CARBON MINERALIZATION AS A NEW FRONTIER FOR CCS PATHWAYS

A solution that turns a natural process into an opportunity

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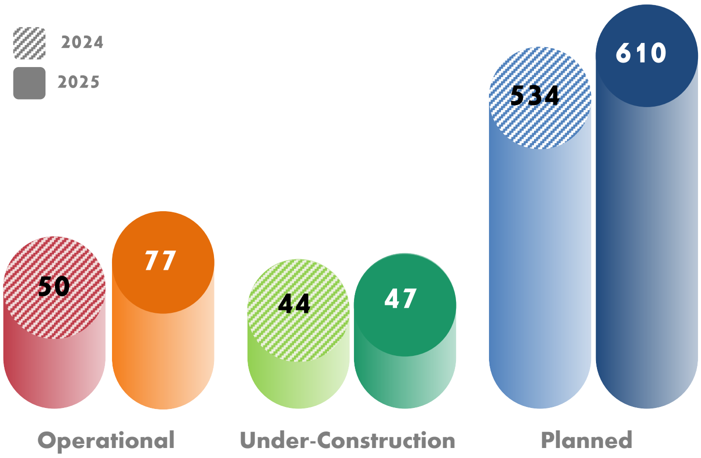
Over the past decades, Carbon Capture and Storage (CCS) activities have been increasingly recognized as strategic instruments for the global energy transition, being regarded as both necessary and technologically viable by many countries. Enhanced Oil Recovery using carbon dioxide (CO_2) (EOR) has been employed in the United States and Canada since the 1960s as a means of increasing production from mature oil fields. In 1972, this technique achieved its first large-scale application worldwide with the launch of the Scurry Area Canyon Reef Operating Committee (SACROC) project in Texas, United States.

The 1990s marked another milestone in the history of CCS activities with the start, in 1996, of the first large-scale CCS project focused solely on reducing carbon emissions rather than increasing hydrocarbon production: the Sleipner project in the North Sea, Norway. Since then, technological advances, growing concerns about climate change, and the maturation of regulatory frameworks in different countries have driven the expansion and diversification of CCS projects on a global scale.

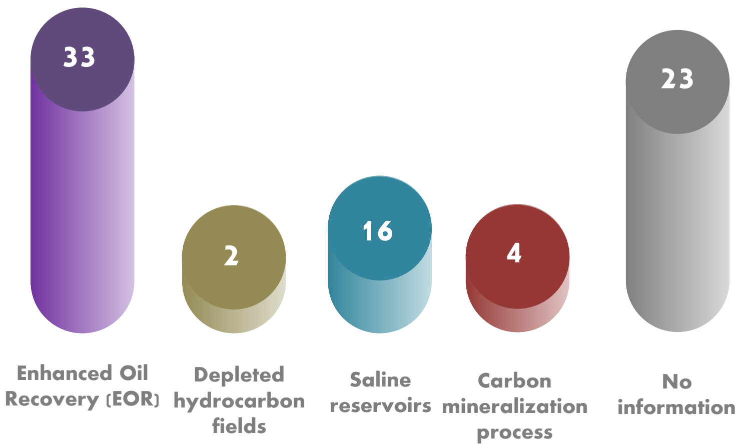
Although its deployment remains gradual, CCS has undergone a phase of significantly accelerated growth in recent years. According to the Global CCS Institute (GCCSI, 2025), the number of commercial facilities (the combined total of operational, under-construction, and planned projects) increased from 628 in 2024 to 734 in 2025. The number of operational facilities rose from 50 to 77, resulting in a 23% increase in global capture capacity in just one year, reaching approximately 64 $MtCO_2$ per year of installed capture capacity.

Number of comercial facilities in the world



Source: GCCSI (2025)

Storage types in operational projects



Source: Adapted from GCCSI (2025)

According to the Global CCS Institute (GCCSI, 2025), there are more operational projects that store carbon through Enhanced Oil Recovery (EOR) and saline reservoirs than projects that store CO_2 in depleted hydrocarbon fields or through the carbon mineralization process.

