keeping open bridges of communication and not wanting to help a country that is aggressively invading another country."

At the individual level, some scientists in the West continue to work with their Russian colleagues. That's easiest for theorists, who can interact by email, telephone, and video. A physicist at the University of British Columbia in Vancouver, Canada, who requested anonymity to protect Russian colleagues, says that he and a half-dozen theorists scattered around the US, Europe, and Russia still meet regularly on Zoom to discuss quantum gravity and quantum cosmology. "We assume the FSB [Russian federal secret service] is listening, so people have become more careful about what they say," he says. "As long as Russian scientists can access the internet, we can work together."

But other scientists are uncomfortable working with people who keep their Russian affiliations. Oleksandr Gamayun is a Ukrainian condensed-matter theorist who has been at the University of Warsaw as a research fellow since 2021. He has long-standing close collaborations with Russian colleagues from when they were postdocs in the UK. "I know these people well," he says. "I would love to keep working with them. But because of their Russian affiliations, it's hard. In my eyes, the affiliation is a representative of the regime. I hope they will move abroad." Their joint work is on hold, he says, but "after peace, I wouldn't have trouble reestablishing the connection."

Alex Buchel is a Ukrainian string theorist who has been at the Perimeter Institute for nearly 20 years. "I have colleagues in Ukraine. They can't do science right now," he says. "They are looking for bulletproof vests." Last fall he gave an online colloquium in Moscow, but he says that he wouldn't give a talk in Russia now. "And if I receive an application from a Russian postdoc or student, I don't look at it. I don't want to have to second guess about their views." To work with someone in Russia, he says, or to publish their papers, "there should be a litmus test. Someone who wants to benefit from funding, collaboration, and publishing must stand and say they do not support the war." Mirzoyan agrees: "I came to the conclusion that one of the ugliest things in society is when people keep silent."

Rybnikov, the Russian mathematician currently in France, is looking for jobs in English-speaking countries. He is pessimistic about the future of science in Russia: "I expect that Russia will stop most international programs in mathematics and other sciences, and you can't do science in a vacuum. It will work both ways—other countries will also stop working with Russia."

"It's very difficult to do physics when this criminal war is continuing," says a theoretical physicist in Moscow who requested anonymity. Many Russian scientists, especially students, consider emigration to be "the most reasonable choice now," he says. Other scientists, both inside and outside of Russia, also worry about the effects on science of Russia's isolation. Alex Levchenko is a Ukrainian theoretical physicist at the University of Wisconsin–Madison. "The damage in Ukraine, including to science, is impossible to grasp," he says. But because of the sanctions, international condemnation, and exodus of talent, "Russian science will inevitably suffer longer term." The ripple effects will reach the rest of the community, he adds. "It's negative for all sides."

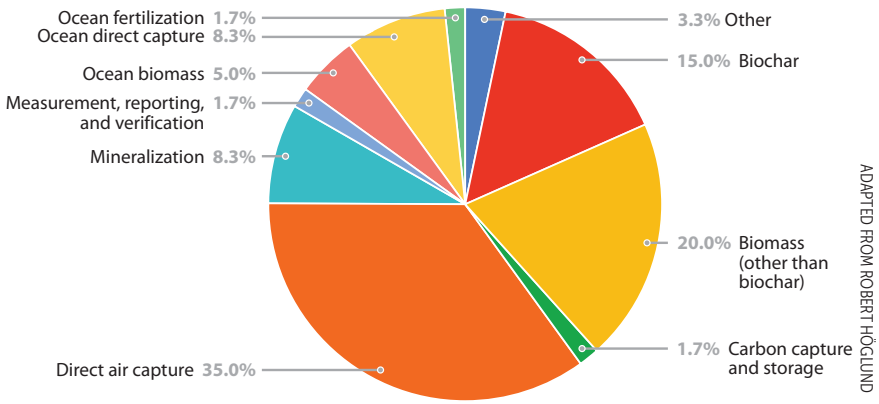
Toni Feder

Carbon dioxide removal is suddenly obtaining credibility and support

The question about carbon extraction is no longer if it will be needed, but whether it can be scaled up quickly enough.

