using mine tailings or waste rock and can take place directly at the tailings storage facility. Feedstocks may or may not be pre-treated by physical, chemical or thermal means to optimize surface reactions ahead of contact with CO_2 ambient conditions to form carbonate minerals.

PROCESS STEPS

① Suitable mine waste such as mafic or ultramafic tailings or waste rock can be used directly or further treated via grinding or via chemical or thermal activation to significantly increase overall reactivity.

② Surficial Mineralization can integrate into mine operations by directly manipulating tailings in existing storage facilities.

③ Surface CO_2 fluxes and samples are measured to determine when material is saturated.

⇨ Carbonate minerals are formed from reactions with CO_2 in the air under ambient conditions. These minerals can remain in storage facilities, for example, with appropriate modifications to storage and closure plans.

Notes and sources : Many variants of this process exist. Surficial Mineralization only requires exposure of an alkaline mineral to CO_2 and water – any CDR derived comes from additional interventions beyond a counterfactual level of carbonation. This can include additional, deliberate grinding material to increase surface area, spreading material manually, churning material to increase exposure, or artificially increasing reactivity through pre-treatment steps. This diagram shows a simplified version of the Surficial Mineralization process.

Resource Requirements

High

Feedstock requirements

Mineral Feedstock
2-5 t/tCO$_2$

Tailings and waste rock from mines that extract from mafic and ultramafic rock are suitable feedstock, as are other alkaline wastes. This may include waste from the mining of nickel, chromium, titanium, platinum group metals, chrysotile, diamond, copper, and lead-zinc mines.[2] The composition and reactivity of available feedstock will determine the feasible scale of deployment. Magnesium-driven reactions in ultramafic rock can take years, which can impact overall logistics and the timing of carbon benefit claims or generation of carbon credits.

Low

Water
contained in tailings

Additional water is not generally required as an input, given high water content in wet tailings. In some cases, dry tailings might require prior hydration leading to higher water consumption levels.

Med

Energy
>0.05 GJ$_{el}$/tCO$_2$

Energy requirements depend on the method of surface manipulation and if feedstock pre-treatment is needed. Requirements can be low if electricity is needed only to power monitoring and manipulation equipment.[3]

Low

Land Use
integrates on-site

Deployment on site, either within existing tailings storage facilities, or within operation boundaries, mean no additional land is needed. For deployments that require spreading on new surfaces, land area would become significant.

Key Resource Constraint

Mineral Reactivity

Without pre-treatment processes to increase reactivity, a large volume of mine tailings or waste rock is needed for significant CDR because reactive components are only a fraction of the total mass. This limits the total potential capacity for CDR by Surficial Mineralization in mining, while also increasing measurement requirements, including difficult estimations of baselines.

Increasing the reactivity of feedstock should not only increase CDR capacity but also decrease the sampling area needed for measurements. This can be achieved through additional processing of materials pre-carbonation. Tradeoffs are expected between additional energy required (i.e., costs, associated emissions) and improvements in reaction rates. Innovations in chemical and thermal pretreatments are showing significant promise in drastically increasing reactivity at a reasonable energetic cost, overcoming this key constraint.

Ideal feedstocks often include those with no other economic value:

- Ultramafic rocks – e.g. olivine (dunite), peridotite, serpentinite
- Mafic rocks – e.g. basalt, gabbro
- Mine tailings – e.g. nickel tailings (olivine-rich), Diamond (kimberlite) tailings, platinum group metal tailings
- Industrial alkaline wastes – e.g. steel slag, cement kiln dust, fly ash

Notes and Sources: [1] Carbon mineralization capacities for relevant minerals in mine tailings are from National Academies of Sciences, Engineering, and Medicine (NAS) (2019). These values are per t of mineral (i.e., brucite). Mine tailings will only be some wt% of this mineral, so total mass of tailings needed will be higher. [2] Liam Bullock, *Geochemical CDR approaches in Mining: Feedstocks and strategies*, Spanish National Research Council and Carbon Neutral Initiative, 2024. [3] Adding a grinding pre-treatment could increase the energy requirement by 0.05-0.9 GJ/tCO$_2$, assuming 1.3-2.5 t mineral per tCO$_2$ removed and 10-100 kWh/t comminution values in Keleman et al. (2020).

Key Economic Drivers

Logistics

Transporting and handling materials can be costly and even emissions intensive.

Feedstock reactivity

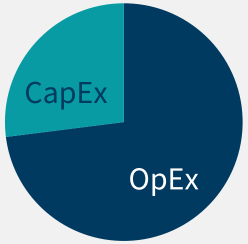
Reactivity of material with CO_2 is a key parameter in determining the quantity of materials needed. For tailings and waste piles, the material costs may be negligible, but reactivity rates will impact all other cost drivers. Preprocessing to increase reactivity will increase costs.

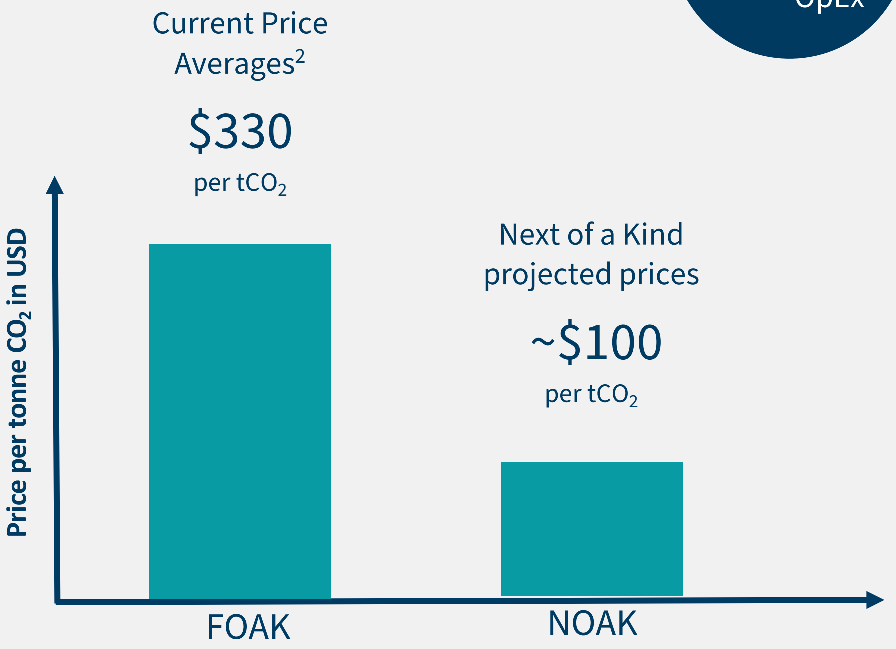
Quantification, including uncertainties in baseline measurements

MRV costs, especially accounting for uncertainties in natural baseline reactivity and counterfactual scenarios, will impact what is considered additional carbon removal and affect overall cost.

Energy costs

Costs related to preprocessing or continual manipulation of materials are dependent on the initial condition of the feedstock as well as the reactivity of the material.





Key Insights:

- Given the multiple configurations for this process, major cost drivers can be avoided by optimizing for one against another. For example, deployment within tailing storage facilities can virtually eliminate logistics costs. For situations that include more active material handling, access to reactive minerals may be increased.

Notes and Sources: [1] Feedstock costs could become a cost driver if tailings are not available burden-free. [2] Price Averages are based on data from CDR.fyi

Mine Site Integration Assessment

Integration Factor	Key Considerations	Integration Factor	Key Considerations
Siting Imperatives	• Access to significant volumes of reactive feedstocks	Implementation Stages	• Operation, Closure, Reclamation
Access to Energy	• Low-carbon energy will be necessary, but requirements depend on equipment and the pre-treatment process used • Timing of processing steps may be flexible to handle downtime from renewable energy intermittency	Access to Water	• Additional water inputs are not anticipated except in situations where tailings are too dry to react or waste rock is used
Waste Use Potential	• Can operate on uneconomic mining waste in tailings and waste rock storage facilities • Can leverage tailings directly within the TSF • Decreases in waste volumes are not expected unless carbonate products can be shipped offsite	Operational Complexity	• Modifications unnecessary for direct manipulation in TSFs • Pre-treatment of tailings would need to be integrated with material handling processes • Tailings deposition rate could be modified to increase CDR potential • Primary impacts will be on tailings management
Regulatory Hurdles	• Local environmental, health, and safety regulations may have specifications for handling tailings and other mining waste. • Impacts on mine closure regulation	MRV requirements	• Baselines for passive carbonation of tailings and other materials must be assessed • Requires additional equipment and measurement infrastructure outside of normal mining operations
Business impacts	• Green premiums on primary mine commodities may be supported, depending on jurisdiction • Carbon credit revenue possible • Reduced carbon tax obligations when applied towards net emissions reduction • Limited potential for sales of carbonated products	Co-benefits[1]	• Potential increase in long-term geochemical stability though stabilization of metals and minerals • Potential increase in geotechnical stability through cementation • Potential mitigation of acid formation

Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis. [1]More information on the integration potential and co-benefits can be found in ARCA's white paper on Repurposing Industrial Waste into Durable Climate Value.

Scaling up

Overcoming Knowledge Gaps

☐ Dedicated research on reaction kinetics in variable climates to better understand how humidity, temperature, and seasonal cycles impact mineralization across geographies.

☐ Investigation of long-term mobility or stabilization of heavy metals.

☐ Improved baseline measurement protocols to distinguish between natural and additional CO_2 uptake.

Improved material efficiency

Decreased costs

Operation in a diversity of contexts (feedstocks, industrial sites, …)

Considerations for Scaling

Feedstock logistics – Managing any additional logistical requirements of transporting and processing millions of tonnes of rocks and minerals.

Co-location of assets – Strategic mapping and clustering of activity to leverage alkaline wastes as storage of industrial CO_2 emissions with minimal pipeline or transport infrastructure.

Historical mine waste – Leveraging undesirable and legacy tailings, such as chrysotile asbestos tailings, can provide environmental benefits alongside acceleration of technologies.

Success Enablers

Technological Improvements

Feedstock reactivity treatments – improvement of pre-treatment processes that increase the feedstock's rate of carbon uptake could increase available feedstock for Surficial Mineralization.

Optimized tailings management – designing storage facilities from the start with carbonation in mind.

Regulations

Waste reclassification – where appropriate, wastes that are suitable for re-use on site can be explored for reclassification and repurposing in circular economy projects.

Liability transfer – clear legal frameworks are needed for long-term ownership and liability of mineralized carbon once it is stored, sold, or repurposed.

Economics & Market Integration

Emissions trading schemes – Carbon Mineralization of industrial wastes, is being evaluated as a distinct CDR method within Europe's Carbon Removal and Carbon Farming Framework, a prerequisite for inclusion in the EU Emissions Trading System (EU-ETS).

Insetting – upcoming net zero policies may require more effort towards lowering net emissions. On-site Surficial Mineralization deployments can support this.

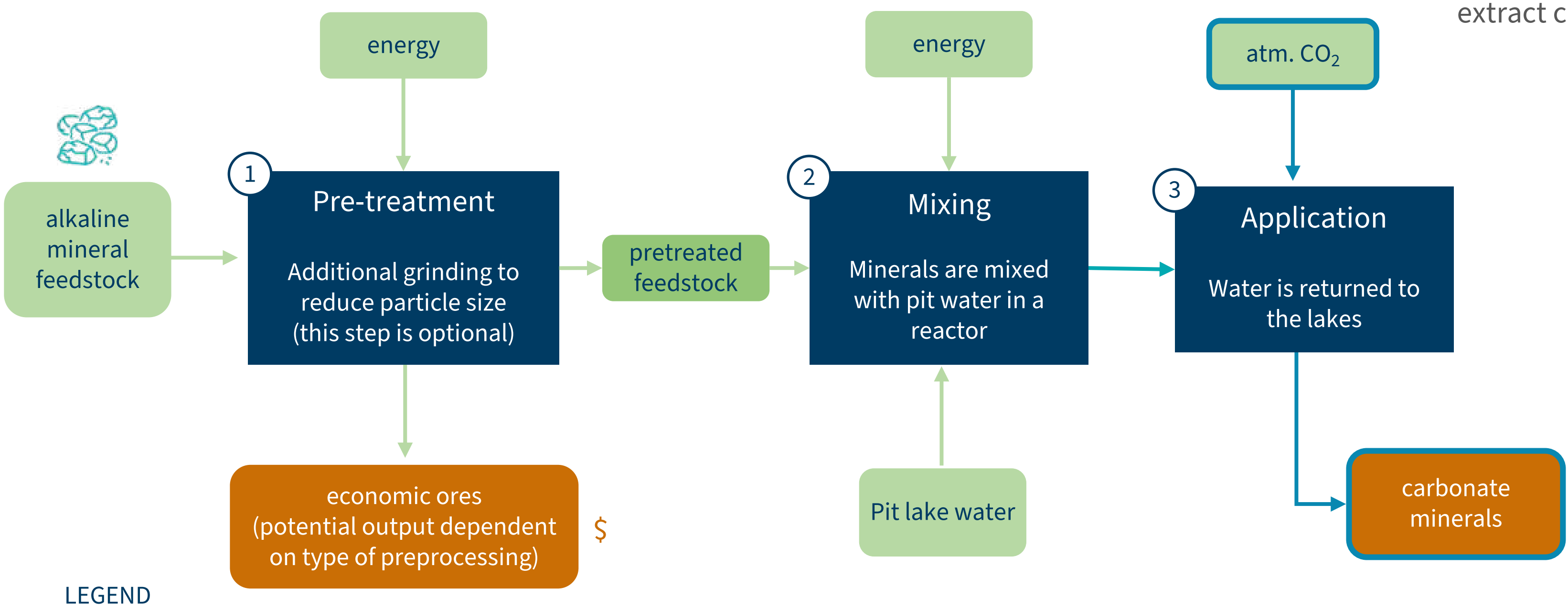
Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis. [1] Thermal and microwave pre-treatments can increase mineral reactivity by at least an order of magnitude (10x) by inducing dihydroxylation. More information on the integration potential and co-benefits can be found in ARCA's white paper on Repurposing Industrial Waste into Durable Climate Value.

Technical Appendix

Surface Water Mineralization

Surface water mineralization adds alkaline materials to mining pit lakes, increasing the pH and promoting the conversion of CO_2 to solid carbonate minerals, which settle at the bottom of the pit lake.

Surface Water Mineralization



energy

energy

atm. CO_2

alkaline mineral feedstock

① Pre-treatment

Additional grinding to reduce particle size (this step is optional)

pretreated feedstock

② Mixing

Minerals are mixed with pit water in a reactor

③ Application

Water is returned to the lakes

economic ores (potential output dependent on type of preprocessing) $

Pit lake water

carbonate minerals

LEGEND

- 🟦 process step
- 🟩 inputs
- 🟩 intermediate
- 🟧 outputs
- ▢ Carbon Flow
- $ = material can be sold

TRL ● ● 3 4 ● ● ● ● ●

PROCESS DESCRIPTION

Surface Water Mineralization makes use of either waste or imported feedstocks to backfill mining pits that have filled with water, creating temporary natural reactors to precipitate carbonates that then settle, storing solid minerals where rock was previously extracted. Materials can be pre-treated via physical means to optimize surface reactions, or potentially to extract commodity materials.

PROCESS STEPS

① Alkaline materials are typically sourced at a small enough particle size; using waste rock as a feedstock may require an additional grinding step. Pre-treatment may also include metal extraction and other thermal or mechanical treatments to enhance reactivity.

② Minerals are mixed with pit lake water in an external reactor, raising pH and dissolving target minerals. Target metals are filtered using a sorption filter, and passive aerators help with the absorption of CO_2.

