Sea *Change*

Why two Caltech-related companies are taking the battle against climate change to the ocean.

Even a January storm in Los Angeles could not dampen the spirits of the four-person team that makes up Calcarea, a carbon-sequestration start-up co-founded by Caltech geochemist Jess Adkins. But they did get wet—very wet.

On January 9, amid a torrential downpour, the group stood in a parking lot at USC donning hard hats and yellow vests as semitrucks delivered the components of a chemical reactor that could one day clean up excess carbon dioxide in Earth's atmosphere by capturing emissions from transoceanic shipping. The heavy rain turned into an afterthought for Adkins and colleagues Melissa Gutierrez (BS '19), Pierre Forin, and Troy Gunderson, whose excitement was palpable. "As long as there's no lightning," Adkins noted.

Carbon capture and storage efforts have long been centered on Earth's atmosphere, with companies scrubbing carbon dioxide from the air and storing it underground. While effective, the process is energy intensive and, thus, expensive. Calcarea and another new Caltech-affiliated start-up, Captura, are two of a handful of companies taking a different approach by switching their focus to the oceans.

By Lori Dajose (BS '15)

Oceanic carbon removal is beneficial for the ocean biosphere, where increased carbon dioxide levels have destroyed swaths of marine ecosystems through ocean acidification, and also enhances the ocean's natural capacity to draw down carbon dioxide from the atmosphere through equilibrium processes. While Captura plans to remove carbon from the ocean directly, Calcarea's team aims to clean the flue gas directly from cargo ships to safely and permanently store carbon dioxide in the ocean by mimicking Earth's natural processes to make carbon dioxide react with limestone to produce bicarbonate ions.

Following a demonstration of an initial prototype in the lab, Calcarea's scaled-up reactor was manufactured in Houston. And so, on that rainy day in January, the team gathered to assemble and test it in an unassuming open-air parking lot at the edge of the USC campus. Though the team scheduled the delivery months before any storms were forecast for that day, the group was still determined to finish the job. After a lull in activity, Gunderson, an oceanographer, strode up and broke some bad news—the last truck of the day, carrying the cradle for the reactor itself, had broken down. Adkins smiled and shook his head. "Of course it did," he said.

Calcarea team members **Jess Adkins, Pierre Forin,** and **Melissa Gutierrez** (BS '19) await delivery of their prototype in the rain.

The CHALLENGE Ahead

Adkins, the CEO, had never led a start-up until Calcarea, but he felt compelled to take the leap because of the pressing urgency of human-made climate change and its consequences. Over the past 200 years, humans have figured out how to get plentiful efficient energy through burning hydrocarbons like oil and gas, enabling rapidly accelerated societal transformation. But the consequences of this progress—a warming, changing climate—have been costly to our planet and to people around the world, particularly those in vulnerable communities, such as developing nations.

Human activity has, in total, emitted 400 gigatons of carbon dioxide. About one-third of that has settled in the atmosphere, where it traps heat and causes global warming. Another third is taken up by the surface biosphere: soil, rocks, and plants that use carbon dioxide for photosynthesis. The final third, meanwhile, soaks into the ocean.

To have a chance of avoiding catastrophic damage to human health and the planet, the Intergovernmental Panel on Climate Change (IPCC) has determined that we must prevent the planet from warming by more than 1.5 degrees Celsius. According to the IPCC's models, this can only be accomplished by both switching to renewable energy and initiating carbon capture and storage practices to clean up the mess of emissions polluting the planet. This dual approach is required because even if fossil fuel use were eliminated tomorrow, the 400 gigatons of carbon dioxide already released must still be dealt with. According to the IPCC, that means removing 2 gigatons per year.

"It's no longer sufficient to only decarbonize the economy by switching to renewables," Adkins says. "We could have done it if we started earlier, but we didn't, and now we have to take carbon dioxide out of the atmosphere, and we also have to decarbonize the economy."

This urgent existential crisis, along with newly available funding for carbon capture and removal, has motivated researchers around the world to pursue daring new ideas: some in parking lots and garages, and others in their own homes. Captura, the other new company spun out of Caltech that is aiming to decarbonize the oceans, tested its first prototypes in the backyard pool of co-founder Harry Atwater, the chair of Caltech's Division of Engineering and Applied Science.