As the likelihood of the world failing to decarbonize rapidly enough to avoid the worst effects of climate change grows, the interest in atmospheric carbon dioxide removal (CDR) has exploded.

April was an eventful month in CDR: A new privately backed nearly $1 billion funding mechanism was unveiled. More than a dozen aspiring CDR startups received $1 million prizes to help further develop their technologies. And the United Nations' Intergovernmental Panel on Climate Change (IPCC) confirmed the necessity of CDR to achieve carbon neutrality by midcentury. The US Department of Energy continued finalizing plans on how it will spend the billions of dollars for direct air capture (DAC) that lawmakers appropriated in November.



ADAPTED FROM ROBERT HÖGLUND

TECHNOLOGIES PROPOSED by the 60 teams that were selected as finalists for the XPrize carbon-removal "milestone" prizes. Fifteen of the teams were awarded $1 million prizes. Up to four prizes, worth a combined $80 million, are to be awarded in 2025. Organizers say the milestone winners won't necessarily be favored in that contest.

In its latest assessment report, released on 4 April, the IPCC for the first time unequivocally declared that CO_2 removal must be part of the solution to limiting the increase in global temperature to 2 °C above its preindustrial level, the ceiling established by the 2015 Paris Agreement. Though the amount of CDR needed will depend on the extent that CO_2 emissions can be mitigated, the IPCC estimated that 5–10 gigatons will have to be extracted each year by midcentury to prevent the world from overheating.

The need for CDR is twofold: to offset continuing emissions from sources that will be very difficult to eliminate—agriculture, aviation, long-haul trucking, and ships—and to extract legacy CO_2 emissions to bring concentrations back to acceptable levels, says Jay Fuhrman, a postdoc at the DOE-funded Joint Global Change Research Institute who was a contributor to the IPCC assessment's CDR modeling. The US would need to remove about 1 gigaton of CO_2 per year by 2050—about the level of emissions from the nation's hard-to-abate sectors—to reach net-zero carbon emissions, says Jennifer Wilcox, DOE principal deputy assistant secretary for fossil energy and carbon management.

The magnitude of that challenge is hard to overstate. "We are at thousands of tons [of annual CDR globally] today. We've got to get six more zeros in less than 30 years," says Wilcox.

The Infrastructure Investment and Jobs Act enacted by President Biden in November 2021 appropriated $3.5 billion for DAC demonstrations. In DAC, CO_2 is extracted through mechanical and chemical means. Additional billions of dollars were allocated for demonstrations of carbon capture and storage from power plants and industrial facilities (see Physics Today, January 2022, page 22).

The measure directed DOE to begin soliciting proposals for four DAC demonstration "hubs" within six months. Interviewed in late April, Wilcox declined to say exactly how DOE will comply with the congressional directive but said the department may issue a notice of intent or a funding-opportunity announcement.