③ Water is carefully returned to the lake, creating alkaline conditions to allow precipitation of solid carbonates which settle on the pit lake floor.

Note: Transportation may or may not be required depending on the source of the feedstock and the location of the application site.

Resource Requirements

High

Mineral Feedstock
2-5 t/tCO$_2$[1]

Feedstock requirements

Tailings and waste rock from mines that extract from mafic and ultramafic rock are suitable feedstock. This may include waste from the mining of nickel, chromium, titanium, platinum group metals, chrysotile, diamond, copper, and lead-zinc mines.[2] Faster reaction rates may require increased grinding energy or energy-intensive pre-treatments.

Low

Water
contained in pit lakes

This process takes advantage of accumulated water within mine pits that has no other use case and does not contain wildlife.

Med

Energy
300-500 kWh/tCO$_2$

Major energy requirements are for water pumping, possibly grinding, or wet milling to accelerate dissolution.

Low

Land Use
integrates on-site

Minimal land required for processing of water and feedstock, plus land over which to move feedstock from tailings pile to plant.

Key Resource Constraint

Mineral Reactivity + Energy Tradeoffs

Surface Water Mineralization faces resource constraints similar to surficial mineralization pathways, though potentially to a lesser extent due to the greater ability to actively manage reaction conditions within the pit lake itself. Capacity is constrained by the availability and reactivity of utilized alkaline feedstocks, as only a fraction of the material may effectively contribute to alkalinity generation and carbonate formation.

Project developers may accelerate reaction rates through interventions such as feedstock pre-treatment, particle size reduction and water chemistry management. However, these approaches require additional energy inputs, creating trade-offs between operational economics, process emissions, and improved carbon removal performance. Emerging pretreatment and process optimization methods may help alleviate these constraints and improve scalability.

Ideal feedstocks will be low-sulfide wastes to avoid generating acidity, and include:

- Mine tailings – e.g. kimberlite tailings, nickel tailings (alkaline residues), processed ultramafic tailings
- Carbonate minerals – e.g. limestone (CaCO$_3$), dolomite
- Low sulfide mining wastes – such as ultramafic waste rock and overburden

Note: The suitability of a feedstock for this process is dependent on the chemical content of the rock surrounding pit lake, as well as the feedstock itself.

Notes and Sources: [1] Carbon mineralization capacities for relevant minerals in mine tailings are from National Academies of Sciences, Engineering, and Medicine (NAS) (2019). These values are per t of mineral (i.e., brucite). Mine tailings will only be some wt% of this mineral and so total mass of tailings needed will be higher. [2] Liam Bullock, *Geochemical CDR approaches in Mining: Feedstocks and strategies*, Spanish National Research Council and Carbon Neutral Initiative, 2024.

Key Economic Drivers

Mineral Dissolution Rates

Wet milling is required to accelerate dissolution rates, and significant amounts of water must be pumped to avoid saturation and keep dissolution rates high.

Energy costs

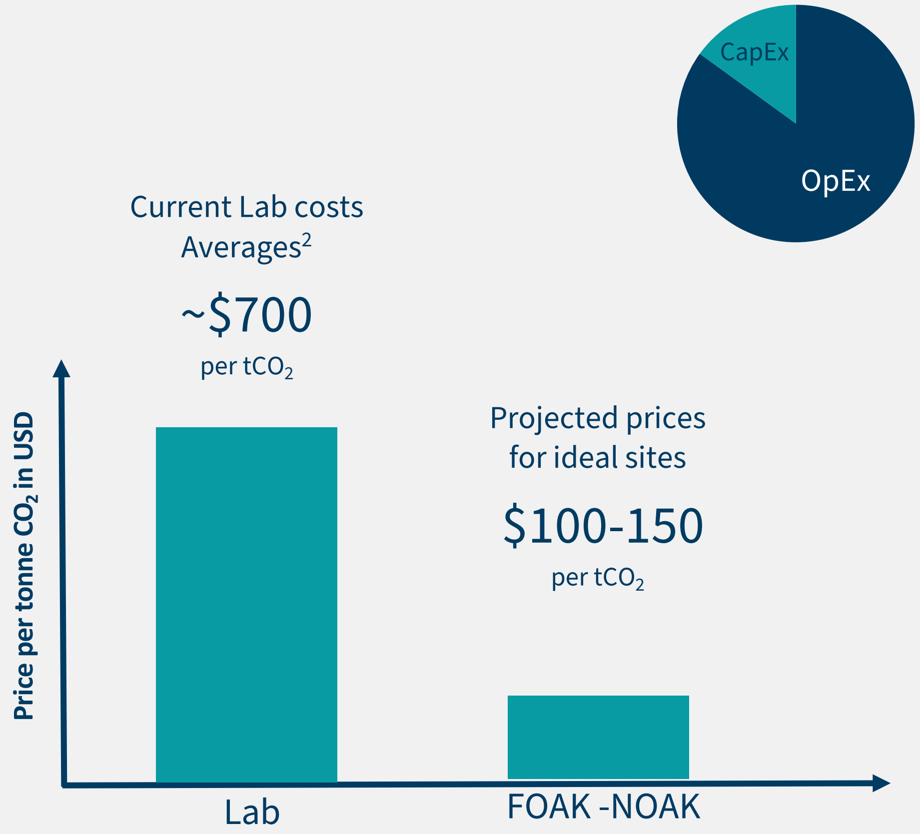
Costs related to preprocessing or continual manipulation of materials are dependent on the initial condition of the feedstock as well as the reactivity of the material.

Weather conditions

Lake surface water must be liquid, which limits operating time in cold climates during winter months.

Contaminant Control

Controlling contaminants that may leach out of feedstocks requires preprocessing and extraction.



Key Insights:

- Preprocessing mineral feedstocks to extract metals before dissolution can help offset costs.
- Potential to lower closure costs and liabilities is promising and merits further exploration.

Notes and Sources: [1]Feedstock costs could become a cost driver if tailings are not available burden-free.

Mine Site Integration Assessment

Integration Factor	Key Considerations	Integration Factor	Key Considerations
Siting Imperatives	• Access to significant volumes of reactive feedstocks • Suitable pit lakes ready for rehabilitation	Implementation Stages	• Closure, Reclamation
Access to Energy	• Low-carbon energy will be necessary, but requirements depend on pumping of water, any necessary mineral pre-treatments, and maintaining reactor conditions	Access to Water	• Water is sourced, and subsequently returned, to pit lakes, which store water generally unusable for other purposes
Waste Use Potential	• This process can make use of tailings and waste rock, returning that material to pits where rock was previously excavated	Operational Complexity	• Material handling may need to be modified or increased • Additional infrastructure will be needed to process water external to the lake • No impacts on the mining or metal extraction processes
Regulatory Hurdles	• Local environmental, health, and safety regulations may have specifications for re-introducing tailings and other mining waste into pits filled with water • Impacts on mine closure regulation	MRV requirements	• Baselines for passive CO_2 absorption and precipitation within pit lake environments • Requires additional equipment and measurement infrastructure outside of normal mining operations
Business impacts	• Green premiums on primary mine commodities may be supported, depending on the jurisdiction and market • Carbon credit revenue possible • Reduced carbon tax obligations when applied towards net emissions reduction • Limited potential for sales of carbonated products	Co-benefits[1]	• Provides additional options for backfill operations that help prevent evaporation of groundwater through lakes. • Potential benefits due to improved lake conditions on local ecosystems • Potential for decreased closure costs

Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis.

Scaling up

Overcoming Knowledge Gaps

☐ Research on quantifying air-water gas exchange rates under different conditions and weather scenarios

☐ Understanding optimizing geotechnical stability of backfill

☐ Increased understanding of positive and negative ecosystem impacts

☐ Optimization of material composition and other properties for specific pit lake chemistries

Improved material efficiency → Decreased costs → Operation in a diversity of contexts (feedstocks, industrial sites, …)

Considerations for Scaling

Site selection – Identifying suitable lakes with suitable volumes and proximity to mineral sources.

Weather Impacts – Depending on geography, weather and climate may negatively impact deployment, for example through frozen lake conditions during winter. However, wind and rain are beneficial, and sites in moderate climates with heavy rainfall could provide optimal conditions.

Regulation – Differences in regulation across national and subnational jurisdictions must be taken into account.

Success Enablers

Technological Improvements

Optimized processing – designing and optimizing throughput systems for reacting pit lake water with minerals, filtering, and then returning it to the lake.

Advanced sensing – improved sensing for deposition of carbonates on the lake floor.

Regulations

Mine closure adjustments – protocols are needed to determine when it is appropriate to modify mine closure rules to include new projects, providing they have beneficial outcomes.

Liability transfer – clear legal frameworks are needed for long-term ownership and liability of mineralized carbon once it is stored, sold, or repurposed.

Economics & Market Integration

Emissions trading schemes – Carbon Mineralization of industrial wastes, is being evaluated as a distinct CDR method within Europe's CRCF Framework, a prerequisite for inclusion in the EU Emissions Trading System.

Insetting – upcoming net zero policies may require more effort towards lowering net emissions. Surficial Water Mineralization can support this by producing negative emissions on-site.

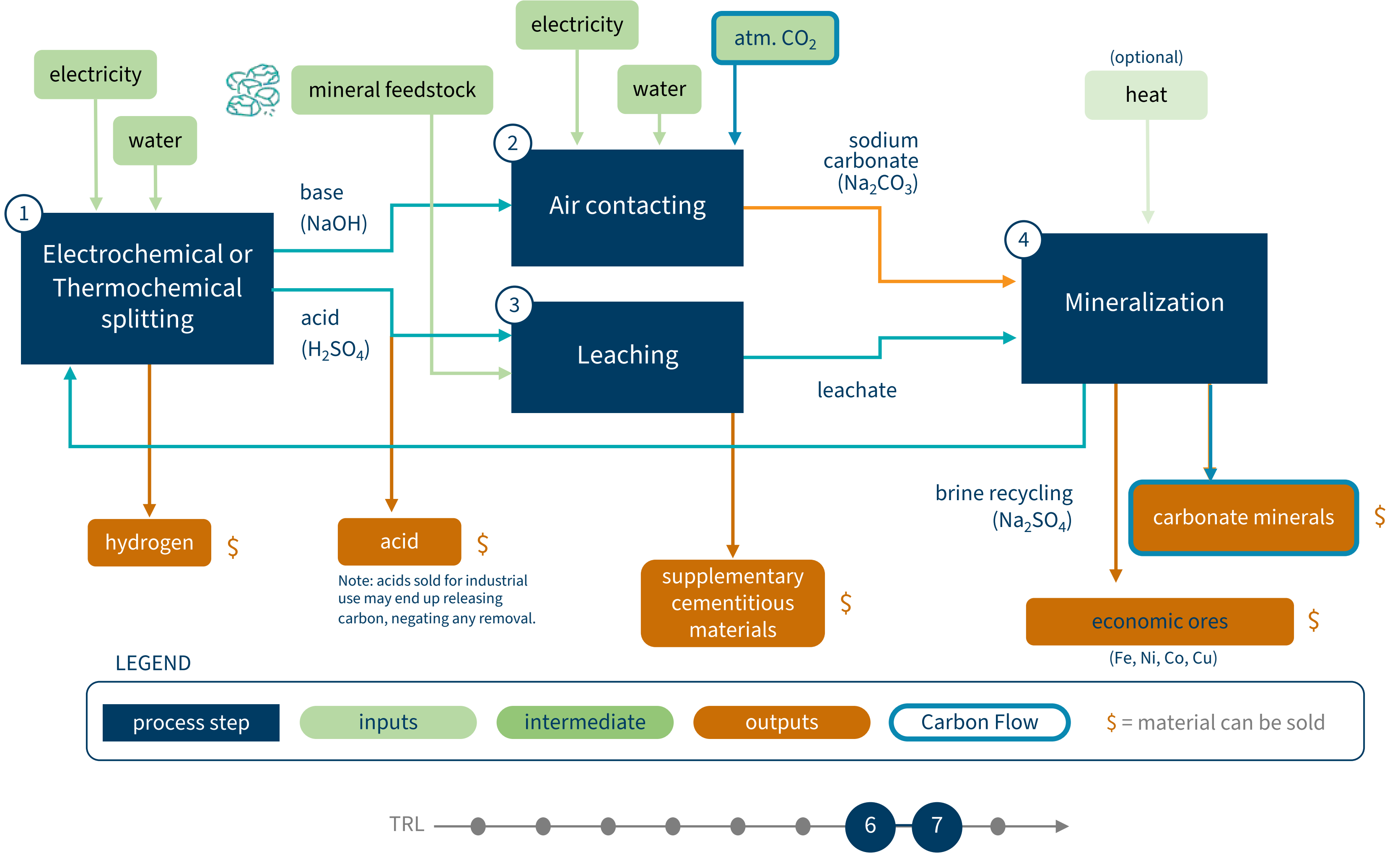
Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis. [1] Thermal and microwave pre-treatments can increase mineral reactivity by at least an order of magnitude (10x) by inducing dihydroxylation. More information on the integration potential and co-benefits can be found in ARCA's white paper on Repurposing Industrial Waste into Durable Climate Value.

Technical Appendix

Reactor-based Mineralization with Co-products

Reactor-based Mineralization with Co-products is a highly integrated process that, through a series of electrochemical or thermal processing steps, creates stable carbonate minerals, acids, hydrogen, and metal oxides/hydroxides using CO_2 sources directly from the atmosphere.

Reactor-based Mineralization with Co-products



PROCESS DESCRIPTION

This diagram shows just one example process of reactor-based mineralization. There are many variations that use other inputs and circulation fluids to take tailings and other uneconomic wastes to produce a range of industrial products using electrochemical or thermochemical techniques. Note that this configuration of reactor-based mineralization is an end-to-end CDR pathway as it produces its own sorbent for direct air capture.

PROCESS STEPS

① An electrochemical cell splits water or brine into an acid (e.g. sulfuric acid) and a base (e.g. sodium hydroxide). Thermochemical splitting is also possible.

② The base goes through an air contactor where it is used to chemically capture CO_2 directly from the atmosphere.

③ The acid is used to leach the mineral feedstock.

④ In a reactor, carbonates are mineralized, metal hydroxides can be extracted while brine is cycled back to the electrochemical cell.

Notes and Sources: This is a generalized process that may not represent specific technologies that are currently being demonstrated. The companies Travertine, Exterra, Atlas Materials, and Revora Materials all have distinguishable versions of this process that begin with different inputs and produce a different range of outputs.

Resource Requirements

High

Feedstock requirements

Mineral waste rock or partially depleted tailings, water, CO_2 and additives are the primary inputs for the process. Pre-treatment may include crushing and grinding of material to decrease particle size. Feedstocks must contain a minimum quantity of desired metals, e.g. nickel, copper, or magnesium, for the process to be economically viable as a secondary extraction process.

Mineral Feedstock

0.8-3[1] t/tCO$_2$

Med

Water

5,000-10,000L/tCO$_2$

Water is required as an input to the electrolyzer and to perform Direct Air Capture in the air contactor. Apart from evaporative losses in the air contactor, the process is not expected to lead to major water losses.

High

Energy

0.5 -2.5 MWh/tCO$_2$

This process can be highly energy-intensive, with a minimum theoretical consumption of 6.8 GJ/tCO$_2$ (mainly electricity). Some process variants may require low-grade thermal energy (below 100°C) during the mineralization step.

Low

Land Use

integrates on-site

Specific land footprint per tonne of CO_2 removed is likely to be minimal, depending on the type of feedstock and energy source. Carbonate minerals can be used as a neutralization source on-site, or sold as by-products.