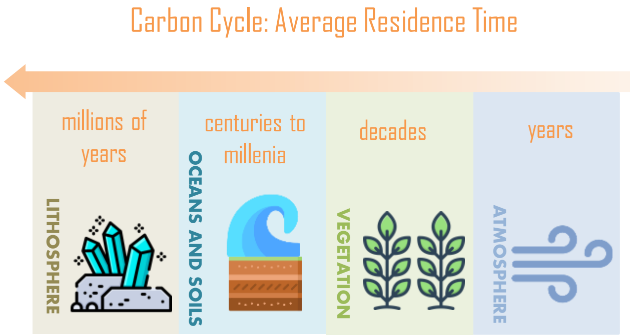
This document presents the CCS process through carbon mineralization, demonstrating its feasibility and advantages at both the global and national levels. This work continues EPE's series of publications dedicated to the CCS topic and constitutes the third fact sheet in the series. The fact sheets already published include:

- CARBON CAPTURE AND STORAGE: A Brief Guide to One of the Key Alternatives for Transforming Brazil's Oil and Gas Sector (EPE, 2023)
- SALINE RESERVOIRS: What Lies Behind One of the Main Targets for Carbon Storage Sites? (EPE, 2024)

[1] According to the GCCSI database, only the CarbFix Storage project is identified as storing CO_2 through carbon mineralization. However, the Climeworks Orca (Orca), Climeworks Mammoth (Mammoth), and Silverstone (Silverstone) projects, which are also included in the database, use the same storage method. The Silverstone project is a continuation of the CarbFix Storage project and, therefore, the two were considered as a single project. In addition, the Nesjavellir (Nesjavellir) project was included in the chart, although it does not appear in the GCCSI database.

Why Explore CO_2 Mineralization?

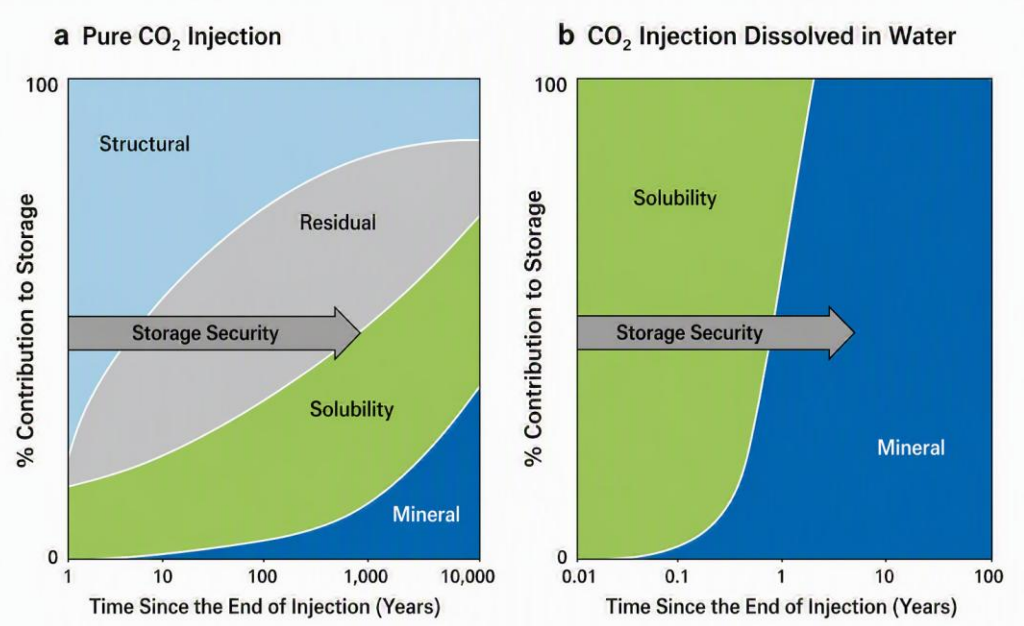
In the natural carbon cycle, the residence time of carbon increases progressively across the Earth's different reservoirs (Snaebjörnsdóttir et al., 2020). Quantitatively, the largest fraction of carbon is stored in the lithosphere, predominantly in the form of minerals that constitute carbonate rocks (e.g., limestone). This provides clear evidence of the stability of mineral carbon storage and serves as a strong indication of why this system can and should be investigated as a carbon sink for the carbon captured through efforts aimed at reducing emissions from point sources or removing CO_2 directly from the atmosphere.