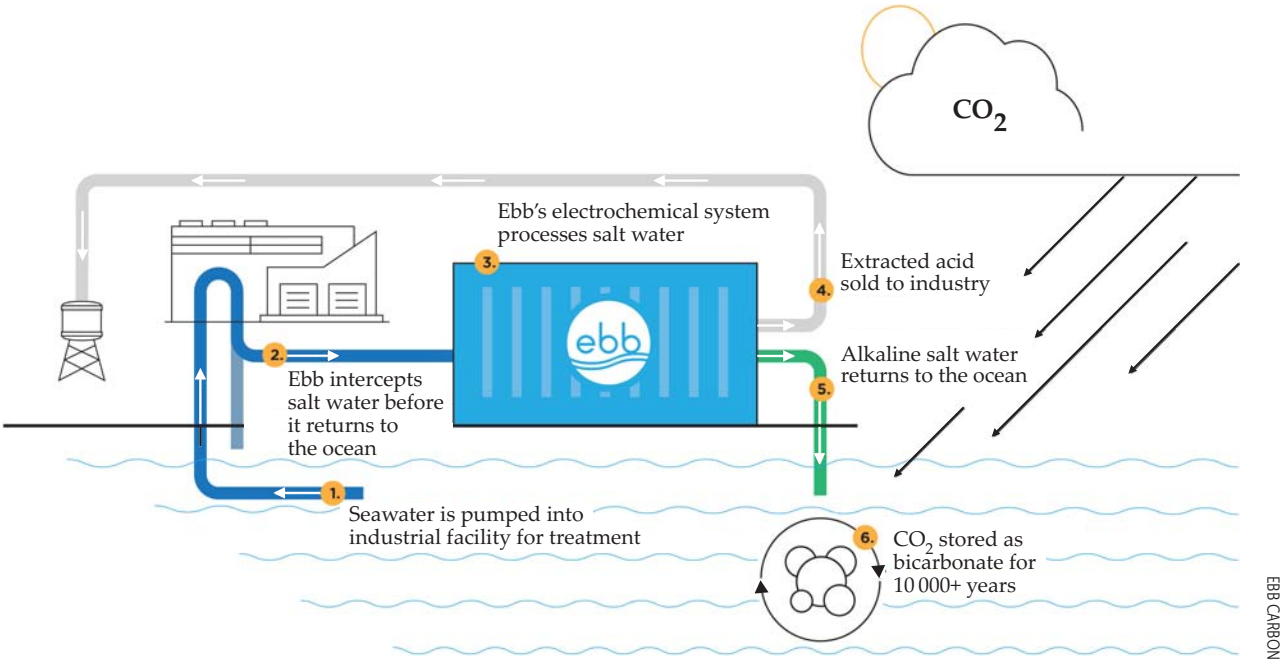
Lawmakers specified that in addition to extracting at least 1 million tons of CO_2 annually, each hub is to have a dedicated CO_2-transport infrastructure, subsurface storage resources, and other carbon-sequestration infrastructure. Wilcox notes there are methods to store CO_2 that don't require the energy expenditures needed to achieve the high-purity product that's appropriate for injection to geological formations. Exposing the captured gas to alkaline-rich rock or mine tailings or using it to stimulate algae growth could be accomplished at CO_2 concentrations of 15–30%, for example. She cites the Tamarack nickel mine in Minnesota, which the partners Rio Tinto and Talon Metals are developing to also permanently store hundreds of millions of tons of CO_2. In February, DOE awarded the project $2.2 million in R&D support.

Asbestos tailings scattered across the country are highly reactive to CO_2, Wilcox says. Gigatons of permanent storage could also be gained in the production of synthetic aggregates such as carbonate rock, which can replace the sand and gravel used in concrete.

"Not all roads lead to pipelines and storage deep underground, although we want to see those pathways move forward too," she says.

Wilcox says that DAC with storage is the only CDR method so far that can accurately and verifiably show how much CO_2 is permanently removed and stored. That means DAC companies are eligible to receive a tax credit that is based on the number of tons captured and utilized or put underground. No CDR company has yet removed and stored the minimum of 25 000 tons of CO_2 to qualify for the credit. But Oxy Low Carbon Ventures plans to open a DAC plant with an annual capacity of 1 million tons, based on technology from Canada's Carbon Engineering. Other CDR methods lack that same degree of verifiably accounting for the CO_2 they fix, the amount of energy expended in doing so, and the durability of storage.

Still, DOE offers support to other CDR options too. Through its "carbon-negative shot" launched last November, the agency invited all types of nascent technologies to apply for R&D funding and help in developing carbon-accounting tools. The initiative is looking to support gigaton-scale approaches that will capture and store CO_2 for less than $100 per ton, offer robust accounting of emissions over their full life cycle, and



EBB CARBON is eyeing desalination plants for its initial commercial carbon dioxide removal plants. It plans to open its first plant this summer at a pipeline located in the US that's used for research purposes.

provide verifiable storage for 100 years or more.

New funding models

Governments aren't the only source of funding for CDR. On 22 April, Elon Musk's $100 million XPrize competition for carbon removal announced its 15 "milestone" winners, each receiving $1 million. While most of the winning teams were US based, Europe, Kenya, the Philippines, and Australia also were represented. More significant, perhaps, were the number of participants the competition attracted. A field of 1133 teams was narrowed to 287 that met the eligibility criteria. Seventy expert reviewers then screened and ranked the proposals.