Key Resource Constraint

Low-Carbon Energy

This process may emit more CO_2 emissions than it removes if grid emissions factors are above 240 gCO$_{2e}$/kWh$_{el.}$ At least 50% of CDR benefits could be lost if the carbon intensity is above 120 gCO$_{2e}$/kWh$_{el}$. This has several key implications for siting projects :

- Regions with low grid carbon intensities should be prioritized for deployments.
- Dedicated off-grid production using renewables may be required to achieve net negative CO_2 emissions. Different types of renewables enable a range of CDR efficiencies: 80% (solar PV), 90% (hydropower) and 95% (on-shore wind).[2]

Ideal Feedstocks often include those with no other economic value:

- Ultramafic rocks – e.g. olivine (dunite), peridotite, serpentinite
- Mafic rocks – e.g. basalt, gabbro
- Mine tailings – e.g. nickel tailings (olivine-rich), Diamond (kimberlite) tailings, platinum group metal tailings and asbestos tailings (e.g. chrysotile tailings)
- Industrial alkaline wastes – e.g. steel slag, cement kiln dust, fly ash
- Synthetic/Processed feedstocks – e.g. $Ca(OH)_2$, $Mg(OH)_2$, CaO, MgO

Notes and Sources: Based on stakeholder interviews and surveys, RMI analysis [1]LLNL's 2022 Report includes a value of 0.48 tCO$_2$/t material, corresponding to ~2 t rock/tCO$_2$.

Key Economic Drivers

Energy costs

High energy consumption can represent a significant fraction of total operational costs, and in some cases this process is not net negative without 100% renewable energy.

Commodity Prices

Overall costs for carbon removal will be offset by commodity pricing and be dependent on market offtakes for common products such as limestone, magnesium oxide, sulfuric or phosphoric acid, and others.

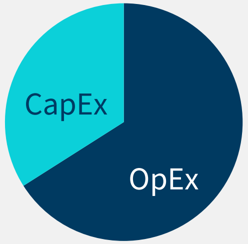
Equipment costs

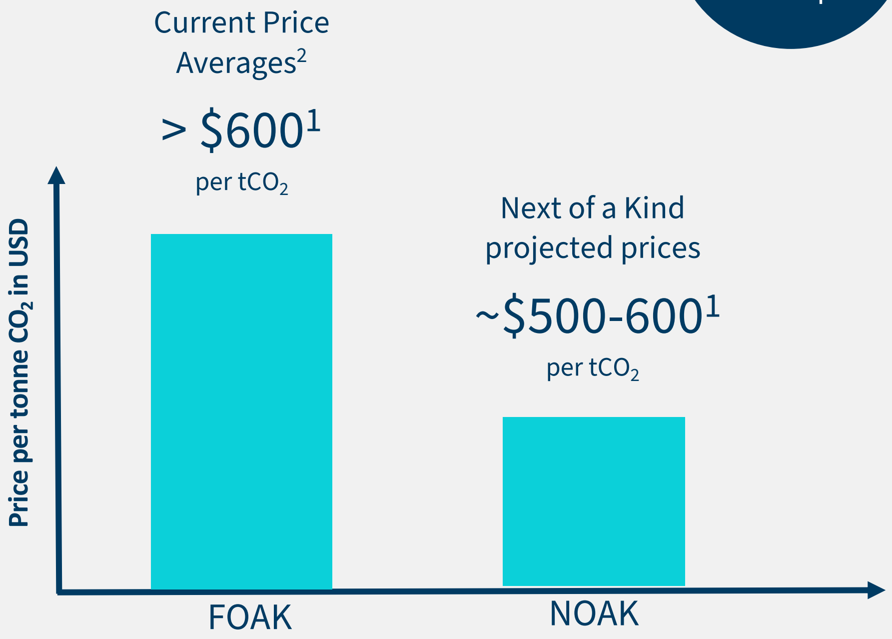
Dominated by electrochemical and thermochemical separation technology, along with the number of reactors needed to recover materials.

Plant Uptime

Continuous processing improves costs and efficiencies compared to batch processing but introduces complexity.

*Prices are reflective of **carbon removal only.** High processing costs should be taken in context, given the dual objectives of this pathway to produce common products in a sustainable and net-negative way.*





Key Insights:

- Costs range wildly, and are highly dependent on the specific use case, including process type, inputs, and outputs.
- Low-carbon energy supply is necessary to ensure net-negativity for energy intensive processes.
- The number of credits subsidized by commodity sales will be limited by markets for those commodities.

:**Notes and Sources:** Based on stakeholder interviews and surveys, RMI analysis. [1]Prices here derive from Techno-economic analysis of indirect carbonation processes for carbon sequestration using mining waste.

Mine Site Integration Assessment

Integration Factor	Key Considerations	Integration Factor	Key Considerations
Siting Imperatives	• Access to significant volumes of relevant feedstocks • Access to sufficient energy	Implementation Stages	• Operation, Closure
Access to Energy	• Significant low-carbon energy and/or waste heat will be necessary, but requirements depend on the specific technology and initial state of the feedstock • Timing of processing steps can be flexible to handle downtime from renewable energy intermittency	Access to Water	• Water inputs are not expected to be significant, but access to water will still be necessary
Waste Use Potential	• Operates on mining waste which contains a significant fraction of un-extracted metals • Decreases in waste volumes are expected when mineralized products, acids, or other materials can be shipped offsite • Potential to make use of waste heat	Operational Complexity	• Additional low-carbon energy generation likely necessary • Additional processing equipment and material storage will be necessary • Pre-treatment of tailings would need to be integrated with material handling processes • Primary impacts will be on tailings management
Regulatory Hurdles	• Remining tailings may require adaptations to current regulatory standards and practices • Production of potential commodities that were not initially anticipated may need additional permitting • Impacts on mine closure regulation	MRV requirements	• Baselines for counterfactual, passive carbonation of feedstocks must be assessed • Requires additional equipment and measurement infrastructure outside of normal mining operations • Complexities expected for monitoring the fate of carbonated products sold off site
Business impacts	• Additional metal extraction can be monetized • Additional acid production as a commodity • Carbon credit revenue possible • Reduced carbon tax obligations when applied towards net emissions reduction • Potential for sales of carbonated products	Co-benefits	• Potential to remediate hazardous wastes while displacing destructive sourcing of common industrial products • Support of circular economy and recycling of wastes • Re-shoring of production of materials previously offshored due to environmental concerns

Notes and Sources: Based on stakeholder interviews and surveys, RMI analysis.

Scaling up

Overcoming Knowledge Gaps

☐ Understand flexibility across a range of energy inputs, including operations using dedicated off-grid renewable power or intermittent power

☐ Better understand the overall life cycle performance of the process

☐ Understand how the process operates using a diversity of feedstocks

☐ Better quantification of co-products at commercial scale and in a diversity of contexts

Improved material efficiency

Decreased costs

Operation in a diversity of contexts (feedstocks, industrial sites, …)

Considerations for Scaling

Additional Renewable Energy – Increasing on-site renewable energy capacity may be necessary where low-carbon grid energy is not available.

Co-location of assets – Strategic mapping and clustering of activity to leverage alkaline wastes as storage of industrial CO_2 emissions with minimal pipeline or other transport infrastructure.

Historical mine waste – Leveraging undesirable and legacy tailings, such as chrysotile asbestos tailings, can be an environmental win alongside acceleration of technologies.

Success Enablers

Technological Improvements

Electrolyzer – increased efficiency of electrolyzers to reduce the overall energy intensity of the process, refined design of three-chamber electrolyzers able to efficiently handle acid and base couples

Air contactor – refined design for air contactors (passive, cooling towers, etc.) to reduce the energy intensity of the process

Regulations

Waste reclassification – where appropriate, wastes that are suitable for re-use on site can be explored for reclassification and repurposing in circular economy projects

Industrial standards – outputs used in further industrial contexts (e.g. carbonated products, metal oxides, phosphoric acid) should comply with local and international standards.

Economics & Market Integration

Lower energy costs – currently a major cost driver, decreased electricity costs could be made possible by higher energy efficiency and cheaper low-carbon electricity sources

Integrating into multiple markets – the process would allow increased rates of metals recovery from metallic ores currently exploited by the mining industry

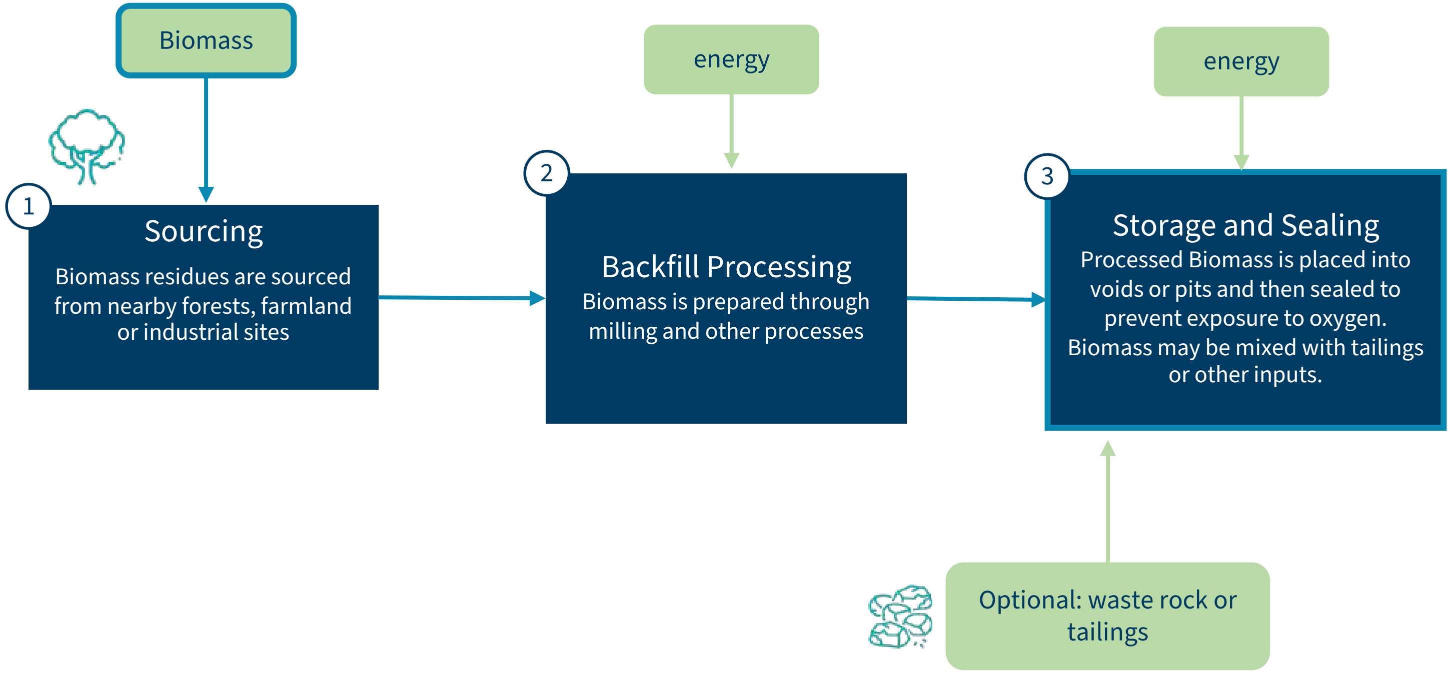
Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis.

Technical Appendix

Biomass Burial

Biomass burial seals sustainable waste biomass in subsurface, anoxic environments where the biomass is unable to decay and release greenhouse gases. In the case of mining, biomass is used as a backfill material before sealing off voids or covering filled open pits.

Biomass Burial



Biomass

1 Sourcing
Biomass residues are sourced from nearby forests, farmland or industrial sites

energy

2 Backfill Processing
Biomass is prepared through milling and other processes

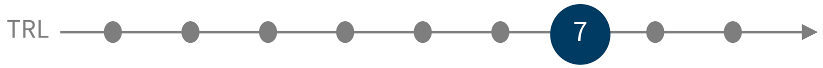
energy

3 Storage and Sealing
Processed Biomass is placed into voids or pits and then sealed to prevent exposure to oxygen. Biomass may be mixed with tailings or other inputs.

Optional: waste rock or tailings

LEGEND

- ■ process step
- 🟩 inputs
- 🟩 intermediate
- 🟧 outputs
- ▢ Carbon Flow
- $ = material can be sold



PROCESS DESCRIPTION

Biomass is sealed in subsurface, anoxic environments in order to prevent decomposition and release of CO_2 into the atmosphere. Mines can provide underground voids and chambers, many of which eventually must be backfilled and sealed.

PROCESS STEPS

① Biomass is sourced sustainably from wood residues, forestry waste or agricultural byproducts.

② Collected biomass is then processed and optimized as backfill material according to the specific mine environment and reclamation requirements.

③ Biomass is placed in underground in mine voids or chambers and sealed to create anoxic conditions.

⇨ Gas composition and structural stability is continuously monitored across sealed chambers.

Notes and sources : More details about this process can be found on the website of the company Rewind, who deploys Biomass Burial on mine sites.

Resource Requirements

High

Feedstock requirements

Biomass
~ 0.5 -1 tonnes dry biomass/tCO_2[1]

To store one tonne of CO_2, approximately one tonne of dried biomass is needed, though this ratio changes based on the type of biomass and its initial moisture content.

Low

Water
2 – 7 m^3 / tCO_2

Water is needed as a transport medium to create a pumpable slurry. Recycled mine water or other non-potable sources are prioritized.

Low

Energy
< 0.05 GJ_{el}/tCO_2

Energy is needed for transport and processing of biomass.

Low

Land Use
integrates on-site

Burying biomass can be done on site using existing voids and chambers. This process can also be done in open pits, if covered and sealed properly with tailings, rock or other material. Some space is needed for processing biomass.

Key Resource Constraint

Sustainably Sourced Biomass

The sourcing of sustainable waste biomass is constrained through transport costs and relies on proximate sources of biomass near suitable mines. While suitable mine sites are globally abundant, the overall process is limited by the logistical challenge of matching them with appropriate biomass inputs.

Annual volumes of suitable biomass residues produced globally are estimated to be over 3 Gt, however these residues must be stored within a 300-mile or smaller radius of their destination storage site. This limits the number of suitable sites to those near managed forests, agricultural activities, or industrial sites producing massive quantities of biogenic wastes.

Prioritizing high volume feedstock sources, such as agricultural hubs, within "Low Transport Corridors" within a 120-mile radius would substantially decrease operational costs.

Ideal Feedstocks Include

- Forest residues from managed forests, including sawdust
- Agricultural residues, especially those destined to be burned openly
- Industrial biomass wastes with no other use cases
- Algae

Notes and Sources: [1]Rewind website

Key Economic Drivers

Transportation

Materials will need to be transported on a continual basis. Both transport emissions and costs impact the overall CDR price, and distances greater than 300 miles could render projects uneconomical. Electric transport can reduce costs.