Although carbonate rocks take millions of years to form naturally, the process of mineral crystallization can be accelerated through the use of existing technologies.

CO_2 Trapping Mechanisms

CO_2 can be injected into geological reservoirs in two distinct ways: in its pure form or dissolved in water.When injected in its pure form (Figure a), carbon dioxide is initially retained beneath impermeable rock layers through what is known as structural or stratigraphic trapping. Over time, part of the gas becomes trapped within small pore spaces in the rock (residual trapping). As the process evolves, CO_2 gradually dissolves into the groundwater (solubility trapping), and eventually a fraction of the dissolved carbon reacts with minerals in the rock, forming new stable minerals (mineral trapping). This combination of mechanisms progressively reduces the mobility of CO_2, enhancing storage security; however, complete mineral conversion may take thousands of years or longer (Benson et al., 2005).In contrast, when CO_2 is injected dissolved in water (Figure b), there is no need for confinement beneath impermeable rock layers, since the fluid is not buoyant and therefore does not tend to migrate toward the surface. Following injection, solubility trapping occurs immediately, and mineral trapping can be achieved within a relatively short period of time, on the order of a few years (less than 10 years) (Snaebjörnsdóttir et al., 2020)



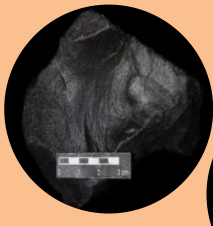
Trapping mechanisms for (a) injection of pure CO_2 and (b) injection of CO_2 dissolved in water.
Figure adapted from Orita and Cruz (2022) modified from Snaebjörnsdóttir et al., 2020

The possibility of accelerating mineral trapping through the injection of CO_2 dissolved in water has attracted growing interest. In this context, it is worth noting that carbon mineralization performs particularly well in reservoirs composed of mafic and ultramafic igneous rocks (Box 1).

What Are Mafic and Ultramafic Igneous Rocks?

Mafic and ultramafic igneous rocks are rich in ferromagnesian minerals, such as olivine, pyroxene, and amphibole, which generally give them a dark color and high density. Mafic rocks contain moderately low silica content, whereas ultramafic rocks have even lower silica content and a greater predominance of ferromagnesian minerals.

Examples of mafic rocks

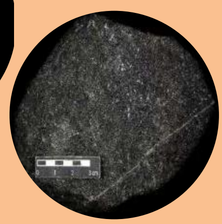


basalt

gabbro

Examples of ultramafic rocks

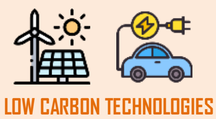
peridotite

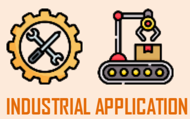


pyroxenite

Figures from Britannica e IGC – USP

Beyond their potential for carbon mineralization, mafic and ultramafic igneous rocks are also important sources of critical minerals, such as nickel, cobalt, chromium, and platinum-group elements, which are widely used in:





Why do mafic and ultramafic rocks favor carbon mineralization?