"My son had just graduated from college and was looking for a biochemistry project," Atwater says. "We had just received funding to develop early prototypes of our technology, so I told him, 'Hey, why don't we take a couple of months and just have some fun with this? We'll set it up in the backyard swimming pool.'" Since its backyard origins, Captura has won millions of dollars in funding and prizes to make its technology a reality.

DECARBONIZING Shipping

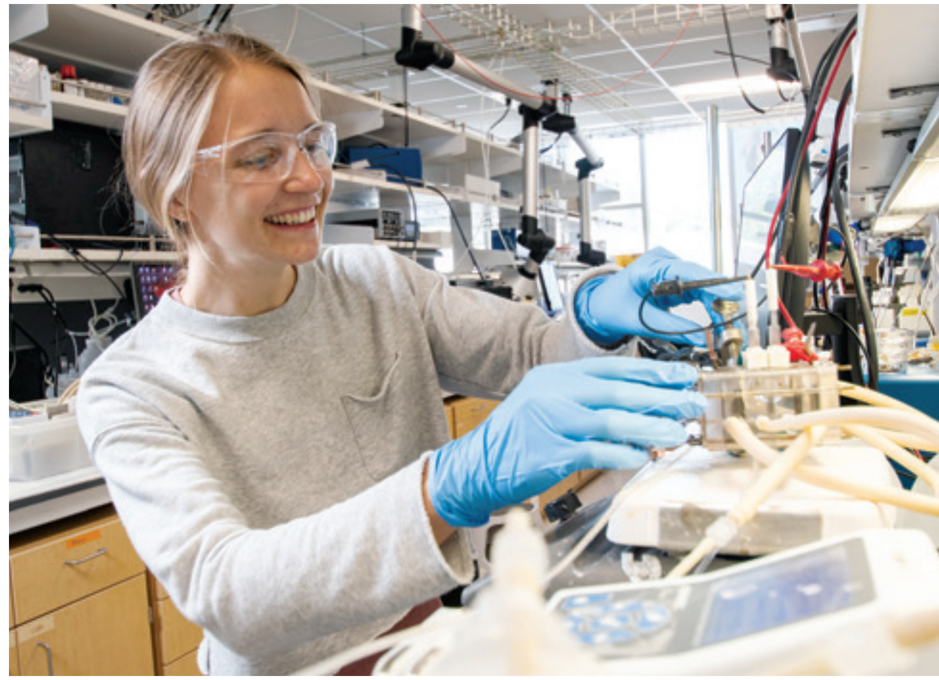
The primary target of Calcarea's cleanup effort is the shipping industry. While cars and homes can often easily be powered by clean wind- and solar-generated electricity, there are no efficient sources of renewable energy for the cargo ships that power our global economy. Cargo ships account for 3 percent, or 1 gigaton, of global carbon emissions per year. Focusing efforts to capture carbon from this sector, therefore, could put us within reach of removing the 2 gigatons per year the IPCC models require.

The Calcarea technology was inspired by natural processes already occurring on Earth. Over long periods of time, carbon dioxide gas in the oceans reacts with limestone ($CaCO_3$) shells on the seafloor in a process called carbonate compensation. The reaction transforms carbon dioxide and produces calcium ions and bicarbonate. In this way, nature equilibrates its carbon dioxide levels naturally. If humans were to disappear from Earth tomorrow, atmospheric carbon dioxide levels would ultimately settle back down to approximately 280 parts per million from our current level of 421 per million, though it would take tens of thousands of years to do so.

For almost a decade before starting Calcarea, researchers in the Adkins Lab worked to understand the kinetics of limestone weathering with the belief that accelerating this process could boost the planet's natural carbon sequestration processes. While they did discover an enzyme that could catalyze the process in the lab, they also realized that at high-enough concentrations of carbon dioxide (5 percent), the weathering reaction would happen much more quickly. The flue gas from cargo ships turns out to meet that bar, and ships can easily carry the limestone necessary to drive the reaction, even without the catalyst.

Adkins began to assemble a team and arrange a sabbatical from Caltech to focus on making accelerated limestone weathering into a viable carbon capture technology that could be sold to large shipping companies to install on their ships. He recruited engineer Forin, who was working in the green shipping industry in Norway, and former Caltech undergraduate Gutierrez. The three of them then spun off Calcarea with fellow co-founder, USC professor and biogeochemist Will Berelson.