Feedstock Processing & Costs

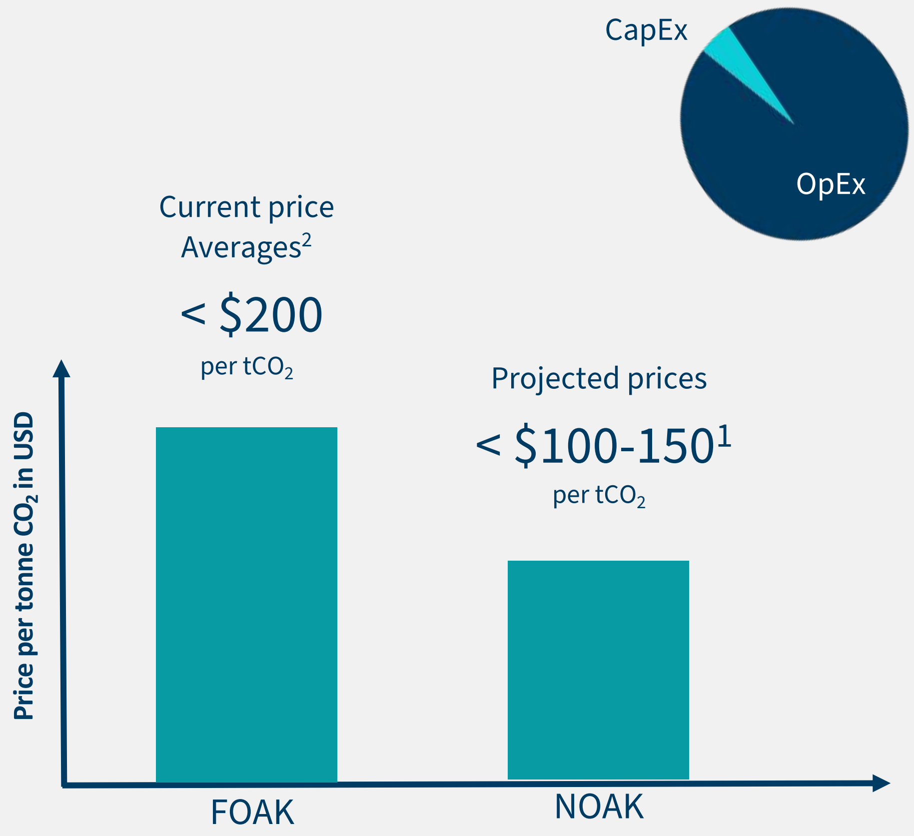
The cost to purchase suitable feedstocks, as well as processing costs to create injectable slurries, is significant. Larger feedstock processing facilities will lead to decreased costs.

Mine storage space

Included in the price of carbon credits derived from mine-based biomass burial is a fee paid to mines for using the space, though this is dependent on the business model. Maintenance costs also factor in.

MRV

The costs of measuring and monitoring are higher at the beginning of a project but come down as projects scale and more chambers are filled , as monitoring can be done collectively.



Key Insights:

- The costs and benefits to the mine are dependent on the project model. This can be a source of income for mines when the CDR supplier retains the carbon credit; alternatively, mines can pay the CDR supplier a fee and retain credits themselves.
- CapEx costs vary based on existing backfill infrastructure.

Notes and Sources: [1] From Rewind’s website.

Mine Site Integration Assessment

Integration Factor	Key Considerations	Integration Factor	Key Considerations
Siting Imperatives	• Access to significant volumes of sealable voids	Implementation Stages	• Operation, Closure, Reclamation
Access to Energy	• Low-carbon energy may be necessary to process biomass before storage.	Access to Water	• Low volumes of additional water may be necessary
Waste Use Potential	• The primary feedstock is biological wastes with no other economic use cases • Mineral wastes on site can be included with the biomass as backfill	Operational Complexity	• Additional equipment to process biomass on site may be necessary • Mineral wastes may be mixed with biomass to optimize conditions, though additional processing is unnecessary • Additional measurement networks may be needed to monitor gas concentrations and overall physical stability, depending on regulations
Regulatory Hurdles	• Backfill permits must allow for organic additives. Where permits are ambiguous, additional lead time can be expected ahead of any approvals • Potential methane formation and leakage or pressure buildup • Groundwater regulations • Impacts on mine closure regulation	MRV requirements	• Baselines for alternate use cases of biomass waste materials must be assessed • Requires additional equipment and measurement infrastructure outside of normal mining operations • Environmental baselines
Business impacts	• Green premiums on primary mine commodities may be supported, depending on jurisdiction • Carbon credit revenue possible • Reduced carbon tax obligations when applied towards net emissions reduction • Reduction of costs associated with environmental liability or closure	Co-benefits[1]	• Land stabilization and restoration • Potential reduction in ARD/AMD • Potential improvements in water quality • Prevention of methane emissions • Subsurface fire prevention

Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis. [1]More information on the integration potential and co-benefits can be found in ARCA's white paper on Repurposing Industrial Waste into Durable Climate Value.

Scaling up

Overcoming Knowledge Gaps

☐ Longer term biomass preservation estimates in mining environment

☐ The amount of biomass that can be integrated into cement paste backfill

☐ Improved baseline measurement protocols to distinguish between natural and additional greenhouse gas emissions

Improved material efficiency → Decreased costs + demonstrated co-benefits → Standardized practice for using biomass as backfill

Considerations for Scaling

Modular process standardization – Developing plug-and-play injection and monitoring modules would allow for rapid deployment across diverse mine sites.

Geographic feedstock proximity – Prioritizing low transport corridors where high-volume biomass sources sit within a 120-mile radius of viable storage mines.

Regulatory harmonization – Establishing a universal 'Organic Backfill' classification would streamline permitting processes across multiple jurisdictions and reduce lead times.

Success Enablers

Technological Improvements

MRV Optimization– streamlining the biomass measurement process during injection can reduce per-unit measurement costs and enables a substantial increase in daily throughput.

Sensor durability – improving the lifespan and calibration stability of alkalinity and pH sensors in corrosive environments.

Regulations

Biomass wastes and landfill taxing – increasing regulatory pressure on landfilling wastes, especially those that produce methane emissions when landfilled, will increase the case for diversion towards CDR.

Mandatory backfill and reclamation requirements – When reclamation regulations get stricter, the economics of including biomass burial become stronger.

Economics & Market Integration

Insurance products – creating new insurance products can help satisfy legal reclamation obligations, allowing for adjustments in reclamation bonds.

Grants for reclaiming abandoned mines– increased funding towards orphaned sites can provide the necessary capital to operate projects at scale.

Notes and Sources: Based on stakeholder interviews and surveys, RMI analysis

Technical Appendix

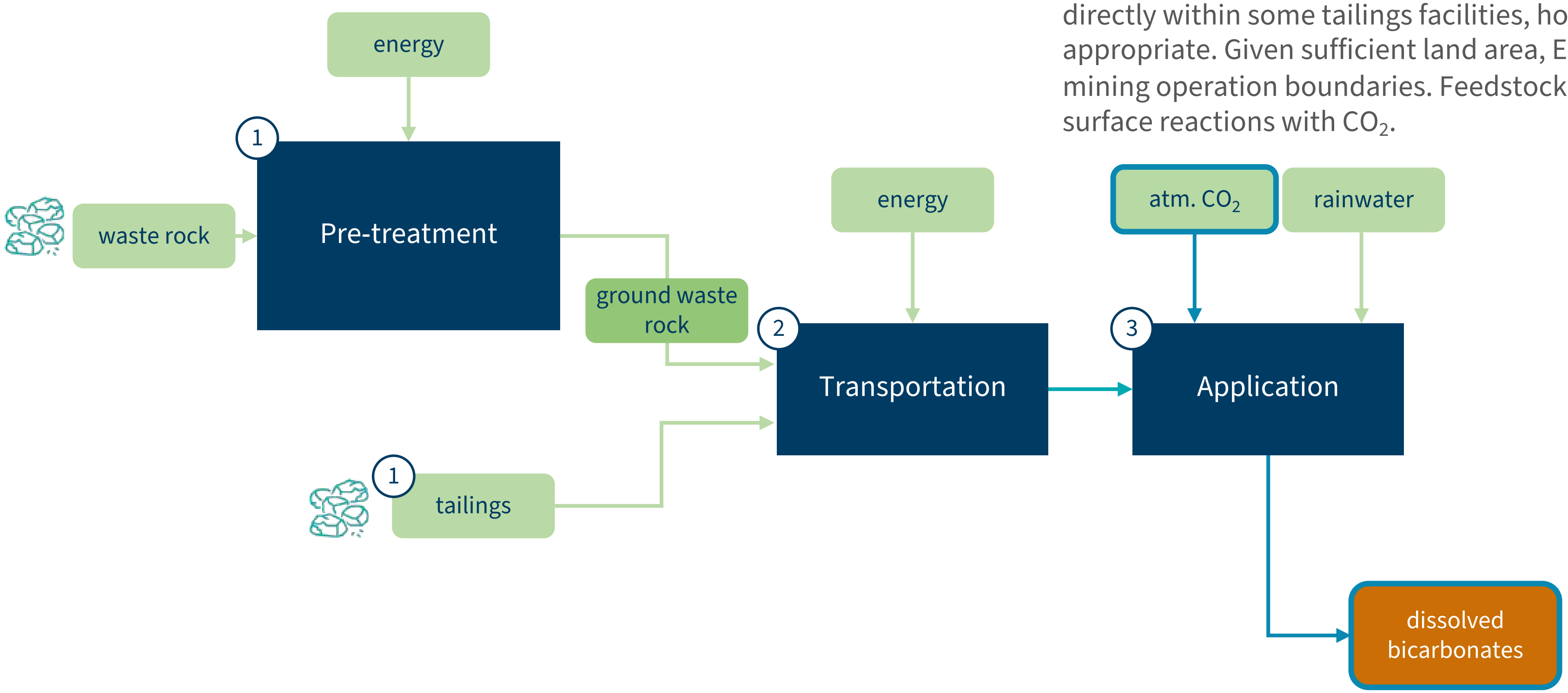
Enhanced Rock Weathering

Enhanced Rock Weathering, also known as Terrestrial Enhanced Weathering, involves spreading finely ground alkaline material onto soils to accelerate geological weathering. Reactions with atmospheric CO_2 and water form dissolved bicarbonates that are transferred through watersheds to rivers and streams and eventually to the ocean, where they remain stable for thousands of years. Enhanced Rock Weathering can be done on or off the mine site in appropriate soils or tailings storage facilities and is commonly done in agricultural settings.

Enhanced Rock Weathering

PROCESS DESCRIPTION

Enhanced Rock Weathering is primarily deployed not on mine sites, but on agricultural land using quarry fines, and in some cases[1], mineral production wastes. It can be done on other soils, or directly within some tailings facilities, however, making use of mine tailings or waste rock where appropriate. Given sufficient land area, Enhanced Rock Weathering can be deployed within mining operation boundaries. Feedstocks may be pre-treated via physical means to optimize surface reactions with CO_2.



energy

1 Pre-treatment

waste rock

ground waste rock

energy

2 Transportation

1 tailings

atm. CO_2

rainwater

3 Application

dissolved bicarbonates

LEGEND

process step	inputs	intermediate	outputs	Carbon Flow	$ = material can be sold

TRL ● ● ● ● ● ● ● 8 ● →

PROCESS STEPS

① Additional grinding of materials is commonly needed to maximize reaction rates within soils on a timescale amenable to measurement of reaction products.

② Feedstocks are generally transported offsite within a fixed radius representing the limit for net negativity of the process, after accounting for transport emissions.

③ Materials are thinly spread over the application site or collected in heaps. If deployed on croplands, materials can usually be applied with existing farming equipment.

⇨ Materials react with CO_2 from the air and rainwater to form dissolved bicarbonates, ultimately flowing through groundwater, surface water, and rivers to the ocean.

Notes and sources : [1] Anglo American's Project Earthstone located in Brazil uses slags on nearby agricultural lands.

Resource Requirements

High

Feedstock requirements

Mineral Feedstock
0.8-5 t/tCO$_2$[1]

The CO$_2$ removal potential depends on overall reactivity, including mineral composition and particle size.[2] Suitable feedstocks include basalt, wollastonite, and olivine, alongside carbonate minerals such as limestone. Both waste rock and tailings use are heavily regulated. Any feedstock applied to agricultural land must be verified to be low in toxic metal content, though for cases where crops are used for phytomining, high metal content is necessary. Using fine-grained materials limits the need for extra pre-treatment steps.

Low

Water
Rainwater or Irrigation Water

Additional water is usually not required as an input. Rainwater is sufficient, and existing water irrigation equipment and practices can be applied directly.

Low

Energy
Variable by process

Energy requirements depend primarily on the mode of transportation and the inclusion of a feedstock pre-treatment process but are generally low.[4] Transportation distances become limited due to LCA constraints on overall net negativity.

Med

Land Use
450-3000 m^2/tCO$_2$[5]

Land requirements are high, though deployments generally take place in agricultural settings without disruption to existing practices. Total footprint depends on the feedstock composition and application rate.

Key Resource Constraint

Local Feedstock Availability

Transportation costs and emissions play a significant role in determining the net negative emissions potential. LCAs can help determine maximum distances from a given feedstock source as a function of both transport type and reactivity of the feedstock.[6] Optimal project siting balances transportation distances against nearby land availability.

Although there are land constraints to applying feedstocks on non-agricultural soils for weathering purposes, enhanced weathering may also be done in nearby forests, or even directly on tailings in storage facilities during reclamation through revegetation.[7] Options that favor heap leaching on site can also avoid transport costs and emissions penalties.

Ideal Feedstocks often include those with no other economic value:

- Ultramafic rocks – e.g. olivine (dunite), peridotite, serpentinite
- Mafic rocks – e.g. basalt, gabbro
- Mine tailings – e.g. nickel tailings (olivine-rich), Diamond (kimberlite) tailings, platinum group metal tailings
- Industrial alkaline wastes – e.g. steel slag
- Alkaline silicate byproducts – e.g. wollastonite, silicate rock powders from quarry fines

Note: Industrial byproducts should only be used in cases where feedstocks meet strict environmental regulations and safeguards.

Notes and sources: [1] The low end of the range is from Campbell et al. (2022) and the high end is from Zhang et al. (2023). [2] Breunig et al. (2024) suggest particle size P80 < 0.02 mm is needed for 100% annual dissolution rates. [3] Webb (2022). [4] Adding a grinding pre-treatment could increase the energy requirement by 0.02-1.8 GJ/tCO$_2$, assuming 0.8-5 t feedstock per tCO$_2$ removed and 10-100 kWh/t comminution values in Keleman et al. (2020). [5] This uses the range of 0.8-5 t feedstock per tCO$_2$ and an application rate of 7 t feedstock per acre. [6] Lefebvre et al. (2019) found an offsetting distance of 990 km, while Zhang et al. (2023) found a range of 25 km to 5000 km depending the type of mineral feedstock, carbon price, and type of transportation. [7] Tailings at a gold mine in Ghana were shown to weather through a revegetation project.

Key Economic Drivers

Feedstock Transportation

Both emissions and costs of transport are major contributors to the final costs of enhanced weathering, limiting application to locations within a short distance to the source of the feedstock.

MRV

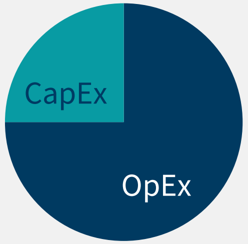
Measurement, modeling and monitoring for enhanced weathering can be costly, though costs are decreasing as the pathway matures. The complex environment of soils and difficulty in tracking bicarbonates can translate to high levels of uncertainty and discounting of tonnes removed.

