SCIENCE & TECHNOLOGY

# Turning carbon emissions into rocks

In Penn's Clean Energy Conversions Lab, researcher Peter Psarras and colleagues are repurposing waste from industrial mines, storing carbon pulled from the atmosphere into newly formed rock.

mine tailings mega pit

Open-pit mines like the one seen here generate millions of tons of waste each year. Researchers in the Clean Energy Conversions Lab are working on technologies that could turn this waste into carbon-storing rocks, potentially keeping a substantial amount of CO2 out of the atmosphere. (Image: Peter Psarras)

Chemist Peter Psarras (https://ceclab.seas.upenn.edu/page/peter-psarras) has good reason to call himself a musical rock star—after all, he plays bass and keyboard semi-professionally—but he's more likely to claim "rock" stardom of the geological bent. Pun most certainly intended. "We're turning rocks into rocks here," Psarras explains, holding up a vial containing a white powdery substance.

What he's showing off in the lab that cold December day is magnesium carbonate, the result of a complicated yet inexpensive and mostly carbon-neutral process aimed at storing CO2 that had previously been in the air. In this case, it was done via waste from an industrial mine in the western United States, sent to the Clean Energy Conversions Lab (https://ceclab.seas.upenn.edu/) (CECL) at the University of Pennsylvania (https://www.upenn.edu/) for analysis and processing.

psarras lab members working

Master's student Haarini Ramesh, research lab manager Daniel Nothaft, and Peter Psarras, interim director of the CECL, show the different stages these materials move through in the lab's process to repurpose and store the mine waste.

The lab, funded by the Kleinman Center for Energy Policy (https://kleinmanenergy.upenn.edu/) in the Stuart Weitzman School of Design (https://www.design.upenn.edu/), and the School of Engineering and Applied Science (https://www.seas.upenn.edu/), focuses on carbon management techniques like carbon capture and the technologies to expand such processes. Psarras is interim director while Jennifer Wilcox (https://kleinmanenergy.upenn.edu/people/jennifer-wilcox/) is on leave to work in the Biden Administration's Department of Energy.

This team sees great environmental potential in mine tailings, the sand and sludge left behind after the sought-after ore gets removed. With samples in the lab, they're trying to determine just how much calcium and magnesium each contains, how to best carbonate it with CO2, how and where they can store the result, and whether the process is scalable. So far, they've partnered with five mines, but there's plenty more material out there; the United States generates enough mine tailings in a year to fill 38 million Olympic-size swimming pools.

## The vastness of the mines

Without physically traveling to one of these open-pit mines, it's hard to imagine their size. "They are absolutely huge, vast," says Katherine Vaz Gomes, a third-year doctoral student in the CECL. "It's really the place where industry meets the Earth, literally and figuratively." Picture a hole in the ground 10 or 20 times larger than a football stadium, Psarras adds.

He and Gomes say experiencing a mine in production engages the senses in unexpected ways. Perspective is skewed; rock-hauling trucks with wheels that tower over any person's head appear as dots on the horizon. In the plant, the noise level only allows for communication by yelling. Everything smells like dust—even through the protective gear required at the mines, Gomes says. "You don't think that dust has a smell but it's actually pungent," she says. "Your shoes get covered in it, too."

Though these mining operations have figured out how to simplify something quite complex, the process itself still produces a significant amount of leftover material, with large sections of rock formations ultimately being dubbed waste. Such mine tailings, also known as gangue material, are stored separately from the mining production, sometimes as far away as a mile. They can be mixed with water and turned into a mud slurry, then moved via a large pipe and stored in a giant pool, or they might get dumped onto and transported by a massive conveyer belt.

"Imagine excavating a mountain, then building basically an entire new mountain of just waste nearby," Psarras says. "We're trying to tap into the moved mountain that's been relocated." Like the mines themselves, the scale here is immense, hundreds of feet deep to receive something like a million tons of waste each month for the lifetime of the mine.

Psarras says it's easy to feel both overwhelmed by the mines and awestruck at the people who run them. "They have everything so fine-tuned," he says. "I always go back to the lab inspired, but also with the understanding that we can't complicate their process when we introduce another element of complexity with our technology."

# From trash to treasure

In October of this year, the Clean Energy Conversions Lab moved into the Pennovation Lab Building, a relatively new space at Pennovation Works (https://pennovation.upenn.edu/). Less than six weeks later, several drawers in the back room were already filled with dozens of vials of varying sizes containing a class of minerals called silicates, as well as calcium carbonate and magnesium carbonate outputs. Two buckets each holding five gallons of mine tailings sit on the floor nearby, awaiting processing.

A handful of boxes remain packed in the room next door, scattered among five rows of lab benches that hold beakers and flasks and other equipment ready for use. Psarras, along with Haarini Ramesh, a master's student in Chemical and Biomolecular Engineering (https://cbe.seas.upenn.edu/masters/), and CECL research lab manager Daniel Nothaft, describe the science happening there and the technology they're creating.

At the highest level, these researchers are shepherding the material from its starting point—rock at the mine—to a sand-like substance, then into a solution, and back to rock. Many intricate steps in between begin by scrutinizing the original material.

"When we receive the tailings, we first test for a couple things. We look for inorganic carbon, so are the tailings taking $CO_2$ out of the air naturally? We don't expect that to happen, but we want a baseline of what carbon was already in there," Psarras explains. They also check the rock's size, to determine whether they'll have to grind it down to the tiny particles they need, and analyze its chemical composition, looking for calcium and magnesium, most importantly, but also other scarcer metals like lithium, cobalt, and nickel.