Mafic and ultramafic igneous rocks—composed predominantly of minerals such as pyroxene, plagioclase, olivine, and amphibole—exhibit high geochemical reactivity with carbon dioxide dissolved in water. During rock–fluid interaction, these minerals undergo dissolution, releasing divalent cations (Ca^{2+}, Mg^{2+}, and Fe^{2+}), which react with carbonate species derived from CO_2, resulting in the formation of stable carbonate minerals. The high potential of these rocks for the permanent conversion of injected CO_2 can be described, in a simplified manner, by the following carbonation reactions:

$$CO_2(aq) + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + 2H^+ \quad (1)$$

$$(Ca, Mg, Fe)^{2+} + HCO_3^- \rightleftharpoons (Ca, Mg, Fe)CO_3 + H^+ \quad (2)$$

$$(Ca, Mg, Fe)^{2+} + CO_3^{2-} \rightleftharpoons (Ca, Mg, Fe)CO_3 \quad (3)$$

In this process, dissolved CO_2 forms carbonic acid, which dissociates into bicarbonate and carbonate ions (1). The cations released from mafic and ultramafic rocks react with these species (2 and 3), promoting the precipitation of carbonate minerals such as calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), magnesite ($MgCO_3$), and siderite ($FeCO_3$) (Orita and Cruz (2022)).

Carbon mineralization is particularly efficient in porous and reactive mafic and ultramafic rocks, especially basalts. These rocks are the most abundant in the Earth's crust, occurring in large volumes in both continental basaltic provinces and, even more extensively, on the ocean floor.

Current Projects Worldwide

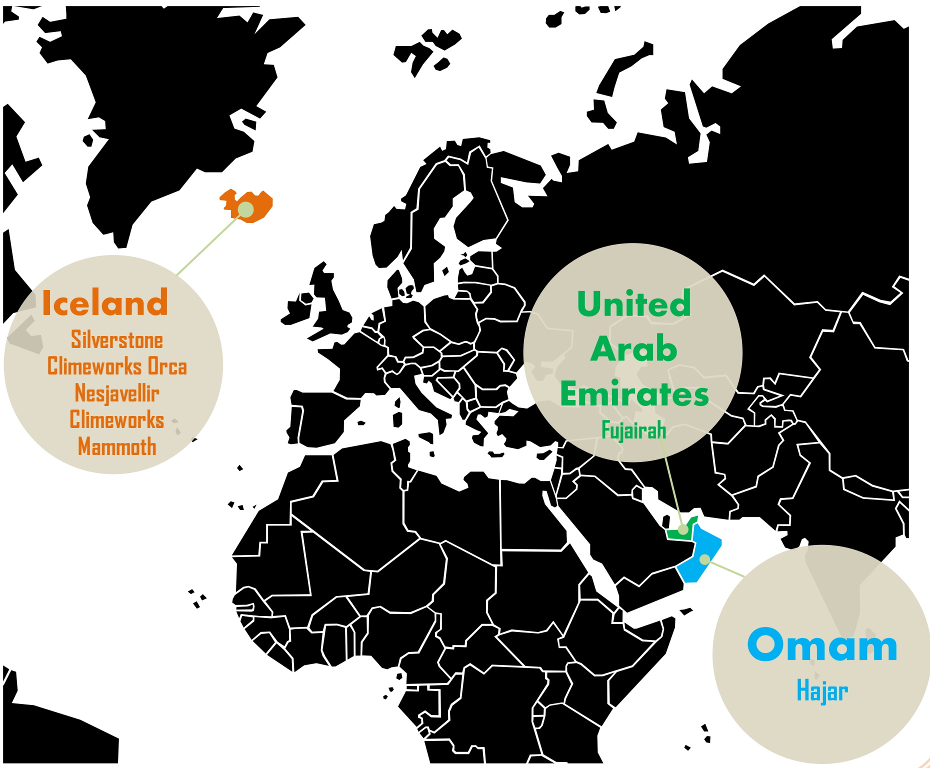
Iceland hosts the four largest CCS projects currently in operation that use basalt mineralization for the permanent storage of CO_2.

