



A primer on In-Situ Mineralization (ISM)

Reaching gigaton-scale carbon removal requires diverse storage solutions

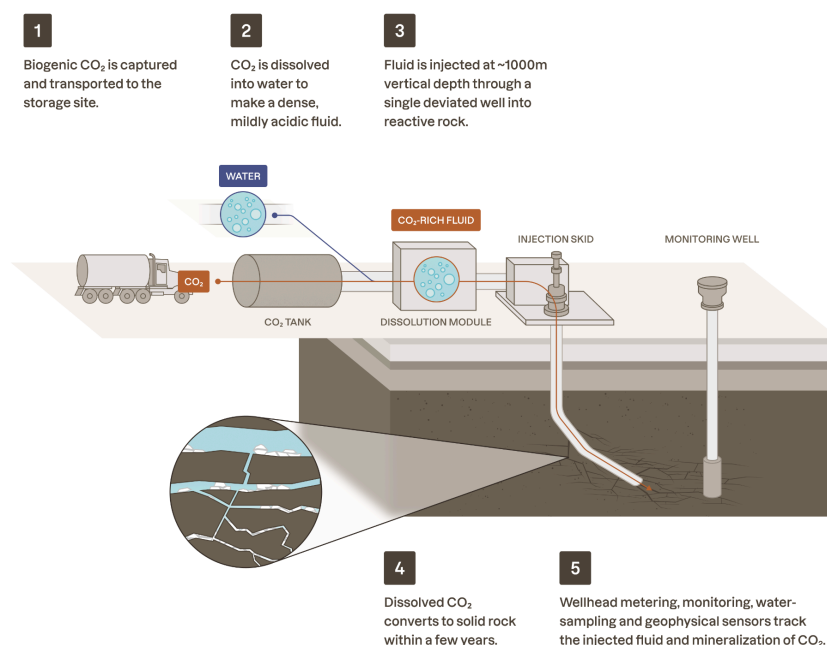
Gigaton scale carbon dioxide removal (CDR) is required to reach global net zero and mitigate the worst effects of climate change. Many of these solutions like direct air capture and bioenergy carbon capture and storage need a way to store the captured CO₂ to permanently remove it from the atmosphere. In addition to carbon removal, decarbonizing heavy industry requires storing vast amounts of CO₂ captured from energy, steel, cement, and chemical production. By some estimates, we need to store hundreds of billions of tons cumulatively across industrial carbon capture and atmospheric removal by 2100, but **storage is finite**¹ and unevenly distributed around the globe. Today, most CO₂ is stored by compressing and injecting the CO₂ as a liquid into sedimentary formations like depleted oil and gas reservoirs or saline aquifers. However, there are many locations where CO₂ could be captured but there is no feasible and cost-effective geologic storage available.

In-situ mineralization is one of these solutions

In-situ mineralization (ISM) provides an alternative to sedimentary geologic storage in some regions. During the process, captured CO₂ and water are injected into reactive alkaline rocks in the earth's subsurface where the CO₂ reacts with the rock, typically basalt or peridotite, and forms solid carbonate minerals that remain stable for millenia.

ISM has the potential to store CO₂ cheaply and durably at scale

ISM is an extremely stable form of storage. It takes the low reversal risk of saline aquifer storage a step further by quickly locking the CO₂ into rock, providing an additional layer of physical durability and reducing the cost of long-term monitoring. While sites operating today store less than 50,000 tons per year, basalt and peridotite formations are abundant and could realistically store **5 billion or more tons per year** of CO₂. Importantly, ISM **unlocks new geographies** for carbon management projects by offering storage where it is too expensive to build pipelines or transport CO₂ by truck or train to geologic storage in sedimentary basins.



Visual diagram of in-situ mineralization

Existing projects demonstrate ISM is effective and safe

So far, decades of lab and field trials around the globe show that ISM works and that the process rapidly stores the majority of injected CO₂ as carbonates within two years of injection. Pacific Northwest National Laboratory **demonstrated mineralization** in US basalts, Cella in Kenyan basalts, and 44.01 in Omani and UAE peridotite. Since 2012, Icelandic company Carbfix has mineralized **70,000 tons** of geothermal plant emissions and direct air captured CO₂ at their Hellisheiði site. Their 2012 pilot showed **> 95% mineralization** of the injected CO₂ within two years and costs today are claimed to be **< \$20/tCO₂**.