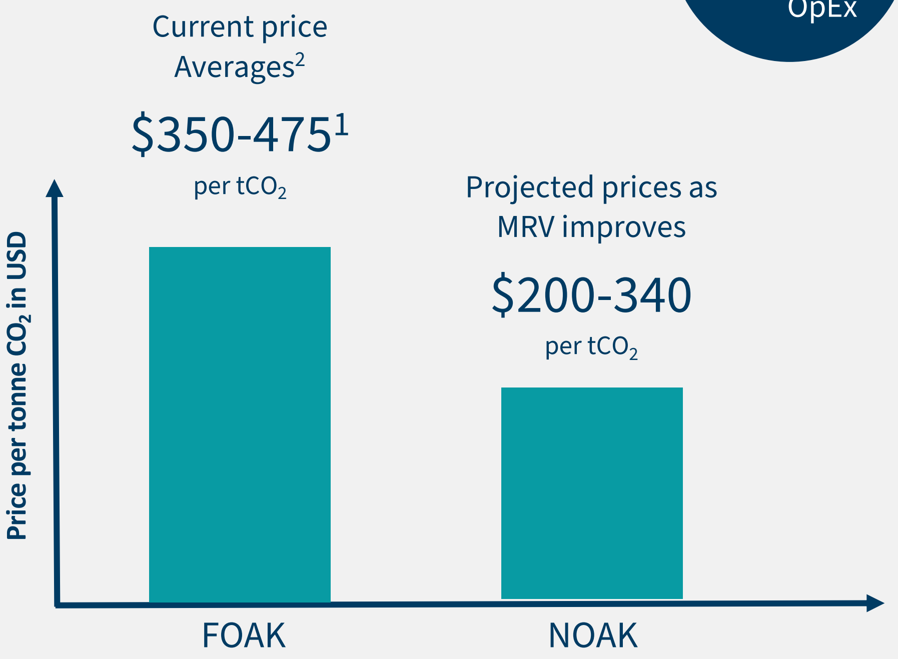
Feedstock reactivity

Reactivity of material with CO_2 is a key parameter in determining the quantity of materials needed. For tailings and waste piles, the material costs may be negligible, but reactivity rates will impact all other cost drivers.

Uncertainties in baseline measurements

Accounting for uncertainties in natural baseline reactivity and counterfactual scenarios will impact what is considered additional carbon removal and affect overall costs. Unknowns in feedstock impurities may also have a large impact on the overall economic performance.





Key Insights:

- MRV and transport costs currently compete for primary cost driver. As a novel, open-system CDR method, MRV is still being developed and is costly. A recent surge in research and innovation suggests costs will come down quickly.
- A switch towards electric vehicles, rail, or barge transport will lower costs and increase possible distances between the source (mine or quarry) and destination fields without incurring net positive emissions.

Notes and Sources: [1] Source – Carbon Direct Proprietary Insights.

Mine Site Integration Assessment

Integration Factor	Key Considerations	Integration Factor	Key Considerations
Siting Imperatives	• For on-site deployment, access to both significant volumes of reactive feedstocks and sufficient land area for spreading. Soils must be within specific pH ranges (~5-6.5).	Implementation Stages	• Operation, Closure, Reclamation
Access to Energy	• Access to energy is not required when deployment takes place on site, with the exception for additional mineral pre-processing, such as grinding.	Access to Water	• Additional water inputs may be needed in cases where weathering is done in heaps. For soil-based deployments, water is generally sourced through rain or irrigation.
Waste Use Potential	• Operates on mining waste otherwise unused in tailings and waste rock storage facilities • Can leverage tailings directly within the TSF[1]	Operational Complexity	• Modifications unnecessary for direct manipulation in TSFs. • Pre-treatment of tailings would need to be integrated with material handling processes. • Primary impacts will be on tailings management, or in permitting to export materials off site.
Regulatory Hurdles	• Local environmental, health, and safety regulations may have specifications for handling tailings and other mining waste. • Tailings may be prohibited from application on croplands, except in cases where metal content (e.g. Cr, Ni) is low and there has been no prior chemical processing	MRV requirements	• Baselines for passive carbonation of tailings or other materials must be assessed • Significant soil sampling both prior to application and during, which is labor intensive and costly • Porewater measurements to determine an increase in dissolved bicarbonates is necessary to reduce uncertainty, but are currently costly and difficult
Business impacts	• Potential revenue from selling previously uneconomic feedstocks to be used offsite • Carbon credit revenue possible from applications done directly on site • Reduced carbon tax obligations when projects deployed on-site count towards total net emissions	Co-benefits	• Improvements in soil pH, soil nutrient content and crop yields • Potential decrease in agricultural N_2O emissions due to decreased soil acidity

Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis. [1]One project deployed a version of Enhanced Rock Weathering as a means of reclamation, by bringing the plants to the minerals versus bringing the mineral to the plants. This project was able to sequester carbon directly in the TSF, through both vegetation and weathering.

Scaling up

Overcoming Knowledge Gaps

☐ Better and faster empirical measurements are necessary both to confirm bicarbonate fluxes and to improve large-scale models

☐ Quantification of multi-year effects of silicate minerals and associated trace elements (e.g. nickel, chromium) on soil health and diverse crop yields

☐ Calibration of weathering rate models across different biomes (tropical vs. temperate) to account for variations in rainfall, temperature, and soil acidity

Improved measurement and verification

Decreased costs + demonstrated co-benefits

Wide-scale operation in a variety of agricultural settings

Considerations for Scaling

Feedstock supply chains – Scaling the ethical sourcing and processing of basalt, wollastonite, or relevant industrial byproducts near high-potential application sites.

Feedstock logistics – Managing costs and logistical requirements of any processing and transporting of millions of tonnes of rocks and minerals.

Landowner engagement – Developing robust incentive structures and educational outreach to integrate Enhanced Rock Weathering into standard farming practices without disrupting food production.

Success Enablers

Technological Improvements

Integrated sensor arrays – Deployment of novel low-cost in situ soil sensors and remote sensing tools to track bicarbonates and monitor moisture and temperature for real-time weathering rate adjustments.

Low-energy comminution – New grinding and milling techniques to maximize reactive surface area while significantly reducing associated energy costs and emissions.

Regulations

Soil amendment reclassification – Updating agricultural and environmental laws to recognize silicate rock as a beneficial soil amendment, where appropriate.

Environmental safety frameworks – Establishing clear thresholds for trace element concentrations to prevent soil contamination and protect groundwater quality.

Economics & Market Integration

MRV standardization – Universal methodology and guidelines on MRV to decrease uncertainty for current and future deployments while building confidence in the market.

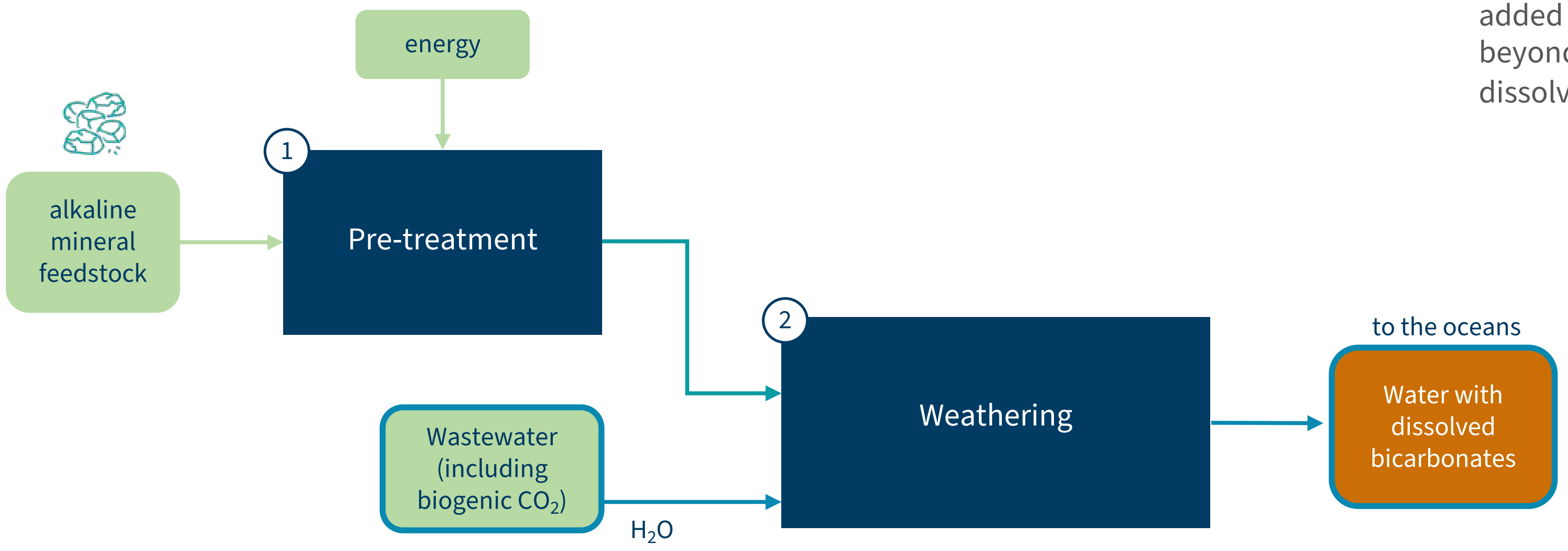
Global South development – Designing financial mechanisms and incentives to unlock the high sequestration potential of tropical regions.

Technical Appendix

Wastewater Alkalinity Enhancement

Wastewater Alkalinity Enhancement, also known as Mineral Alkalinity Enhancement or Engineered Enhanced Weathering, is a form of weathering that takes place in a closed system, contacting a CO_2-bearing fluid, namely wastewater, with alkaline materials to rapidly create stable dissolved bicarbonates, which can then be safely released into rivers and oceans. This process is similar to Accelerated Weathering of Limestone, which is not covered explicitly here, but could also be applicable with the right infrastructure and sources of CO_2. Electrochemical Alkalinity Enhancement is not covered here but may also be applicable where waste brines are available and acids or bases (e.g., HCl or caustic soda) are needed for commodity production.

Wastewater Alkalinity Enhancement



energy

① Pre-treatment

alkaline mineral feedstock

② Weathering

Wastewater (including biogenic CO_2)

H_2O

to the oceans

Water with dissolved bicarbonates

LEGEND

process step | inputs | intermediate | outputs | Carbon Flow | $ = material can be sold

TRL ● ● ● ● ● ● ● 8 ●

PROCESS DESCRIPTION

Wastewater Alkalinity Enhancement takes advantage of high biogenic CO_2 content within domestic wastewater treated at large-scale industrial scales. Alkaline mineral feedstocks are added to water processing to neutralize pH levels above and beyond business-as-usual scenarios and store carbon as dissolved bicarbonates in water bodies.

PROCESS STEPS

① Alkaline materials are typically sourced at a small enough particle size. These materials may replace other minerals more commonly added for pH management but less efficient at removing CO_2.

② Materials react with CO_2-bearing water as part of existing wastewater processing turning carbonic acid into bicarbonate ions.

⇨ Processed water with bicarbonates is released in outflows as usual.

Notes and sources : Transportation may or may not be required depending on the source of the feedstock and the location of the application site.

Resource Requirements

High

Mineral Feedstock
3-3.5/tCO_2[1,2]

Feedstock requirements

This process relies primarily on carbonate minerals such as limestone, which will most likely need to be sourced offsite, creating a barrier to implementing where sources are too distant. Other options to use materials such alkaline hydroxides or silicate minerals exist but may not be as effective overall.

Low

Water
No additional Water

Water is already provided through existing water processing activities.

Low

Energy
<0.5 GJ_{el}/tCO_2

Energy requirements depend on the method of surface manipulation and if feedstock pre-treatment is needed. Requirements can be low if electricity is needed only to power monitoring and manipulation equipment.

Low

Land Use
Integrates on-site

Space is required on site for dosing equipment as well as any feedstock storage next to any domestic wastewater processing facilities.

Key Resource Constraint

Quality Feedstock Sourcing

High-quality, fine-grained limestone is necessary to effectively implement alkalinity enhancement techniques for CDR. This means grain sizes must be sufficiently small (<400 mesh) and calcium content must be sufficiently high (>90%) to ensure the limestone dissolves rapidly when dosed into existing domestic wastewater processes[2].

Because significant quantities of limestone are required, transportation logistics become a constraint that must be closely managed to prevent costs from skyrocketing. This limits deployments to locations within cost-effective distances from limestone quarries.

Ideal Feedstocks often include:

- Carbonate minerals – e.g. limestone ($CaCO_3$), dolomite
- Alkaline hydroxides/oxides – e.g. $Ca(OH)_2$, NaOH, KOH, CaO
- Alkaline silicate minerals – e.g. wollastonite, olivine, basalt fines

Note: Industrial byproducts, such as steel slags or mining wastes may be used for WAE processes, where strict environmental safeguards are put in place.

Notes and Sources: Based on stakeholder interviews and surveys, RMI analysis. [2]Further information can be found in Carbon Gap's report No Wasted Opportunities.

Key Economic Drivers

Feedstock Costs

Costs for continual purchases and transport of feedstock with the right characteristics (e.g. grain sizes) for optimal processing.

Feedstock Processing

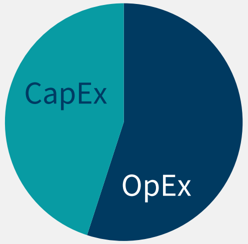
This process requires uncommon grain sizes that are not always readily available. Specialized milling for the smaller volumes needed for pilot and demonstration plants mean higher processing costs, though these are expected to come down through economies of scale.

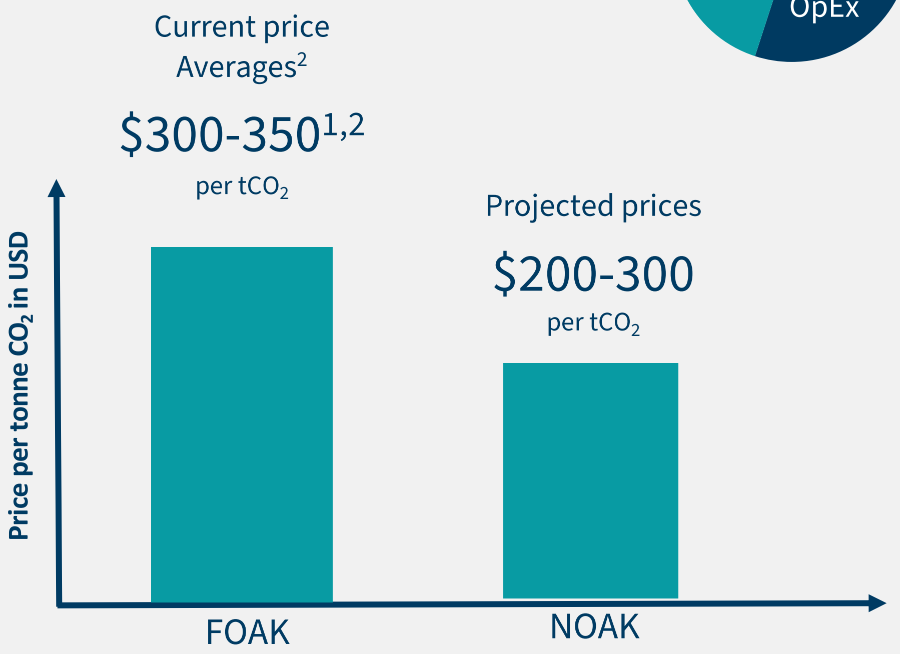
Transportation

Materials will need to be transported on a continual basis. Both transport emissions and costs impact the overall CDR price.

Uncertainties in baseline measurements

Accounting for uncertainties in natural baseline reactivity and counterfactual scenarios will impact what is considered additional carbon removal and affect overall costs. Unknowns in feedstock impurities may also have a large impact on the overall economic performance.





Key Insights:

- Overall feedstock costs should drop through economies of scale, as it becomes more cost-effective for feedstock suppliers to process minerals to exact specifications.
- This pathway may also provide cost savings due to increased operational efficiencies in processing domestic wastewater. Those savings are not reflected in the prices above.

Notes and Sources: Based on stakeholder interviews and surveys, RMI analysis. [2]Further information can be found in Carbon Gap's report No Wasted Opportunities.

