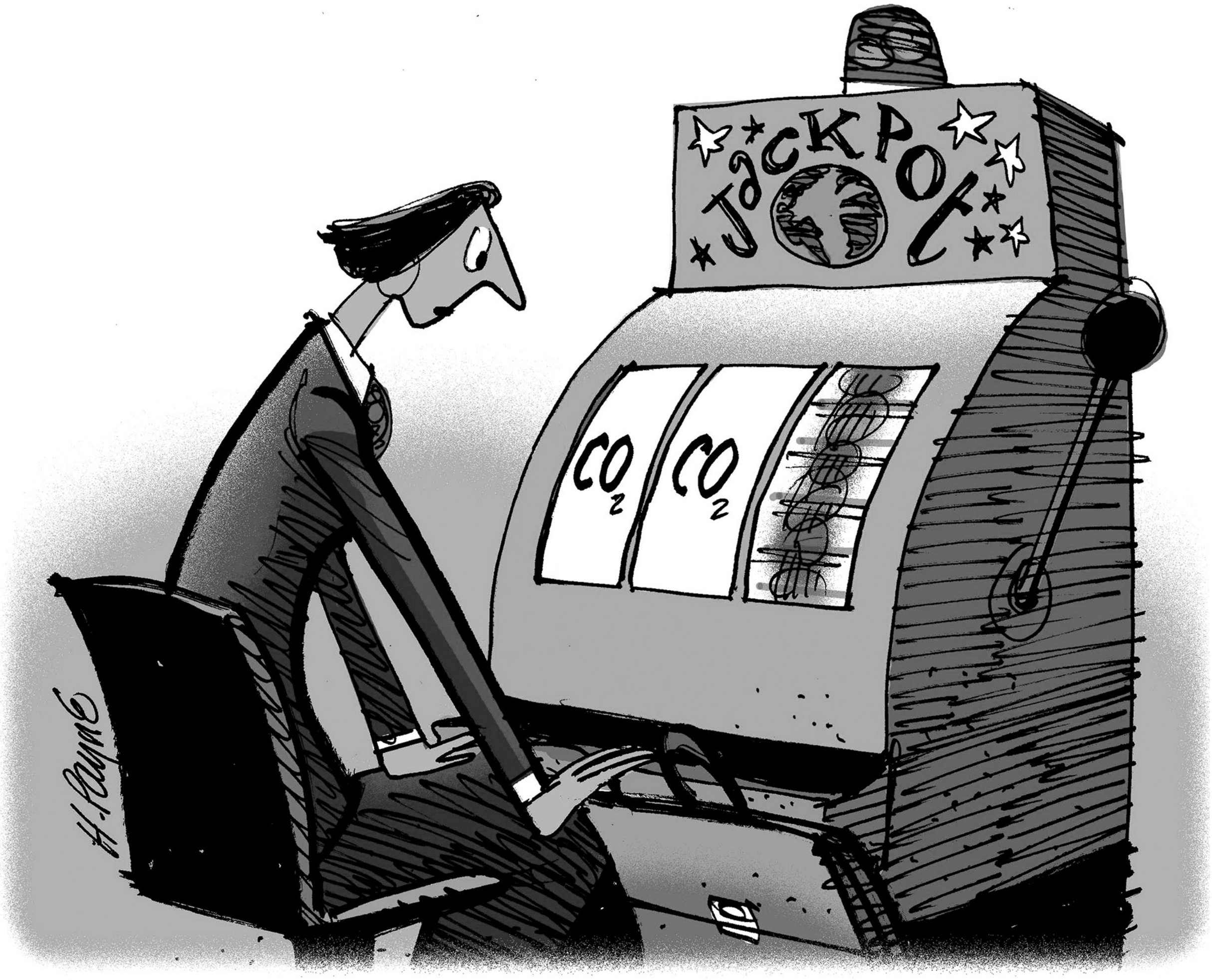

Don’t Bet on Carbon Removal

“Net zero” emissions depends on a dangerous myth. Proposals now center on three prominent strategies for CO_2 removal—tree planting, bioenergy with carbon capture and storage, and direct air capture—but they are not scalable, and could make things worse

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AT the annual climate meeting in 2015, the world's nations unanimously agreed to reduce greenhouse gas emissions to a level that would avoid dangerous climate impacts. The resulting Paris Agreement required "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C." In 2018, the Intergovernmental Panel on Climate Change stated, "Limiting global mean temperature increase at any level requires global CO_2 emissions to become net-zero at some point in the future." Net-zero means that whatever emissions can't be abated must be offset by *carbon dioxide removal.* Theoretically, if a great deal of CDR were available, net-zero means we wouldn't have to work so hard to reduce greenhouse gas emissions.

