Reimagining mining for a net-zero future

Carbon-negative mining offers a promising path to meeting the mineral demands of the energy transition while shrinking the industry's carbon footprint. In this article, Dr Estibalitz (Esti) Ukar examines how innovative geochemical and geomechanical processes could turn mining into a net-negative carbon industry

The global energy transition depends on mining. Every electric vehicle, wind turbine, and solar panel relies on a steady supply of critical minerals such as nickel, lithium, cobalt, copper, and rare earth elements. Yet mining remains one of the world's most carbon-intensive industries. As nations race toward net-zero emissions, this dependence poses a paradox: we need more mining to decarbonize, but we must also decarbonize mining itself. To achieve both goals, mining must evolve beyond simply reducing emissions toward methods that actively remove CO_2 from the atmosphere. This is the promise of carbon-negative mining – an emerging approach that leverages the natural reactivity of rocks to capture carbon, unlock metals, and make mineral extraction more efficient and sustainable.

Harnessing the carbon-negative reactivity of mafic rocks

Mafic and ultramafic rocks, such as peridotite, serpentinite, and basalt, form much of the Earth's oceanic crust and mantle. Composed primarily of magnesium- and iron-rich minerals like olivine and pyroxene, these rocks often host valuable concentrations of nickel, cobalt, copper, and platinum-group elements essential for renewable energy technologies and battery storage systems.

Despite their critical importance, these metals typically make up less than one percent of the rock mass.

The remaining material is usually treated as waste. Yet this "waste rock" holds remarkable potential: when CO_2-bearing fluids interact with magnesium- and iron-rich minerals, they react to form stable carbonate minerals, permanently trapping carbon in solid form.

The fundamental reaction can be summarized as: $\mathbf{Mg_2\,SiO_4 + 2CO_2 \rightarrow MgCO_3 + SiO_2}$ which transforms olivine into magnesite (a type of carbonate) and amorphous silica.

This process, known as carbon mineralization, is one of nature's most secure mechanisms to store carbon. Unlike conventional carbon capture and storage (CCS), which relies on maintaining subsurface seals, mineralization locks carbon safely and permanently into solid form. In essence, what begins as a greenhouse gas ends as solid stone. This natural process can be accelerated through engineered CO_2 injection into reactive rock formations in the subsurface.

The interplay between chemistry and mechanics

Carbon mineralization is not only a chemical process; it also changes the physical and mechanical properties of the rock. When CO_2-rich fluids react with magnesium- and iron-bearing minerals, dissolution and precipitation reactions create local stresses that fracture the rock, a phenomenon known as reaction-driven cracking.

This self-sustaining cracking increases the rock's permeability, allowing fluids to flow more easily and accelerating reactions. At the same time, hard minerals like olivine and pyroxene are gradually replaced by softer carbonates, weakening the rock mass. The result is a naturally fractured and softened rock body that is easier to extract and process, all while permanently locking away CO_2.

This coupling of chemical reactivity and mechanical transformation opens new opportunities for sustainable carbon- negative mining. By harnessing carbon mineralization to pre-condition rocks and selectively dissolve metals, future operations could reduce the need for energy-intensive blasting and crushing, lower extraction costs, and minimize environmental impact.

Two pathways to carbon-negative mining

Researchers are currently developing two complementary in-situ approaches to carbon-negative mining, both of which rely on carbon-negative reactions within mafic and ultramafic rocks.

1. Reactive geomechanical pre-conditioning

In this method, CO_2-rich fluids are injected into the subsurface before mining begins. As these fluids react with magnesium-bearing minerals, carbonate formation causes the rock to expand – because carbonate minerals are less dense than the mafic minerals that they replace – generating fractures and cracks through reaction-driven cracking.

This process naturally breaks the rock into smaller, weaker compartments and replaces hard silicates with softer carbonates. The result is a pre- conditioned rock mass that is easier and less energy-intensive to process during crushing and flotation – the beneficiation steps used to separate the valuable metals from waste rock.

Whether mining is performed in open-pit or underground tunnels, this pre-conditioning reduces the need for blasting, lowers crushing and grinding costs, and decreases the energy required for separation through flotation. Importantly, because the newly formed carbonate remains in the waste fraction, the stored carbon is not released back into the atmosphere during processing. The result is a mining process that is both more efficient and less costly and permanently carbon negative.

2. In-situ carbon-assisted dissolution (in-situ leaching)

A second approach involves extracting minerals directly from underground deposits without the need for excavation by dissolving them with a reactive fluid and pumping the resulting solution to the surface for recovery. This process, known as in-situ leaching (ISL), is already used in uranium mining, where chemical solutions are injected into the ore body to dissolve uranium, which is then recovered at the surface. ISL avoids large-scale excavation and ore crushing, reducing operational costs.

However, conventional ISL methods often raise environmental concerns due to the use of aggressive acids and the potential for groundwater contamination. Instead of using aggressive acids, this dissolution could be done using CO_2-rich fluids as a mild acid to dissolve rock underground. When CO_2 dissolves in water, it forms carbonic acid, a weak acid capable of breaking down silicate minerals and leaching metals such as nickel, cobalt, and copper into solution.

These metal-rich fluids can then be pumped to the surface and processed using low-energy, low-carbon extraction methods such as bioleaching – which employs microorganisms to recover metals – or electrochemical separation powered by renewable electricity. In this process, critical elements are mobilized and recovered, while the remaining solid residues are converted into stable carbonate minerals.

This approach significantly reduces the surface footprint of mining operations, eliminates the need for tailings ponds, and minimizes many of the ecological impacts traditionally associated with metal extraction, all while consuming and permanently storing CO_2.

The path forward

Turning carbon-negative mining from concept to practice will require clear economic value, regulatory support, and early integration into mine planning. Mining companies will only adopt these methods if they improve profitability – by lowering energy use, reducing waste, and/or generating measurable carbon credits that strengthen ESG performance and investor confidence.

Encouragingly, beneficiation, the process of separating valuable metals from waste rock, accounts for roughly half of a mine's operational costs. The two carbon-negative methods described above have the potential to cut beneficiation costs by as much as half, providing a strong and immediate financial incentive. With this economic driver, previously uneconomic critical mineral deposits could become viable, expanding access to much-needed resources to meet growing global demand.

Governments can accelerate this transition by recognizing mineralized CO_2 under carbon accounting systems, offering tax incentives, and funding pilot projects that demonstrate technical and economic feasibility. At the same time, collaboration among industry, academia, and regulators will be essential to develop standardized verification frameworks and build public confidence through transparent monitoring and reporting.

Ultimately, carbon management must become a design principle of mining, not an afterthought. If sound economics, policy support, scientific validation, and transparent collaboration align, carbon-negative mining could redefine the industry within a decade. It offers a rare win-win opportunity: an approach that meets the world's growing demand for critical minerals while actively restoring the planet's carbon balance. For an industry historically associated with environmental impact, that transformation would mark nothing short of a revolution – turning mining from a carbon source into a cornerstone of a net-zero future.

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