Project	Silverstone	Climeworks Orca	Nesjavellir	Climeworks Mammoth
Stakeholders	CarbFix, ON Power	CarbFix, ON Power, Climeworks	CarbFix, ON Power	CarbFix, ON Power, Climeworks
Start of operations	2014	2021	2023	2024
Capture technology	Point-source CO_2 capture from geothermal power plant emissions	Direct Air Capture (DAC)	Point-source CO_2 capture from geothermal power plant emissions	Direct Air Capture (DAC)
Capture and Storage Capacity	~12,000 tCO_2/year since 2014. With integration into the Silverstone project (2021), ~34,000 tCO_2/year	~4,000 tCO_2/year	~3,0 mil tCO_2/year	~36,0 mil tCO_2/year
Cost	Received up to €3.9 million in funding from the European Union Innovation Fund	US$ 10-15 Million	No information available	

Project references: Silverstone and Nesjavellir – Carbfix (carbfix.com) Orca and Mammoth – Climeworks (climeworks.com). Additional information: cinea.ec.europa.eu and geoengineeringmonitor.org

Furthermore, the Hajar project (Oman), with an estimated capacity of 1,000 tCO_2 per year, is currently under construction (GCCSI, 2025). 44.01 and AirCapture will capture CO_2 through Direct Air Capture (DAC), and the carbon dioxide will be dissolved in water before being injected into peridotites, which are ultramafic igneous rocks (Hajar).

Holcim and 44.01 have announced the launch of the first pilot project to mineralize CO_2 captured from the cement industry: the Fujairah project (United Arab Emirates). Injection into peridotites, which are ultramafic igneous rocks, has begun at a rate of 5 tonnes per day and is expected to increase to 20 tonnes per day. The well has an estimated CO_2 storage capacity of 25,000 tonnes per year (Fujairah).



Carbon Mineralization in Brazil

International experience demonstrates that carbon mineralization can provide a safe and permanent method for CO_2 storage by converting it into stable solid minerals.

In Brazil, this approach is particularly attractive due to the widespread occurrence of mafic and ultramafic rocks, which are found in both ancient geological terrains and large volcanic provinces and sedimentary basins. These formations are concentrated mainly in the states of Rio Grande do Sul, Santa Catarina, Paraná, São Paulo, Goiás, Minas Gerais, Pará, Bahia, Mato Grosso, and Mato Grosso do Sul.

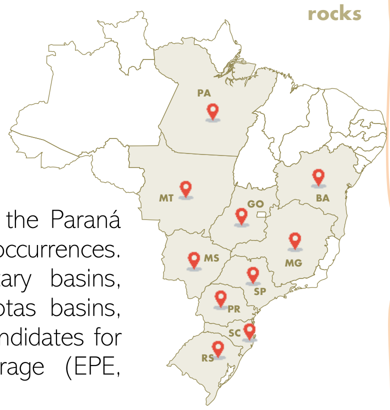
However, the large-scale deployment of this technology in Brazil still depends on overcoming strategic and technical challenges, many of which are shared with other countries, including the costs associated with CO_2 capture and storage, as well as the energy requirements of these processes.

In the Brazilian context, additional challenges include water management and the need for detailed aquifer mapping to protect freshwater reservoirs, since areas suitable for carbon mineralization may overlap with aquifer systems of strategic importance

Therefore, the advancement of carbon mineralization in Brazil is likely to rely on the development of techniques, methodologies, and institutional arrangements tailored to the national context, with the participation of academic institutions, research centers, and companies in the energy sector.

To date, most studies have focused on the Paraná Basin due to its extensive basalt occurrences. Nevertheless, other Brazilian sedimentary basins, such as the Santos, Campos, and Pelotas basins, have also been identified as potential candidates for evaluating this type of geological storage (EPE, 2026).

Main brazilian states with occurrences of mafic and ultramafic rocks



A project developer interested in implementing CCS projects can consult the Groundwater Information System (SIAGAS) as an initial reference. However, it is essential to conduct high-resolution hydrogeological studies in the project area to ensure an adequate characterization of local conditions and thereby prevent contamination of freshwater aquifers (salinity ≤ 500 ppm).