Limiting warming to "well below 2°C" requires slashing emissions now and approaching global net-zero by mid-century. But what does that mean in terms of the role of CDR compared to ceasing to burn fossil fuels? A 2022 report on mitigation by the IPCC examined the scientific literature and concluded, "CDR options in pathways are mostly limited to" three strategies. One is *afforestation*—planting trees—which in theory has been underway since the 1992 Earth Summit's adoption of forest principles. Another is *bioenergy with carbon capture and storage,* BECCS, whereby growing biomass removes CO_2 from the air, and a power plant burns the plants and permanently buries the carbon dioxide. Finally, *direct air carbon capture and storage*—known as DACCS or sometimes simply DAC—involves pulling CO_2 directly out of the air and sequestering it underground, The last two both involve *carbon capture and storage*, or CCS.

Yet even though many computer models include substantial amounts of CDR from these three approaches, none appears to be particularly scalable in the real world, and the last two would make things worse. In a November 2023 white paper on bioenergy, I reviewed the recent literature and presented new results from a global model designed by Climate Interactive to examine major proposed solutions using real-world data and scenarios.

Although planting trees sounds sustainable and nature-friendly, that report and other recent research have made clear that afforestation is not a scalable solution. In part, that's because we must plant a staggering number of trees over vast tracts of land to make a difference, as the CI global model revealed. And in part, the world doesn't have anywhere near that much land to devote to tree planting today—let alone in 2050, when increased population will require more space. A 2023 article I wrote with CI's executive director, Andrew Jones, showed that their model "found that planting 1 trillion trees, under optimistic conditions, would remove only 6 percent of the needed CO_2 reduction" by 2050 to limit total warming to 1.5°C. "And that would require a wildly unrealistic amount of land, over 2 billion acres, which is to say over 2 billion football fields—greater than the total land area of the contiguous United States."

And if bioenergy is aggressively pursued, that would be another 800 million acres or more for tree planting to feed facilities' energy needs. BECCS, in actuality, is not carbon removal but is much more like deforestation. Additionally, the modeling showed why policies to scale up plain bioenergy lacking CCS and even BECCS would increase global warming for several decades, with net cooling not occurring until 2100 or beyond. It also showed that scaling up BECCS to 2 to 3 billion tons of CO_2 per year would require a land area the size of India. Finally, the model showed that the best bioenergy strategy right now would be to forego BECCS and let existing biomass facilities, which lack carbon capture, retire without replacement rather than putting CCS systems on them.

Thus, the first question to ask anyone advocating massive afforestation or sharply scaling up bioenergy is, Where will the trees be planted? Not on good cropland. Several models project we need over 1 billion new acres of agricultural land to feed the world in 2050. Also, "It would be a mistake to plant trees in natural grassland and savanna ecosystems," explained César Terrer, lead author of a 2021 *Nature* study. "Our results suggest these grassy ecosystems with very few trees are also important for storing carbon in soil." But we also shouldn't plant them in wildfire-prone areas, which are expanding due to climate change. And we shouldn't plant trees in permanently snow-covered northern areas. The dark forests would absorb more heat than the white snow, and so would "have a warming effect that exceeds the cooling effect of reducing GHGs," as the National Academy of Sciences explained in 2019. Finally, most of the supposedly "empty" land targeted for tree planting is actually claimed and used by Indigenous peoples and local communities.

Simply seizing it to plant trees would worsen centuries of injustice.

SO, if we are going to scale up any CDR effort, it can't realistically rely on tree planting or vast amounts of land—and that leaves one prominent contender right now, direct air carbon capture and storage, which is far less land-intensive. But DACCS has many other problems. David Keith, the founder of one of the first big companies to enter this industry, Carbon Engineering, told me in 2022, "There is so much overhype around air capture. The public discussion is disconnected from reality." He added, "We should focus on cutting emissions." Ultimately, most of those problems go back to the core flaw with DAC—it is incredibly inefficient. A 2022 European Academies' Science Advisory Council review noted, "up to 20 times as much energy is required to remove a tonne of CO_2 from the atmosphere than to prevent that tonne entering in the first place." And that's before the additional energy costs of storing the carbon permanently.