Mine Site Integration Assessment

Integration Factor	Key Considerations	Integration Factor	Key Considerations
Siting Imperatives	• Co-location with existing domestic water processing	Implementation Stages	• Operation
Access to Energy	• Energy requirements are low and are unlikely to exceed the existing energy usage on site, as energy is needed primarily for feedstock dosing, a practice already common to wastewater processing	Access to Water	• Access to domestic wastewater processing with a high biogenic CO_2 content
Waste Use Potential	• Makes use of wastewater as a vehicle for CDR but also can improve water quality	Operational Complexity	• For mining operations with on-site wastewater processing, this process can easily be integrated into existing infrastructure with limited interruptions • Feedstocks may replace existing pH management of wastewater, with consequences to processing time and costs
Regulatory Hurdles	• Environmental, health, and safety regulations for water processing must be respected, though many applicable feedstocks for CDR can provide similar benefits as other pH management minerals	MRV requirements	• Requires some additional equipment and measurement infrastructure outside of normal tracking of pH and other environmental variables • Baselining the biogenic versus fossil CO_2 content of water is important to determining net negativity
Business impacts	• Potential cost savings through replacement of chemicals used in water treatment • Carbon credit revenue possible • Reduced carbon tax obligations when applied towards net emissions reduction	Co-benefits	• Stabilization and enhancement of the biological treatment process can reduce water pollution • Potential to reduce N_2O production from the treatment process.

Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis.

Scaling up

Overcoming Knowledge Gaps

- ☐ Determining the costs and benefits of integrating into domestic wastewater processing within mining operations, given their lower processing volumes
- ☐ Better understanding of mineral-wastewater interactions for feedstocks and diverse biological and chemical loads found in both municipal and industrial wastewater
- ☐ Improved baseline measurement protocols to distinguish between natural and additional CO_2 uptake

Improved material efficiency → Decreased costs + demonstrated co-benefits → Standardized practice for wastewater processing

Considerations for Scaling

Feedstock processing – Costs must come down for processing of feedstock, including higher efficiency milling equipment.

Infrastructure Integration – Designing modular systems that can be bolted on to existing wastewater treatment plants without disruptions to processing, health or safety.

Mines as suppliers of feedstock – Mines and quarries may play a more important role in scaling this pathway by partnering with nearby domestic wastewater facilities and providing cost-effective minerals at required specifications.

Success Enablers

Technological Improvements

Low-energy comminution – New grinding and milling techniques can maximize reactive surface area while significantly reducing associated energy costs and emissions.

Sensor durability – improving the lifespan and calibration stability of alkalinity and pH sensors in corrosive environments.

Regulations

Discharge permitting – working with environmental agencies to ensure mineral addition complies with discharge permits and environmental regulations.

MRV – standards are needed to assign carbon credits based on bicarbonate release into open waterways with full consideration of the fate of that carbon.

Economics & Market Integration

MRV standardization – Universal methodology and guidelines on MRV to decrease uncertainty for current and future deployments while building confidence in the market.

Global South development – Designing financial mechanisms and incentives to unlock the high sequestration potential of tropical regions.

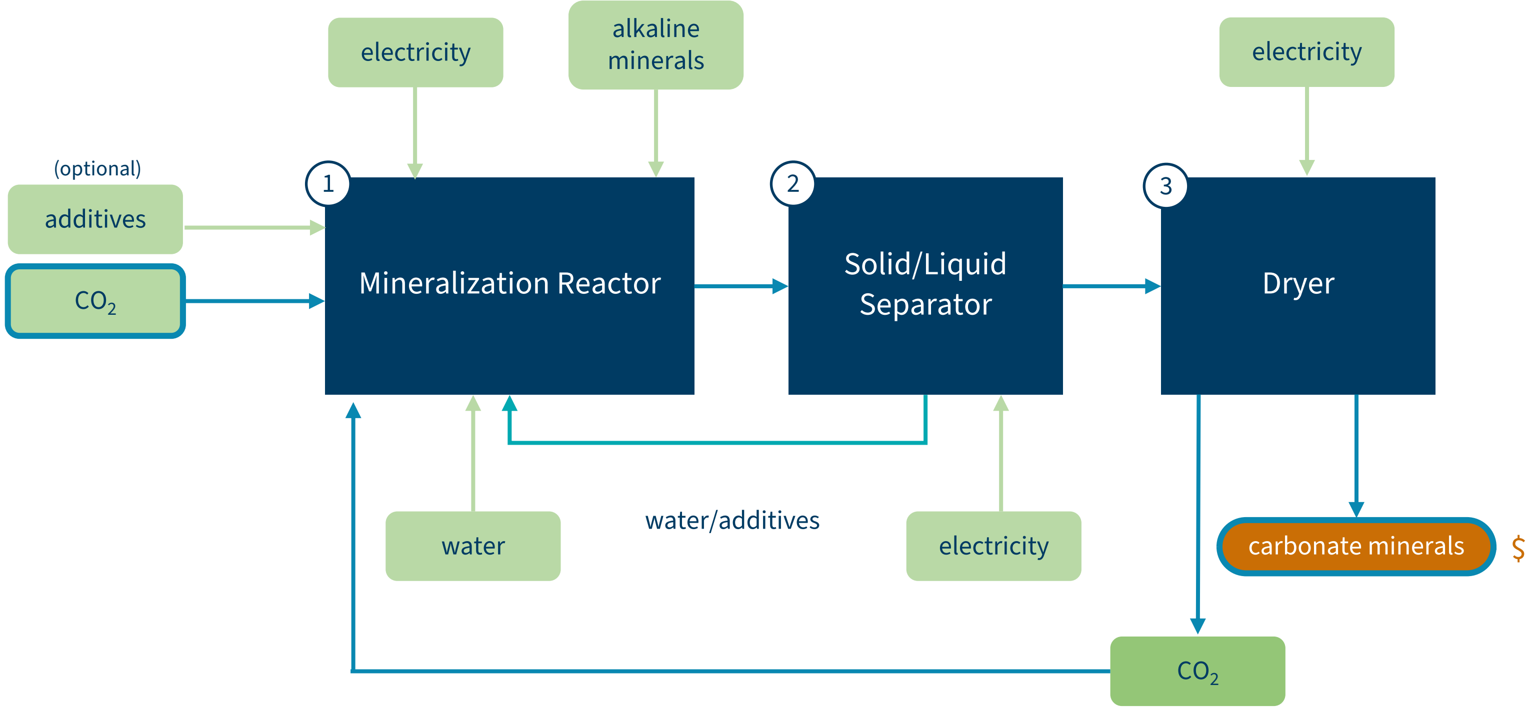
Notes and Sources: Based on stakeholder interviews and surveys, RMI analysis.

Technical Appendix

Reactor-based Mineralized CO_2 Storage

Reactor-based Mineralized CO_2 Storage, also sometimes referred to as simply Ex Situ Mineralization, involves reacting previously captured CO_2 with alkaline minerals in a controlled environment. The process accelerates natural mineralization processes to quickly form solid carbonate minerals, permanently storing carbon. Applicable feedstocks can vary widely, including mine tailings and waste rock, as well as other industrial wastes or byproducts.

Reactor-based Mineralized CO_2 Storage



electricity

alkaline minerals

electricity

(optional)

additives

CO_2

① Mineralization Reactor

② Solid/Liquid Separator

③ Dryer

water

water/additives

electricity

carbonate minerals $

CO_2

LEGEND

process step | inputs | intermediate | outputs | Carbon Flow | $ = material can be sold

PROCESS DESCRIPTION

Reactor-based mineralization accelerates reactions with concentrated CO_2 and alkaline minerals to store carbon as a solid carbonate, using high temperatures and/or optional catalytic additives. Mineral carbonates produced can then be stored as is, utilized, or sold to other industries, such as construction.

PROCESS STEPS

① Crushed mining waste rock, water, CO_2 and optional additives are mixed to form a slurry at elevated temperatures and pressures to induce weathering and subsequent mineralization to form solid carbonates.

② In the Solid/Liquid separator, excess water and any additives are removed and recycled. The carbonate minerals may then be sent to the Dryer to remove excess moisture.

③ In the Dryer, excess moisture is removed so that the final, dry carbonates can be stored or sold as products.

⇨ CO_2 losses from out-gassing of un-mineralized carbon can be recycled back into the process.

Notes and sources : [1] Many variants of this process exist, and the technology readiness can differ depending on the technology, innovations in chemical additives, and end use cases.

Resource Requirements

High

Feedstock requirements

Mineral Feedstock
1.4-5 t/tCO_2

Mineral feedstocks, water, CO_2 are all required for this process. Pre-treatment generally includes crushing and grinding of material to decrease particle size. Location, access to water, energy supply and chemical composition of available feedstock all affect the rate of operation and efficient production of final carbonates.

Low

Water
5,000L/tCO_2

Water is used to create a slurry mixture to be sent to the reactor. In a slurry form, the rate of mineralization is increased.

Med

Energy
4-5 GJ_{el}/tCO_2

The majority of energy is used to pressurize, heat and maintain reactor conditions. The costs due to energy consumption can be reduced from utilizing waste heat from nearby facilities.

Low

Land Use
integrates on-site

Land use requirements are dependent on local storage conditions and opportunities to export carbonated materials offsite. The production of carbonates requires minimal land beyond that required for reactor processing.

Key Resource Constraint

Low Carbon Energy

Maintaining high temperatures and pressures requires a high energy intensity, as do separation processes (filtration and drying). Making use of available waste heat may allow for direct energy requirements to be lowered.

➡ As the Mt-Gt scale is desired, larger reactors, requiring larger amounts of energy and water would be needed.

Additional considerations include material reactivity and residence times, which would both affect carbonation rates. Both factors can influence the amount of energy being used.

Ideal Feedstocks often include those with no other economic value:

- Ultramafic rocks – e.g. olivine (dunite), peridotite, serpentinite
- Mafic rocks – e.g. basalt, gabbro
- Mine tailings – e.g. nickel tailings (olivine-rich), Diamond (kimberlite) tailings, platinum group metal tailings and asbestos tailings (e.g. chrysotile tailings)
- Industrial alkaline wastes – e.g. steel slag, cement kiln dust, fly ash
- Synthetic/Processed feedstocks – e.g. $Ca(OH)_2$, $Mg(OH)_2$, CaO, MgO

Notes and Sources: Based on stakeholder interviews and surveys, RMI analysis.

Key Economic Drivers

Energy costs

Costs related to preprocessing or continual manipulation of materials are dependent on the initial condition of the feedstock as well as the reactivity of the material.

Feedstock reactivity

Reactivity of material with CO_2 is a key parameter in determining the quantity of materials needed. For tailings and waste piles, the material costs may be negligible, but reactivity rates will impact all other cost drivers. Preprocessing to increase reactivity will increase costs.

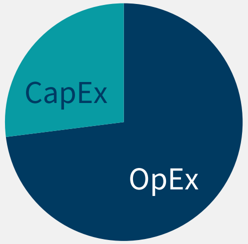
Logistics

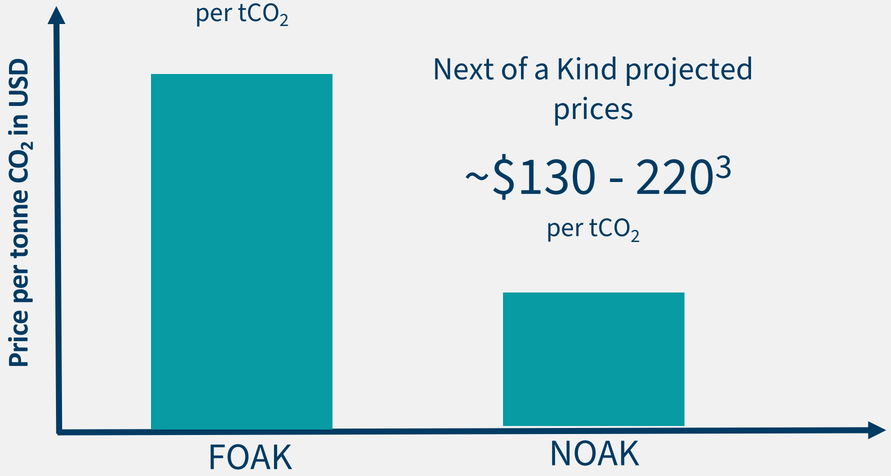
Transporting and handling materials can be costly and even emissions intensive. On-site handling is likely to be minimal, but offsite transport for carbonate mineral products to be sold could be significant.

Concentrated CO_2 costs are separate, and variable

The costs on this page refer only to storage costs. Including costs of capturing CO_2 will depend on the capture technology, local energy costs, and whether the CO_2 was collected from an industrial point source or from Direct Air Capture.

Prices are reflective of ***carbon storage only.*** *Additional costs for capturing, pressurizing and transporting CO_2 need to be included to compare to end-to-end CDR approaches.*





Current Price Averages[2]

$300

per tCO_2

Next of a Kind projected prices

~$130 - 220[3]

per tCO_2

Key Insights:

- This approach is OpEx dominated, driven by energy usage for processing materials.
- As an alternative to pipeline-dependent, subsurface CO_2 storage, higher storage costs may be justified.
- Waste heat utilization could help reduce costs
- Monetizing carbonate products requires careful consideration of counterfactual use cases and displacement of other materials.

Notes and Sources: [1]Feedstock costs could become a cost driver if tailings are not available burden-free. [2]Price Averages are based on data from CDR.fyi [3]Costs and prices derived from Techno-economic analysis for the integration of ex situ CO2 mineralization and mineral mining.

Mine Site Integration Assessment

Integration Factor	Key Considerations	Integration Factor	Key Considerations
Siting Imperatives	• Access to significant volumes of reactive feedstocks	Implementation Stages	• Operation, Closure, Reclamation
Access to Energy	• High energy demand, but potential to make use of waste heat produced elsewhere on site • Batch vs. throughput processing will determine flexibility in renewable energy intermittency	Access to Water	• Depending on the feedstock, significant additional water inputs are likely required, except in the case of wet tailings.
Waste Use Potential	• Operates on mining waste otherwise unused in tailings and waste rock storage facilities • Decreases in waste volumes are possible if carbonate can be shipped offsite	Operational Complexity	• No modifications to the mining process necessary • Pre-treatment of tailings would need to be integrated with material handling processes • Additional infrastructure, including reactors, would be needed on site to process materials • Waste and tailings management may be reduced where products can be shipped off-site
Regulatory Hurdles	• Waste management policies and environmental compliance measures may factor in to where and how materials can be processed, stored or disposed of, and which materials are suitable for upcycling into usable products.	MRV requirements	• Baselines for passive carbonation of tailings and other materials must be assessed • Additionality concerns for cases where products are created and sold, including counterfactuals for any displaced product usage.
Business impacts	• Green premiums on primary mine commodities may be supported, depending on jurisdiction • Carbon credit revenue possible • Reduced carbon tax obligations when applied towards net emissions reduction • Potential revenue for sales of carbonated products	Co-benefits[1]	• Reduced mining and extraction of materials used for construction or other activities • Potential reduction in total mine waste on site

Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis. [1]More information on the integration potential and co-benefits can be found in ARCA's white paper on Repurposing Industrial Waste into Durable Climate Value.

Scaling up

Overcoming Knowledge Gaps

☐ Optimization of reaction kinetics under various pre-treatments, including novel thermal pretreatments, alongside reactor conditions

☐ Understanding of tradeoffs between input energy and kinetics

☐ Testing of physical and chemical properties of carbonate materials for high standards in construction and engineering projects

Improved material efficiency → Decreased costs → Operation in a diversity of contexts (feedstocks, industrial sites, …)

Considerations for Scaling

Processing rates – Engineering reactor designs that can efficiently handle large volumes of materials continuously rather than in small batches.

Co-location of assets – Strategic mapping and clustering of activity to leverage alkaline wastes as storage of industrial CO_2 emissions with minimal pipeline or transport infrastructure.

Offtake of carbonate products – Purchase agreements for carbonated products would enable deployment and guarantee financing.