"A big aspect of my work is on environmental justice," says Gutierrez, who conducted research in Adkins' s lab throughout her undergraduate years at Caltech. "We want to make sure that Calcarea is building relationships with local communities—like the people who live near the ports where we are setting up our prototypes—and environmental policy groups to ensure their involvement and buy-in with what we're doing."



Caltech graduate student **Éowyn Lucas** (MS '19), a member of the Captura team, develops materials that capture carbon dioxide directly from ocean water.

The team designed a chemical reactor that could bubble the exhaust gas from cargo ships into a tank full of limestone and flowing seawater, scrubbing the carbon dioxide from the ship's emissions and producing saltwater in its place. Calcarea's technology should be able to scrub up to 75 percent of carbon dioxide from a given cargo ship's emissions.

"During COVID, working alone in the back of my garage, I got into my own head asking what's the most important thing that I could work on right now," Adkins recalls. "Don't get me wrong—questions about glacial cycles and corals and the sulfur cycle still get me out of bed in the morning. But none of them are as important as sequestering carbon dioxide at scale. We're either going to try to solve the problem or we're not."

An ELECTROCHEMICAL Equation

As an electrochemist, Captura's Harry Atwater is approaching the problem of carbon capture from a different angle. The company uses an electrochemical process to filter seawater and remove carbon dioxide gas. Though the Captura lab benches are far from the ocean, crystalline salt patterns left by seawater from experiments can be seen all over the company's workspace in Pasadena,

The start-up environment, says Melissa Gutierrez (BS '19), requires creativity, flexibility, and a lot of teamwork. "We have a dynamic where you're allowed to not know all the answers—and then we figure them out together."

leaving a physical reminder of the company's eventual goal: to deploy its technology at sea.

When carbon dioxide is absorbed into the ocean, it undergoes chemical reactions with water to change from a dissolved gas into ionic salts, a process that occurs due to seawater's pH level of 8.1. Once this transformation happens, it becomes harder to remove carbon from the water. It is much easier to pull out its gaseous form.

The basis of the Captura system is to transform the carbon in seawater, which is in the form of salts, back into carbon dioxide gas and then sequester the gas. This is done by temporarily lowering the pH of a given volume of seawater. The seawater's pH is dropped from 8.1 to 4, which forces carbon to take the form of carbon dioxide. The gas is then stripped out of the water, and the team restores the pH back to a slightly more basic level of 8.2 before releasing the water back into the ocean.

Modulating pH is a critical component of the Captura system, and it hinges upon a bipolar membrane, which is a technology that splits seawater (H_2O) into acidifying protons (H+) and "base-ifying" hydroxyls (OH-). Chengxiang "CX" Xiang, a research professor at Caltech and Atwater's longtime collaborator, had studied how to develop bipolar membranes for decades. He and Atwater founded Captura in 2021, each putting their own money into the project on the belief that it would work. So far, their investment has paid off. With Xiang as chief technology officer and Atwater as chief science officer, Captura recently closed a $12 million Series A financing round, coming on the heels of a $1 million award in 2022 from the XPRIZE Carbon Removal competition.

Further development of the bipolar membrane was tasked to graduate student Éowyn Lucas. While working on her PhD, Lucas created a bipolar membrane that is more efficient and powerful than any other currently in development. She will join the Captura team full time after her graduation from Caltech later this year.

"I was able to create these membranes in the lab, and now I get to work on scaling them up and implementing them to solve a really important, real-world problem," she says. "I considered other possible routes after my PhD, but I just had to see this work through. I'm excited but nervous—I've never not been in school."

"Leaders of industry have recognized that in order to maintain their customer base, they need to commit to total decarbonization of their operations in the coming decades. That is a really transformative change."

-Harry Atwater, Captura co-founder

The major cost of scaling such a technology is the input of energy to run the process. Captura's plan is to install its systems at desalinization plants to share their energy infrastructure and, once the company grows in capacity, build standalone Captura platforms. Currently, a small prototype is operating at Caltech's Kerckhoff Marine Laboratory in Newport Beach, where it removes 1 ton of carbon dioxide from seawater per year. The team is currently building a kiloton system that will be the size of a 40-foot container, with the aim of constructing a system that can sequester 1 million tons of carbon dioxide each year.