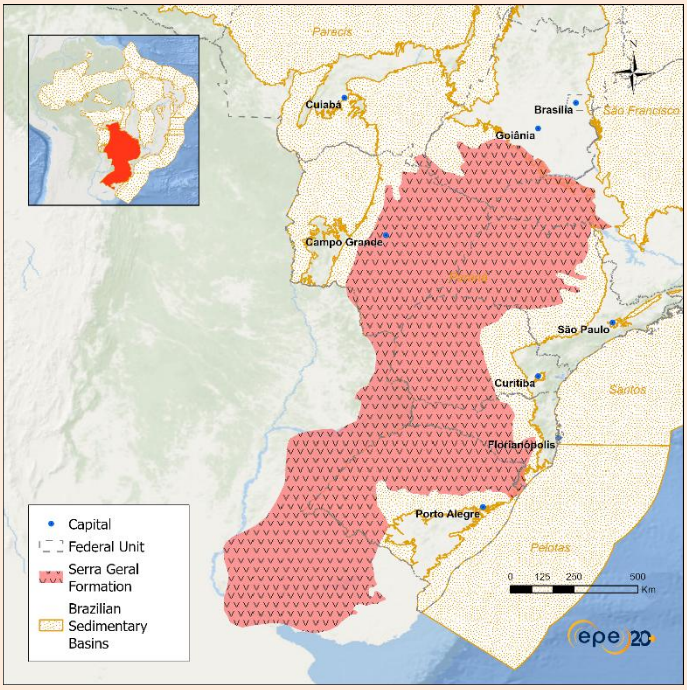
In Brazil, SIAGAS, developed by the Geological Survey of Brazil (SGB), serves as a database for storing and accessing information on groundwater wells. However, the spatial representativeness of this database remains limited, since the distribution of registered wells covers only a small portion of the national territory. Moreover, most records correspond to relatively shallow wells, which restricts the availability of information on deeper aquifers.

Paraná Basin

The Paraná Basin has been the primary focus of carbon mineralization studies in Brazil due to the extensive occurrence of the Serra Geral Formation basalts, which constitute one of the world's largest igneous provinces, with volcanic sequences reaching up to 2,000 meters in thickness (ANP, 2017). At a regional scale, these basalts have potential as geological reservoirs, particularly within fractured intervals, where effective porosity and permeability allow fluid circulation and promote carbonation reactions (Orita and Cruz (2022)).

The basin's location in a densely populated and industrialized region also represents a logistical advantage, as it reduces the distance between CO_2 emission sources and potential storage sites.

However, the fractured basalts of the Serra Geral Formation are part of the Serra Geral Aquifer System (SGAS), one of the country's most important groundwater reservoirs, which imposes significant technical constraints. According to Orita and Cruz (2022), CO_2 injection should take place in hydrogeologically isolated portions of the system, away from recharge zones and disconnected from shallow aquifers, in order to minimize the risks of CO_2 migration and impacts on water resources. Therefore, the protection of the SGAS is a key prerequisite for the feasibility of carbon mineralization projects in the basin.



Repsol Sinopec Brasil

PUCRS

IPR INSTITUTO DO PETRÓLEO E DOS RECURSOS NATURAIS

In 2024, Repsol Sinopec Brasil, in partnership with the Institute of Petroleum and Natural Resources (IPR-PUCRS), inaugurated the first Direct Air Capture (DAC) pilot plant in Latin America in Porto Alegre, Rio Grande do Sul. With a capacity to remove approximately 300 tonnes of CO_2 per year, the initiative is part of the DAC.SI (Direct Air Capture System Integration) project, which aims to develop negative-emissions technologies in Brazil.

The potential for CO_2 mineralization in the basaltic rocks of the Paraná Basin is being investigated to assess the suitability of this pathway under Brazilian geological and environmental conditions. Still in the research and development stage, with no operational-scale application defined to date, these efforts take into account the need to reconcile subsurface utilization with multiple uses, including the protection of water resources associated with the Serra Geral Aquifer System (SGAS). (PETRONOTÍCIAS, 2024; REPSOL, 2022).

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