Success Enablers

Technological Improvements

Exothermic heat recovery – development of systems to capture and reuse heat generated during mineralization reactions to power upstream or drying processes.

Operational process conditions – including additives and other synergetic improvements.

Regulations

Waste reclassification – where appropriate, wastes that are suitable for re-use on site can be explored for reclassification and repurposing in circular economy projects.

Building code integration – work with construction standards bodies to evaluate and approve carbonated materials for use in concrete and infrastructure projects.

Economics & Market Integration

Green premiums – create market demand for carbon-negative building materials, allowing companies to monetize the climate benefit and the physical aggregate.

Insetting – Align CDR implementation with corporate Scope 1 emissions reduction goals either by storing on-site emissions or by removing CO_2 from the atmosphere, e.g. when coupled with Direct Air Capture.

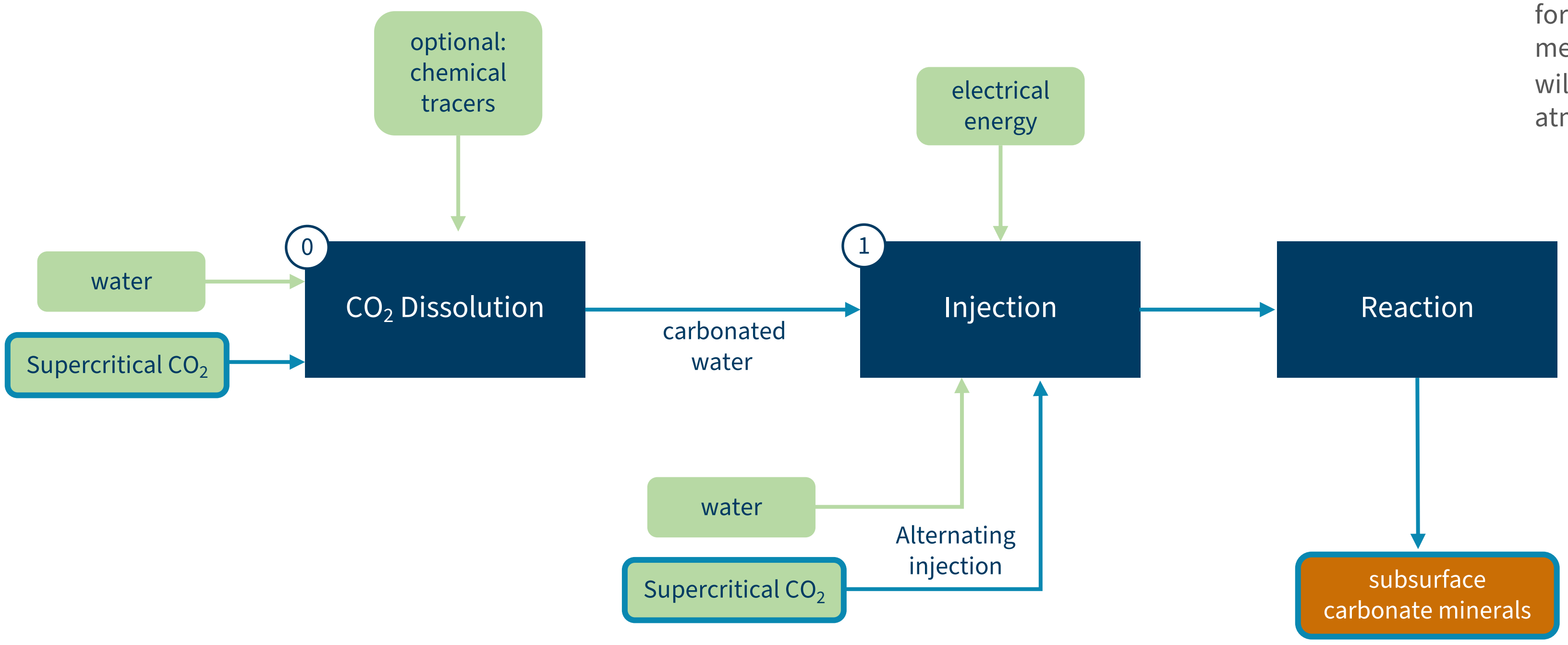
Notes and Sources: Based on stakeholder interviews and surveys, RMI analysis.

Technical Appendix

In Situ Mineralized CO_2 Storage

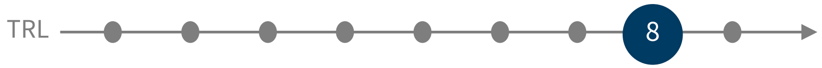
In Situ Mineralized Storage, involves injecting captured CO_2, and usually water, into wells where the CO_2 mixes with water to form carbonic acid. The carbonic acid circulates and reacts with rock formations to permanently store carbon underground in the form of carbonated minerals.

In Situ Mineralized Storage



LEGEND

process step | inputs | intermediate | outputs | Carbon Flow | $ = material can be sold



PROCESS DESCRIPTION

In Situ Mineralization involves injecting CO_2 and water into underground mafic or ultramafic rock formations where it reacts to form solid carbonates in available cracks and pore spaces. This storage mechanism can be used to store any concentrated stream of CO_2 but will result in carbon removal when the CO_2 is sourced from the atmosphere or biogenically.

PROCESS STEPS

⓪ Supercritical CO_2 may optionally be mixed with water before injection. Chemical tracers may be added to track water dispersion. Measuring any depletion of CO_2 from traced water serves as a proxy for carbonation in the absence of physical sampling.

① Either the CO_2 charged water, or alternating streams of supercritical CO_2 and water, is injected into subsurface mafic or ultramafic rocks through wells drilled in advance. Injecting high concentrations CO_2 can be done if there is sufficient subsurface water to facilitate reactions.

⇨ Mild carbonic acid reacts with minerals present in the rock formations to form solid carbonates that permanently store carbon.

Notes and sources : More information about this process can be found in Carbon dioxide storage through carbon mineralization.

Resource Requirements

High

Water

10,000-50,000L/tCO_2

Input requirements

As a mechanism for storing CO_2, water requirements are significant, but may be met with brackish or saline water, including seawater or water from existing underground aquifers may be used[1]. Alternatively, supercritical CO_2 may be injected directly depending on conditions. Siting projects depends primarily on the geological deposit, but water availability must also be considered. CO_2 may be generated on site, through Direct Air Capture, or transported from industrial sources.

Low

Subsurface Deposits

Available, sufficient underground deposits of magnesium and calcium bearing rock must be accessible.

Med

Energy

75kWh/tCO_2

Energy is required for drilling, for any pumping of water, and to pressurize the CO_2 pre-injection.

Low

Land Use

integrates on-site

Above-ground land requirements are minimal and needed only to cover CO_2 storage and pumping infrastructure.

Key Resource Constraint

Water

While geological suitability is the primary prerequisite, water intensity remains the dominant operational constraint for using In Situ Mineralization as a CO_2 storage option. Standard solubility-based injection can use up to 20-30 tonnes of water per tonne of CO_2. This presents significant challenges for sites in water-stressed regions or those requiring careful integration with existing mine water circuits. While seawater use may be possible in some geographies,[1] it can introduce corrosion risks and other complexities.

Pilots are demonstrating that water use can be minimized by alternating injection streams of CO_2 and water.

Ideal geological formations for In Situ Mineralization may include:

- Ultramafic formations – e.g. peridotite, serpentinite, dunite (olivine-rich formations)
- Mafic formations – e.g. basalt, gabbro
- Mafic/Ultramafic sedimentary systems – e.g. basaltic sandstones, volcaniclastic formations
- Fractured mafic/ultramafic systems – e.g. faulted basalts, ophiolite complexes

Notes and Sources: [1] Project SeaStone has verified that the use of seawater is possible.

Key Economic Drivers

Drilling costs

Given the number of wells for initial characterization and sampling, primary injection, and downstream monitoring, drilling costs can be significant. Further costs are incurred for corrosion-resistant alloys.

Energy Costs

Costs for compressing CO_2 and for pumping and injecting liquids can be significant and will be dependent on local renewable energy costs.

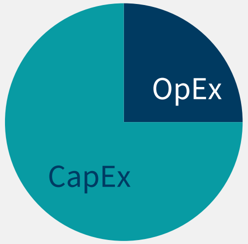
Water

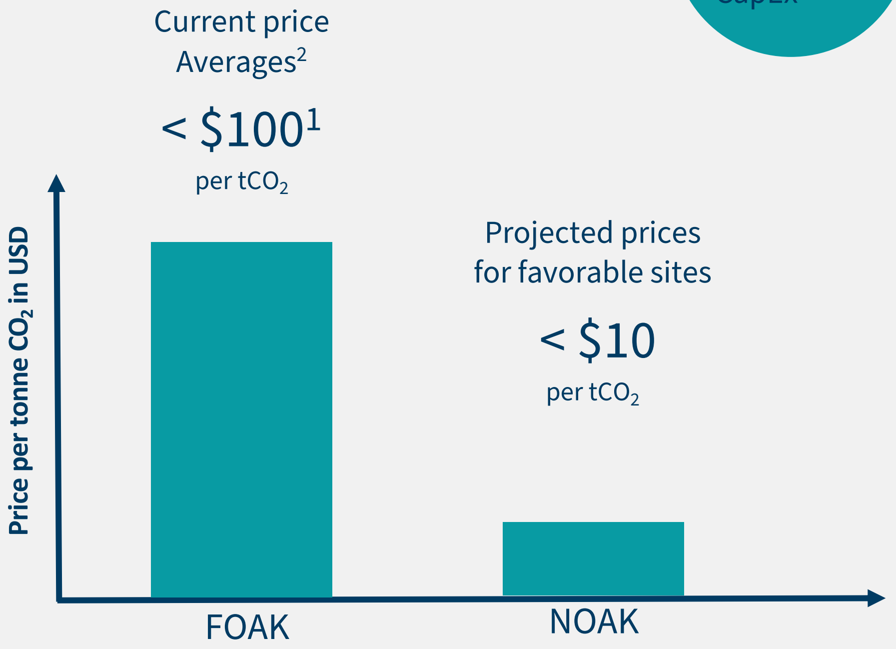
Where water is needed, securing rights to water can be costly. Additional processing of water, for example to removal biological material, can increase costs further.

Concentrated CO_2 costs are separate, and variable

The costs on this page refer only to storage costs. Including costs of capturing CO_2 will depend on the capture technology, local energy costs, CO_2 transport costs and whether the CO_2 was collected from an industrial point source or from direct air capture.

Prices are reflective of ***carbon storage only.*** *Additional costs for capturing, pressurizing and transporting CO_2 need to be included to compare to end-to-end CDR approaches.*





Key Insights:

- Most costs are front-loaded, occurring primarily in the drilling phases.
- Reducing water use can lower overall operational costs.
- Costs are expected to decrease over the coming decade to levels comparable with more conventional CO_2 storage costs in saline formations or depleted oil and gas fields.

Notes and Sources: [1]Source – Carbon Direct Proprietary Insights.

Mine Site Integration Assessment

Integration Factor	Key Considerations	Integration Factor	Key Considerations
Siting Imperatives	• Access to appropriate subsurface geology	Implementation Stages	• Operation, Closure, Post-Closure
Access to Energy	• Low-carbon energy is needed for drilling and pumping, but primarily important for any Direct Air Capture taking place to supply CO_2	Access to Water	• Significant water usage, potential for seawater use.[1] Water should be free from biogenic matter and nutrients to avoid clogging and biofouling
Waste Use Potential	• CO_2 emissions from nearby industrial sources may be permanently stored using In Situ Mineralization. Waste heat may be utilized, for example, in CO_2 compression	Operational Complexity	• Initial surveying of mining operations could include additional surveys to explore mafic or ultramafic formations suitable with potential for carbon storage • No major modifications to the mining process would be required for sites that include suitable subsurface deposits separate from extractable ores
Regulatory Hurdles	• Obtaining permits to drill • Assessing seismic impacts and complying with regulatory limits on seismicity, assuring negligible risks • Accessing rights to water usage • Local community approval is necessary	MRV requirements	• Chemical tracers are generally added but must be tracked and sampled downstream through monitoring wells. • Longer term (decadal) monitoring is not required, as it is for more conventional CO_2 storage, as mineralizing carbon to solid form renders it unnecessary
Business impacts	• Additional revenue for sequestering CO_2 on site as storage costs for CO_2 producers	Co-benefits	• Potential to simultaneously inject other pollutants, e.g. H_2S or industrial brines • Low above-ground footprint

Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis. [1]Project SeaStone has verified that the use of seawater is possible.

Scaling up

Overcoming Knowledge Gaps

- ☐ Developing high-resolution 3D models of subsurface rock formations to accurately estimate regional storage capacities
- ☐ Investigation of reaction rates in various geologies and how pore-clogging, and any subsequent cracking, might affect carbon storage or injectivity
- ☐ Establishing clear geological baselines to distinguish between natural seismic activity and induced seismic events due to high-pressure fluid injection

Improved material efficiency

Decreased costs

Operation in a diversity of contexts (formations, industrial sites, …)

Considerations for Scaling

Geographic constraints – While mafic and ultramafic rock are ubiquitous in the Earth's crust, sites meeting the specific conditions required for mineralized storage are not. Prioritizing sites with ideal geology, access to water and low-cost, low-carbon energy can lower risks and associated costs.

Water resource management – Obtaining the significant water volumes necessary will require access and permission from local communities.

Co-locating with Direct Air Capture + additional renewable energy – Minimizing transport of CO_2 will improve costs and reduce issues with developing pipelines.

Success Enablers

Technological Improvements

Low-water injection techniques – advancing technologies that forego water usage and inject supercritical CO_2, or those that use recycled brines.

Optimized well design and injection strategies – engineering injection wells to maximize CO_2 reactions without risking clogging or blockages due to passivation.

Regulations

Pore space ownership – clarifying legal frameworks regarding who is liable long-term for stored carbon post mine closure.

Transboundary concerns – including legal agreements for regional carbon storage hubs that can safely store CO_2 from multiple sources, including those from other jurisdictions.

Economics & Market Integration

Shared infrastructure – including pipelines and injection clusters, to share upfront infrastructure and drilling costs while maximizing carbon storage potential.

Insetting – upcoming net-zero policies may require more effort internally for lowering net emissions. Based on evolving accounting and crediting standards, carbon stored on site may provide a means to balance hard-to-abate emissions.

Notes and Sources: Based on stakeholder interviews and surveys, and RMI analysis.

SECTION 13

Appendix 2: Market and Regulatory Drivers

Mining and Carbon Dioxide Removal
A responsible path forward for mine operators, policymakers, and other key stakeholders

Emerging market forces and regulation are likely to motivate Mining CDR

Markets and regulation are evolving in ways that are likely to motivate more CDR activity. Some of the key dynamics emerging create incentives for corporates to purchase CDR carbon credits; others encourage CDR by motivating emissions accounting, disclosure, and mitigation at the corporate or product level. This appendix assesses the implications of five external dynamics likely to drive and shape Mining CDR adoption over the coming decades.