Both Captura and Calcarea are performing quality control on their technologies and trying to determine all the ways things could go wrong as they scale up their prototypes. In addition to the technological challenges, the ocean is a complex, interconnected biogeochemical ecosystem, and many scientists have been wary of manipulating the environment with the targeted objective of offsetting the effects of climate change out of concern for its potential unforeseen side effects. Open questions for the two teams are how their systems scale up from the lab bench to the ocean, and how the ocean surface ecosystem might be perturbed by the byproducts of the Calcarea and Captura systems.

Adkins believes the potential good far outweighs the bad, however. "We're *already* perturbing the planet by dumping carbon emissions into the biosphere, and we're seeing the effects of that right now," he says. "Accelerated limestone weathering is simply mimicking what the environment already does to balance its carbon budget."

The GREEN Economy

For entrepreneurs trying to save the planet, there are billions of dollars in government funding for projects such as these, and industry is also recognizing the importance of fighting climate change. The Inflation Reduction Act passed by the federal government in 2022 allocates $370 billion for myriad sustainability-related projects, such as decarbonizing public transit, making manufacturing cleaner, and funding climate justice projects for underserved communities.

"Carbon removal is a technology that involves significant deployment of capital and energy at scale," Atwater says. "In 30 or 40 years, a huge amount of infrastructure in the world is going to be devoted to removing carbon dioxide. Governments have been leading the way on policy but, lately, leaders of industry have recognized that in order to maintain their customer base, they need to commit to total decarbonization of their operations in the coming decades. That is a really transformative change."

Many private companies acknowledge the need to combat climate change through carbon removal and curbing their own emissions. For example, Microsoft has pledged to sequester the same amount of carbon as it has emitted since its founding in 1975. With these ambitious goals, there is a need for partnerships between industrial polluters and carbon removal companies such as Captura and Calcarea.

Both the government and private sectors are funding and facilitating these partnerships, giving these early start-ups access to a revenue stream and path to profitability. Captura, for example, recently received a pledge of $500,000 from the private carbon market Frontier, which acts as a broker between Fortune 500 companies that are trying to decarbonize and the companies that will help them to do so. Simultaneously, the U.S. government has updated a former tax credit program called 45Q to provide direct payments to companies in exchange for each ton of carbon dioxide sequestered.

A major benefit of both Captura and Calcarea's proposed carbon capture solutions is that they are cost-effective. While the current leaders in atmospheric carbon capture can sequester carbon dioxide for about $1,000 per ton, Calcarea can do so for $76 per ton, while Captura aims to do so for $65 per ton.

"Ultimately, what we're trying to do only works when there's an economic balance sheet," Adkins says. "Environmental laws and government policies can really make a big difference in planetary health."

From left to right: Captura's **Cory Atwater, CX Xiang, Ibadillah Digdaya,** and **Harry Atwater** standing in front of the company's pilot system in Newport Beach.

FRIENDLY Competition

In addition to the timeliness of the problem, the infusion of new funding sources is driving many researchers to enter the carbon capture business. There are now new efforts underway to grow kelp and algae, to shift ocean circulation, and to enhance the ocean's alkalinity. The Caltech teams say they welcome this competition and creativity.

"We need a diversity of tactics to take on the immense challenge that is climate change," Lucas says. "We're all trying to get grant money and attract the best scientists, but we're also all cheering each other on."

Adkins adds that the problem is too important not to have as many people working on it as possible. "My approach is informed by where I come from as a scientist studying oceanography and paleoclimates. Harry's comes from his electrochemistry background. There's a lot of carbon to sequester, so it's all hands on deck. Rain or shine." [C]

Jess Adkins is the Smits Family Professor of Geochemistry and Global Environmental Science. He serves as CEO of Calcarea.

Harry Atwater is the Otis Booth Leadership Chair of Caltech's Division of Engineering and Applied Science, Howard Hughes Professor of Applied Physics and Materials Science, and director of the Liquid Sunlight Alliance. Atwater is the co-founder of Captura and serves as chief science officer.

Environmental laws and regulations have successfully reduced the emissions that created acid rain and depleted the ozone layer.

Fact:

Carbon dioxide gas extracted from the oceans can be safely pumped deep into the earth, where it is stored and does not contribute to global warming.