Here, calcium and magnesium matter most because the process requires alkalinity, which neutralizes the acidic carbon in a reaction that stores $CO_2$ in mineral form. Because the mineral diversity of tailings changes by site, this is a crucial set of steps in the process. "After we answer the composition and extraction questions," Gomes says, "we need to figure out how to carbonate it."

Most people understand carbonation as it relates to fizzy drinks; add carbon dioxide to water and it becomes seltzer. In this process, Psarras' team adds $CO_2$ to a pressurized vessel that contains the calcium- or magnesium-rich liquid they created in the previous step. That vessel then goes into a machine that heats and mixes what's within. Gomes describes it simply: "The middle product is a solution. You pump in $CO_2$. When you add the gas to the solution, you get a solid." Beyond keeping carbon out of the atmosphere, that newly formed carbon-storing rock has many potential applications.

# Benefits of mineral carbonation

Psarras has always disliked the argument in energy circles that the solution to the carbon problem must involve either reusing $CO_2$ or storing it. He and his Penn colleagues think this mine tailings work represents a third option—one that both repurposes and stores carbon in an economical and nearly carbon-neutral way.

"We're creating minerals that have a lot of use today," Psarras says. For instance, carbonate can go into paper as a filler material or into building materials by replacing gravel in concrete. "Another benefit of mineral carbonation reactions is that they release energy," adds Daniel Nothaft, who earned a Ph.D. in geology before joining CECL in January 2021. "While in practice, some energy input is needed to speed up the reactions, the energetics are more favorable than other $CO_2$ utilization pathways such as $CO_2$-to-fuels."

psarras showing 2 forms of rocks close up of lab equipment lab member opening fume hood

Often, industrial mine waste starts as rock, which the researchers then turn into a sand-like substance (left). After analyzing its chemical composition, they extract calcium and magnesium, creating a solution (center) then put into a pressurized vessel injected with CO2. Finally, the vessel goes into a machine that heats and mixes what's within (right).

Finding a second life for this waste can also help the mines, which often must figure out how to restore previous dump sites. "This process has a lot of potential because it's about using waste to remediate another waste," Gomes says. And given that this problem isn't unique to the United States, she adds, it could be a way to treat mine tailings globally.

Plus, it's an almost carbon-free process. Of course, the steps to do it require energy, but for the most part, the overall carbon footprint is assigned to the mining itself, not the waste it creates. "It comes with next to no carbon, outside of the incremental work to process it, which would be pennies on the dollar to what you'd encounter trying to mine it fresh," Psarras says. None of this accounts for the added benefit of material that unintentionally comes along for the ride during extraction, high-value metals like nickel that can be repurposed and resold.

# Can it be scaled?

The outstanding question now is how to scale this up to make it what Psarras describes as a "disruptive force" in the industry. After all, it does shorten something that would naturally take thousands of years down to hours, and the mines already involved in the project seem game to having their samples analyzed and to showing the CECL team around. But Psarras admits the technology is still a few steps away from the ability to use it everywhere.

One Nevada mine is acting as a test case to help the researchers better understand the true cost of this process and what a business model might entail. Based on the mine tailings analysis they've done, the researchers are also creating a database to track how well their technology works for different materials, an attempt at greater standardization.

"These technologies will eventually be able to address the critical mineral needs and the carbon management needs that are two of the most pressing environmental and technological challenges of our time," Nothaft says. "That's definitely what motivates me to work on this."

It's an exciting time to work in the carbon capture space, adds Psarras. He guesses their technology could be ready to scale within the next two years, and with the right partners, says this work could eventually remove millions of tons of $CO_2$ from the atmosphere. Should that come to pass, these carbon-storing rocks will indeed be stars in the fight against a warming planet, bolstered by the research team that created them.

*Peter Psarras* (https://kleinmanenergy.upenn.edu/people/peter-psarras/) *is a research assistant professor at the Kleinman Center for Energy Policy* (https://kleinmanenergy.upenn.edu/) *in the Stuart Weitzman School of Design* (https://www.design.upenn.edu/) *and in the Department of Chemical and Biomolecular Engineering* (https://cbe.seas.upenn.edu/) *in the School of Engineering and Applied Science* (https://www.seas.upenn.edu/)*. He is interim director of the Clean Energy Conversions Lab* (https://ceclab.seas.upenn.edu/) *run by Jennifer Wilcox* (https://kleinmanenergy.upenn.edu/people/jennifer-wilcox/)*, who is currently serving as principal deputy assistant secretary in the Office of Fossil Energy and Carbon Management in the Department of Energy.*

*Other members of the Clean Energy Conversions Lab* (https://ceclab.seas.upenn.edu/) *include third-year doctoral student Katherine Vaz Gomes, Research Lab Manager Daniel Nothaft, and Haarini Ramesh, a master's student in Chemical and Biomolecular Engineering* (https://cbe.seas.upenn.edu/masters/).

CREDITS

**Michele W. Berger**
Writer

**Scott Spitzer**
Photographer

**David Lowe-Bianco**
Videographer

DATE

**December 15, 2022**

SUBTOPICS | Chemical Engineering, Earth and Environmental Science, Kleinman Center for Energy Policy, Pennovation Works

SCHOOLS | School of Engineering & Applied Science, Stuart Weitzman School of Design

Penn Today