More than one-third of the 60 finalist teams proposed DAC solutions (see the chart on page 26). DAC captured six of the $1 million prizes. Biochar—biomass heated in the absence of oxygen to form a carbon-dense material to be spread onto soils—and other biomass solutions were advanced by five of the winners, while ocean-based capture took three and rock mineralization one.

The first-place XPrize winner and up to three runners-up will be selected in 2025 and will split $80 million. Prize officials say the milestone winners aren't necessarily favored in that competition.

Also in April, the payments company Stripe announced the formation of Frontier, an advance market commitment to buy $925 million of permanent carbon-removal services over the next eight years. The founding contributors are Alphabet, Shopify, Meta, McKinsey & Company, and Stripe customers who donate a small portion of their transaction costs to CDR contenders. Frontier's concept, first employed a decade ago to speed development of pneumococcal vaccines for low-income countries, is to provide a binding commitment to buy a product that doesn't yet exist once it becomes available. Instead of taking an equity stake in startups, Frontier will pay CDR companies by the tonnage of CO_2 they remove, guaranteeing revenues for those that are judged by reviewers to have viable technologies—regardless of their initial cost per ton removed.

"Frontier is focused on accelerating the scale of carbon-removal solutions that we think can be a meaningful part of the 5–10 billion tons of carbon removal the world needs by 2050," says Hannah Bebbington, head of strategy for Stripe Climate, a Frontier organizer. "[Advanced market commitments] can help create market certainty that entrepreneurs and investors can use to confidently build new technologies over a long period of time."

Frontier will select CDR technologies that can store carbon for greater than 1000 years, cost less than $100 per ton of CO_2 removed, offer a path to more than 500 million tons of CO_2 removal per year, have transparent monitoring and verification capabilities, and be safe and environmentally sound. Frontier also will look for CDR methods that don't require arable land.

Frontier members don't get a price or volume guarantee with their purchase. Instead, Frontier will facilitate purchases from emerging CDR technologies that meet its target criteria as volume becomes available. The goal is to support a wide portfolio of technologies at large scale by 2050.

Frontier estimates that fewer than 10 000 tons of carbon have been removed by DAC to date. "As this market grows, a whole carbon-removal economy will need to grow with it, including robust measurement, reporting, and verification infrastructure and a network of storage sites around the world," says Bebbington.

Another philanthropic CDR-support effort is expected to be announced soon by the First Movers Coalition, a public–private partnership between the US Departments of State, Commerce, and Energy; the World Economic Forum; and nearly three dozen international corporations. Those firms have already pledged to buy clean technologies in advance of a market for them in hard-to-abate industries such as steel, cement, air travel, and shipping. The Bill Gates–founded

Breakthrough Energy is collaborating with the coalition.

Varun Sivaram, senior director for clean energy and innovation in the office of John Kerry, the presidential climate envoy, said in mid-April that the coalition would announce a CDR-specific initiative and new members within weeks. "These companies are making a truly meaningful commitment by creating an early market that can help technologies scale and literally change the world," Sivaram said. "It's far more impactful than a company reducing their own emissions or buying offsets."

The Swedish company Milkywire has set up the Climate Transformation Fund, which invests in carbon-removal technologies. Its largest contributor is Klarna, a Stockholm-based financial technology firm, which has raised $2 million for the fund over the last two years through an internal tax on its carbon emissions. Robert Höglund, who manages the fund, credits XPrize in part for the rapid growth of nascent CDR technologies and startups. Still, fewer than 40 firms have yet produced sales—half of those employing biochar.

Question of durability

Höglund's fund has invested in two biochar companies: the Cambodia-based Husk, which produces the carbon-rich material from rice husks, and MashMakes, an Indian firm whose feedstock is crop residues. As with some other biomass CDR solutions such as reforestation, biochar provides less permanent storage than DAC. Höglund says available evidence shows a durability of more than 100 years, depending on such variables as soil acidity and temperature. But some biochar will oxidize in as little as 10 years, says Wilcox, who explored the technology in depth as a member of a National Academies of Sciences, Engineering, and Medicine review committee. "Is that carbon removal? Absolutely not. That won't impact climate in a positive way." Yet she acknowledges biochar's side benefits of improving the carbon content of soils and reducing the need for fertilizers.