¹To keep global temperatures < 2 degrees requires ~10 Gt/year of storage across DAC and BECCS in 2100.

FAQs

What other options exist to durably store point-source-captured CO₂?

In addition to ISM and geologic storage, CO₂ can also be stored through above ground, ex-situ mineralization, where CO₂ is mineralized in engineered reactors using alkaline mine tailings or other industrial residues, or injected and mineralized into fresh or curing concrete.

How is in-situ mineralization permitted?

The permitting framework varies by jurisdiction. In Iceland, ISM is regulated under [Iceland's CCS framework](#). In the UAE, for example, there is not yet dedicated regulation, so individual and project-specific subsurface, water, land-access, and industrial approvals are required.

Does ISM remove CO₂ permanently? How is carbon storage actually measured and verified?

Yes. ISM permanently immobilizes CO₂ in the subsurface as carbonates which remain stable for [millions of years](#). To measure the CO₂ stored, operators inject CO₂ dissolved in water and use reactive tracers, directly measure the amount of CO₂ and water injected at the wellhead, and subtract any process emissions. They follow a comprehensive monitoring and measurement program during- and post-injection which includes sampling groundwater and formation-fluids, assessing injection pressure and flow data, and conducting reactive-transport modeling, geochemical analysis, and mass balance calculations to quantify mineralized CO₂ and its rate of formation. This data is reviewed and verified by a third party registry.

How does ISM compare to geologic storage?

The key advantage of in-situ mineralization over geologic sequestration in sedimentary basins is the speed at which solid carbonates are formed underground, providing an additional layer of physical durability and reducing the duration of long-term well monitoring. ISM also provides flexibility to store CO₂ across more geographies. However, ISM is a newer technology that requires specific rock permeability and reactivity, and water co-injection, and as a result is likely to cost more than conventional saline storage. Conventional storage will likely remain the lowest-cost option where suitable sedimentary basins and shared transport infrastructure are available.

What is needed to accelerate the scale up of ISM?

Accelerating the scale up of ISM requires clearer, mineralization-specific permitting pathways; more rock characterization and demonstration well data on injectivity, pressure response, mineralization rates, and groundwater protection at promising sites; the development of more water-efficient injection approaches, including using wastewater, brines, seawater or water recycling; lower-cost drilling, well completion, and CO₂ transport; and field-tested measurement and verification.

Who is Frontier, and why are they involved in ISM?

Frontier is an advance market commitment to buy high-quality carbon removal. We believe that to avoid the worst impacts of climate change, we must both rapidly reduce emissions and permanently remove CO₂ already in the atmosphere. We work with over 60 independent experts to define what “high-quality” removal looks like: it must be permanent, safe, additional, and measurable. Then we support early-stage companies and researchers working on solutions that meet that bar, which includes in-situ mineralization. Learn more about our evaluation criteria [here](#).

Where can I learn more?

- 44.01 – [Rapid mineralization of carbon dioxide in peridotites](#)
- 44.01 – [Scientific Drilling in the Samail Ophiolite, Sultanate of Oman Proceedings of the Oman Drilling Project](#)
- 44.01 – [Rapid CO₂ Mineralization in Oman's Peridotite Formation: Insights from Reactive Transport Simulation](#)
- CarbFix – [Summary of scientific findings](#)
- IEAGHG – [Review of CO₂ Storage via In-Situ Mineralization in Mafic–Ultramafic Rocks](#)
- Isometric – [Protocol for CO₂ Storage via In-situ Mineralization in Mafic and Ultramafic Formations](#)
- National Academies – [Carbon Mineralization of CO₂](#)
- Pacific Northwest National Laboratory – [Advancing CO₂ storage through carbon mineralization in the US](#)
- USGS – [Making Minerals](#)