1 Carbon Border Adjustment Mechanisms (CBAMs)

Apply to products; may motivate CDR credit purchasing or CDR in-chain

2 Emissions Trading Schemes (ETSs)

Apply to companies; motivate CDR credit purchasing

3 Science Based Targets initiative (SBTi)

Applies to companies; motivates CDR credit purchasing

4 Advances in Carbon Accounting

Apply to companies and products

5 Differentiated Downstream Products

Apply to products

How these dynamics have been reviewed:

Per dynamic

- What is the signal
- Why does it matter for Mining CDR
- What is needed for it to unlock Mining CDR
- Expected guardrails

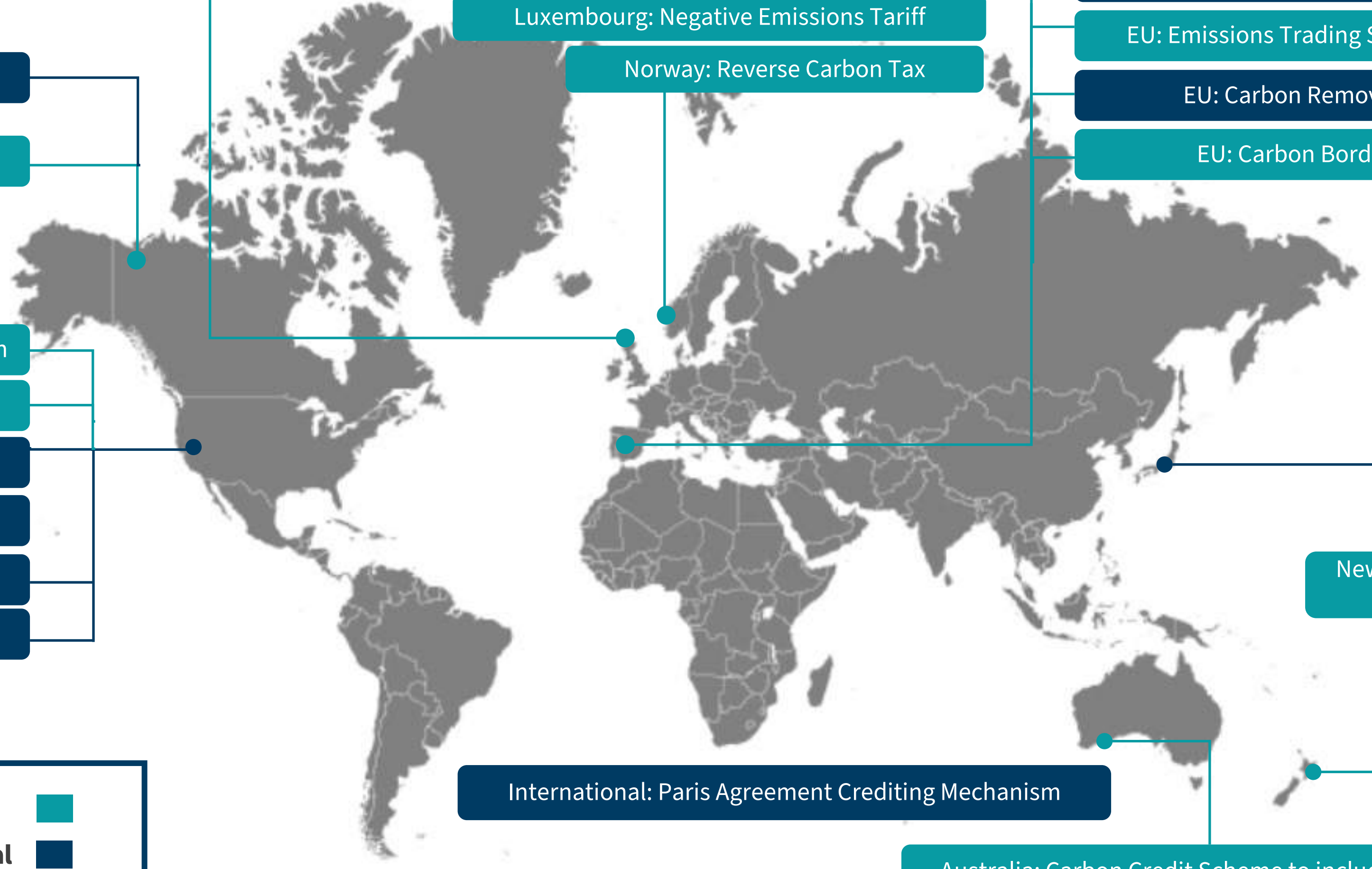
Across dynamics

- Evidence requirements, e.g., emissions accounting, reporting, and disclosure
- What stakeholders can do now

What these dynamics will do for Mining CDR

- **Set criteria** for performance, quality, and accounting that Mining CDR must meet
- **Shape willingness to pay** for either low-carbon products or CDR credits by changing procurement behavior, improving eligibility screens, and creating economic incentives
- **Create value pathways** that Mining CDR can tap into
- **Raise the evidence bar** for product emissions disclosure tied to mining outputs and for other claims; weak quantification and ambiguous claims become harder to sustain as rules for assurance, disclosure and product standards harden

Policy is advancing, building incentives and requirements for CDR investment



UK: ETS Integration

Sweden: Reverse Auction

Luxembourg: Negative Emissions Tariff

Norway: Reverse Carbon Tax

EU: Net Zero Industry Act

EU: Emissions Trading Scheme CDR integration

EU: Carbon Removal Certification Framework

EU: Carbon Border Adjustment Mechanism

Canada: CCUS Investment Tax Credit

Canada: DACS Protocol

Washington: Cap-and-Invest CDR integration

California: Cap-and-Invest CDR integration

California: SB 905

California: Low-Carbon Fuel Standard

US Federal: Inflation Reduction Act

US Federal: CDR Purchase Prize

Japan: J Credit

Japan: Green Transformation Emissions Trading Scheme

New Zealand: Inclusion of biochar under the emissions trading system

International: Paris Agreement Crediting Mechanism

Australia: Carbon Credit Scheme to include biochar

In discussion 🟩

In implementation or operational 🟦

Notes and Sources: Policy drivers highlighted from 2025 CDR Outlook: Policy Drivers Shaping the Carbon Removal Market. Map adapted from Defining net zero in policy: The Meta-Map on Policy of global mechanisms supporting the growth of CDR.

The EU CBAM is already creating a product-level carbon signal in Europe

The EU CBAM has moved from a 2023–2025 transitional reporting phase to its definitive regime from January 2026, and it currently covers cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen.[1] Mining CDR can potentially lower verified emissions in covered imports.

What CBAMs are

Carbon Border Adjustment Mechanisms (CBAMs)[1] apply a carbon-related cost or compliance requirement to imports based on their emissions intensity. The purpose is to reduce carbon leakage and level the playing field between domestic and imported production. The European Union enacted a CBAM in 2023. Several other countries, including the UK, Australia, and Canada, are considering similar measures.

Why they matter for Mining CDR

CBAMs matter for Mining CDR by creating a product-level carbon signal in import-exposed value chains that mining feeds into, especially steel and aluminum. In practice, that means Mining CDR can become relevant to CBAMs where a mine-site intervention can be translated into lower embedded emissions for a covered good or precursor within CBAM's accounting boundaries. Additionally, the EU CBAM is proposing to allow international credits for up to 10% of reported embedded emissions, suggesting that mining companies that supply CDR could sell CDR credits to CBAM-covered entities.[2]

What's needed to unlock Mining CDR potential

- Clear system boundaries and allocation rules linking a mine-site intervention to a covered product
- Primary data, traceability, and chain-of-custody strong enough to support actual embedded-emissions calculations
- Verification robust enough for CBAM declarations - from 2026 the EU has formal rules for both the calculation and verification of declared embedded emissions

Expected guardrails

- Activities can only claim CBAM relevance if the action directly lowers the verified embedded emissions of a CBAM-covered product, according to CBAM rules
- Product claims must be separate from carbon credit claims to avoid double counting

Notes and sources: [1]European Commission, 2026; European Union, 2023. [2]European Commission, 2026.

ETSs are beginning to create strong compliance-based demand for CDR

ETSs are now mainstream globally: 41 systems are in force worldwide, covering 26% of global GHG emissions. The EU ETS is in Phase IV (2021–2030), and Japan's national ETS entered full operation in 2026.[1]

What ETSs are

ETSs are "cap-and-trade" programs where regulators set an overall emissions cap and require covered entities to surrender allowances (or eligible credits, where permitted) for their emissions. The result is usually an explicit, often rising, carbon price signal that rewards lower emissions and penalizes higher emissions along with increasing expectations for measured, auditable, emissions data.

Why they matter for Mining CDR

ETSs create compliance-based demand for carbon credits that deliver CDR, a source of demand expected to be significantly higher that voluntary corporate demand. The clearest near-term signal is the UK ETS, where the Authority has committed to integrating engineered greenhouse gas removals, with legislation targeted by end-2028 and operations by end-2029.[2] Another example is the EU ETS. In July 2026, the European Commission proposed the purchase of up to 250 Mt of permanent, domestic carbon removal credits from 2031-2040, using funds from auctioned allowances. The EU's CRCF informs which projects are allowed - currently BioCCS and DACCS. Additional approaches could be incorporated after a 2034 review.

What's needed to unlock Mining CDR potential

- ETSs must explicitly allow carbon removals alongside emissions reductions and define how they interact with, replace, or supplement allowances
- A tightening emissions cap must create structural demand for removals as allowances become scarce
- ETSs must specify where eligible removals occur and under which system boundaries, and Mining CDR activities must be eligible

Expected guardrails

- Durability, liability and reversal risk controls must meet ETS compliance thresholds
- ETS claims must be separate from product claims and voluntary carbon credit claims
- The number of removals allowed under an ETS could be capped

Guardrails follow directly from the UK and EU ETS design directions.

Notes and sources: [1] International Carbon Action Partnership, 2026. [2] UK Department for Energy Security and Net Zero, 2025. [3] European Commission Revision of the EU ETS, 2026.

SBTi is likely to spur strong corporate demand for long-lived CDR credits

SBTi is already shaping corporate climate strategy at scale: it lists over 13,500 companies with targets or commitments, including over 11,500 with validated targets and over 2,500 with net-zero targets.[1]

What SBTi is

The Science Based Targets initiative (SBTi) is a widely used corporate climate target-setting framework that influences how companies set decarbonization targets and how they position CDR in their climate strategies.

SBTi released its updated Corporate Net-Zero Standard V2.0 in June 2026. It provides new guidance on how companies can use CDR in addressing residual emissions.[2]

Why it matters for Mining CDR

SBTi governs how removals can be used and claimed within corporate net-zero strategies that seek SBTi validation.

Under V2.0 of the standard, “long-lived removals” are required to neutralize residual emissions at net zero.

Companies can optionally procure removals before 2035, at which point long-lived removal targets become required.

For Mining CDR, this creates a potential market and use case: delivering durable removals to meet SBTi requirements for “long-lived” greenhouse gas emission neutralization.[2]

What's needed to unlock Mining CDR potential

- Robust understanding of Mining CDR reversal risks and its ability to qualify under SBTi as “long-lived removals”
- Assessment and documentation that Mining CDR meets integrity criteria as outlined by SBTi, such as on additionality, no double-counting, and transparency

Expected guardrails

- Mining CDR cannot be used to substitute for value-chain decarbonization
- Validation through pilots before Mining CDR is used to neutralize residual emissions
- Separation of neutralization and other claims
- Rigorous MRV conforming to accepted standards to ensure removal occurs and is not reversed

Notes and sources: [1]Science Based Targets Initiative, 2026. [2]Science Based Targets Initiative, 2026.

Carbon accounting is advancing, including in its coverage of CDR

Carbon accounting continues to advance, including through the revision and extension of leading programs, and through a ledger-based product-level accounting movement that aims to make carbon data more auditable, timely, and transferable through value chains. In both cases there is movement towards more coverage of carbon removal credit purchasing and trading and of carbon removal activities that occur within production processes.

What the relevant advances in carbon accounting are

Mainstream carbon accounting and disclosure programs have completed revisions and extensions recently, evolving toward disaggregated reporting of gross emissions, removals, and credits. There are also more revisions and extensions underway:

- The **GHG Protocol** released its Land Sector and Removals Standard, which provides methods to quantify, report, and track land emissions, along with various forms of CO_2 removals[1]
- The **IFRS S2** disclosure standard, which applies globally under the ISSB, is effective for annual reporting periods beginning on or after 1 January 2024. It requires companies to disclose carbon crediting activities, distinguishing between reductions and removals credits, disclosing third-party certifiers, and sharing underlying assumptions about removal permanence.[2]
- In Europe, **ESRS E1** separately requires disclosure of gross Scope 1, 2, and 3 emissions and GHG removals / mitigation projects financed through carbon credits.[3]
- **ISO and GHG Protocol** are also jointly developing a product-level GHG accounting standard.

The movement to advance ledger-based emissions accounting is also advancing:

- **Carbon Measures[4]** is developing a framework for product-level carbon accounting and advocating for mandatory product carbon intensity standards.
- **The E-ledgers Institute[5]** recently published an E-asset proto-standard, to establish accounting principles under which carbon removals could be recognized as assets in ledgers that account for emissions as they transact and flow through value chains.

Why they matter for Mining CDR

The economic value of a carbon removal intervention depends on how fully its effect can be counted, disclosed, transferred, and claimed. Accounting systems are evolving in ways that should more fully support these functions. As a result, Mining CDR should become more legible in emissions disclosure, product standards and differentiation based on carbon intensity, and CBAM-type contexts, in particular.

What's needed to unlock Mining CDR potential

- Accounting and reporting that captures the following dynamics: removals generation; removals transfer, trading, and crediting; and product attributes
- Product-level rules on boundaries, allocation, and chain-of-custody
- Interoperability and complementarity between mainstream and ledger-based programs

Guardrails

Reform of how emissions are measured and attributed should not be confused with what is allowed to be subtracted from reported totals.

Notes and sources: [1] Greenhouse Gas Protocol, 2026. [2] IFRS, 2026. [3] European Sustainability Reporting Standard, [4] Carbon Measures, [5] E-ledgers Institute.

Differentiated downstream products are emerging

One of the strongest signals for Mining CDR includes the product-level differentiation occurring for mining-adjacent products, such as low-carbon steel. Applying CDR in a mining context to lower emissions associated with products looks increasingly viable; it will require new standards, buyer commitments, and regulated product-data systems that reward verified lower-emissions, traceable, or certified product attributes for chains downstream of mining.

What differentiated downstream products are

Three signal types are already visible:

Standards/certification: ResponsibleSteel says steelmaking sites that achieve at least Progress Level 1 for both decarbonization and materials sourcing can market products as “Certified Steel.”[1]

Buyer commitments: FMC steel purchasers commit that at least 10% of their annual steel procurement by 2030 will meet their near-zero steel definition, and members commit to procure low-carbon aluminum for at least 10% of annual primary aluminum procurement by 2030.[2]

Regulated product data: under the EU Batteries Regulation, information will be carried via QR code and, for light means of transport, industrial, and EV batteries, via a battery passport; the regulation also creates carbon-footprint rules for key battery categories.

Why they matter for Mining CDR

For Mining CDR, differentiated products can provide a value pathway beyond standalone carbon-credit sales. On-site interventions can translate into lower product footprints, buyer-recognized certifications, or procurement-relevant carbon attributes and can strengthen competitive positioning in downstream value chains.

What's needed to unlock Mining CDR potential

- Product-level accounting rules that connect mine-site interventions to downstream product footprints
- Recognized categories or thresholds that buyers actually use, such as certified steel, near-zero steel, low-carbon aluminum, or regulated battery-footprint data
- Scaling and alignment: these are real market signals, but they are still sector-specific and uneven - the clearest current examples are in steel, aluminum, and batteries

Guardrails

Differentiated product claims should not be used unless the effect is recognized inside relevant methodologies, standards, or procurement rules.

Notes and sources: [1]ResponsibleSteel, 2026. [2]First Movers Coalition, 2026.

Cara Maesano, Kunal Khandelwal, Evvan Morton, Daniel Pike, *Mining and Carbon Dioxide Removal: A Responsible Path Forward for Mine Operators, Policymakers, and other Key Stakeholders*, RMI, 2026, https://rmi.org/resources/mining-and-carbon-dioxide-removal/.

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