The Milkywire fund has backed California-based Heirloom, a partner in one of the $1 million XPrize winning teams. The company hopes to soak up CO_2 with calcium carbonate, then heat the rock to release the concentrated gas for geological storage. The carbonate would then be chemically regenerated. As with other DAC processes, the heat and electricity required should come from renewable sources to produce negative emissions. Fossil-fuel-powered DAC could produce more CO_2 than it removes.

One of a handful of DAC firms to attract significant investment to date is Climeworks, the Swiss company that last year in Iceland opened the world's largest capture plant. Carbfix, its partner in the venture, injects the CO_2 underground. The plant's annual capacity is 4000 tons. In April, Climeworks reported it had raised $650 million in an equity funding round, which it described as the largest investment ever in a DAC company.

DOE in April awarded a combined $14 million to five teams for front-end engineering design studies of DAC that utilize carbon-free energy sources. AirCapture is a partner in two of those projects, both of which propose to adsorb CO_2 from air blown by fans across chemical contactors. The concentrated gas is then desorbed using low-temperature steam. A nuclear plant supplies the steam for one of the projects. A fertilizer plant is the heat source in the other.

AirCapture's refrigerator-sized machines can remove 100 tons per year, says CEO Matt Atwood. The plan for the other project is to use captured CO_2 from the fertilizer plant to produce formic acid, which is used industrially and can also be a hydrogen carrier or a precursor to synthetic fuels. The CO_2 produced with nuclear energy will be shipped offsite for geological storage.

Although plenty of potential geological storage is available in the US, and the US Geological Survey has produced detailed maps of the formations, the Environmental Protection Agency has approved just two wells for CO_2 injection nationwide. Beyond requiring assurances that the gas won't escape, regulators must consider the potential for induced seismicity from injection operations.

On 5 May, DOE acted to begin distributing the $2.5 billion that was included in the infrastructure act for expanding the nation's geological CO_2 storage capacity. The agency's notice of intent begins the process for distributing $2.25 billion over five years in cost-shared funding for an unspecified number of projects capable of storing at least 50 million tons of CO_2—equivalent to the annual emissions from roughly 10 million gasoline-powered cars. In addition, DOE issued two funding opportunities, totaling $91 million, to help increase the number of available CO_2 storage sites and to advance carbon-management technologies.

Atwood says his company hasn't decided whether to apply to participate in Frontier. "But it's very encouraging to see companies coming together and saying we need to get on the learning curve and that we're willing to pay a high price for CO_2 to help these companies scale and get their cost down."

Ben Tarbell, CEO of ocean-capture company Ebb Carbon, is also encouraged by the new funding models. "For a long time, most of the attention has been on compliance," based on the expectation of regulation, he says. "What's happened recently is a number of subnational entities, corporations, cities, and universities have stood up and said we're going to do what's right here and commit to neutrality and pay for the waste we're dumping."

Ebb Carbon's electrochemical process raises the alkalinity of the water it processes and returns to the sea, reducing the ocean acidification that has come with climate change. A by-product is hydrochloric acid, which is used in steelmaking, food and chemical processing, and other industries. Tarbell says the company's business plan doesn't depend on revenues from acid sales; he's counting on corporate and government carbon-emissions pledges instead.

Lennart Joos has reviewed ocean-capture proposals for Frontier. The organization, he says, will be backing "moonshot ideas that still have to manifest themselves" in a working plant. Joos tried unsuccessfully for several years to attract investors to his own ocean CDR technology. "Investors would all tell me that they want a pilot plant before they give you money," he says.

But Joos warns that the concentration of investments in a small number of successful CDR companies will be to the detriment of many other good CDR concepts. "Climeworks has now raised more than $800 million, and their capacity is 4000 tons a year. It's not too hard to make a joke out of that," he says. "Imagine how many smaller ideas you could fund with that amount of money."

David Kramer PT