DACCS systems generally use enormous fans to push large volumes of air over a liquid solvent or solid sorbent that extracts CO_2. Then, a large amount of energy is needed to release these molecules and regenerate the absorbent chemicals. Because CO_2 in the air is so diluted, the Houston Astrodome contains only about one ton. Put another way, atmospheric carbon dioxide is 300 times more diffuse than the CO_2 in a coal plant's flue gas. Thus, the overall efficiency of this process is understandably very low, 5 to 10 percent, the National Academy of Sciences reports, and the price is accordingly very high.

All of the CO_2 captured by traditional CCS on coal and gas power plants—plus that captured from bioenergy and direct air capture—has to be stored somewhere permanently. The scale of this challenge is enormous

One implication of this inefficiency is that DACCS "energy needs appear to be 6x-10x higher than traditional [power plant] CCS energy estimates, a process which itself is stuck in neutral," noted JP Morgan in 2021. This sums up a significant challenge faced by DACCS and BECCS as well. Traditional carbon capture systems recover CO_2 from industrial facilities—particularly power plants—and sequester it. They use much less energy and cost far less than DACCS, yet for the past two decades, even flue-gas CCS, with its relatively concentrated stream, has been stuck in neutral because it is an inherently inefficient process for limiting emissions compared to replacing fossil fuels with renewable energy sources.

All of the CO_2 captured by traditional CCS on coal and gas power plants—plus the CO_2 captured from BECCS and DACCS—has to be stored somewhere permanently. The scale of this challenge is enormous. Annual global greenhouse gas emissions have soared to 50 billion tons of CO_2 equivalent. Sequestering just 3 billion tons per year works out to 8 million tons per day. Permanently storing it would mean capturing, transporting, and storing a volume of compressed CO_2 greater than the more than 90 million barrels of petroleum a day extracted by the global oil industry, the infrastructure of which took a century to develop. As one expert said, "Needless to say, such a technical feat could not be accomplished within a single generation."

"Capturing CO_2 from the air is the most expensive application of carbon capture," explained the International Energy Agency in a 2022 report. Per ton of CO_2 captured and stored, current DACCS costs range from several hundred dollars to one thousand dollars per ton or more. A 2018 assessment of DACCS concluded, "CO_2 separation from air is unable to economically compete with CCS" from coal plants. So, if coal CCS ever proves to be commercially scalable, it makes much more sense to put such systems on existing coal or gas facilities than on DAC systems.

At a June 2023 DACCS summit hosted by industry leader Climeworks, co-CEO Jan Wurzbacher "told the crowd his company could see its prices remain as high as $300 by 2050." A 2021 paper soliciting the judgment of 18 experts projected "removal costs to decline significantly over time but to remain expensive." They projected that median prices at mid-century will be around $200 per ton of CO_2 removed.

In a 2022 analysis, CCS expert Howard Herzog assessed future estimates for DACCS. He is skeptical that the price in 2030 will be below $600 per net ton of CO_2 removed. He explains that most studies

Continued on page 42

Math for Carbon Removal Doesn't Add Up

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"Capturing even 10 percent of a single year's worldwide emissions would require 8,000 kilometers of high walls of fans, sufficient to stretch a third of the way around the equator"

Removing carbon dioxide from the air is like trying to capture billions and billions of tiny invisible flying horses after you've opened the stable door and let them fly free. The metaphor is apt and suggests an alternative—lower emissions in the first place.

In the past 15 years I've assessed most methods of direct air capture, the leading contender for carbon removal, and spoken to many of the engineers and scientists researching and building them. This is a technology that cannot scale to the required level. It is not a solution to keep us below 2°C of global heating, as the Paris Agreement mandates.

There are some applications where removing carbon dioxide directly from the effluent stream of very-high-concentration point sources might be cost competitive with alternative means of limiting emissions. Limestone kilns at cement plants are the obvious example. But there are no means of direct air capture from the atmosphere that are cost competitive, on a per-ton basis, with lowering emissions by giving up fossil fuels and electrifying the global economy.

Let's examine the scale of the problem. There is about 3 trillion tons of carbon dioxide in the Earth's atmosphere. (For comparison, the entirety of the Grand Canyon only has about 1,270 tons in the air it contains.) About a third of the atmospheric CO_2 has come since the start of the industrial revolution. We are adding around 40 billion tons more every year. Those molecules are spread relatively evenly through the atmosphere.

Given these figures, and the high temperatures required to release the carbon dioxide from whatever removes it, direct air capture is prohibitively expensive. To remove just 1 million tons, a solution proposed by Carbon Engineering would require a 2 kilometer row of fans 20 meters high operating every hour of every day for a year. And you would need 40,000 more such installations to capture humanity's annual addition. The energy required to move all of the air is remarkable, too, and that energy has to come from renewables for direct air capture to make sense.

Every solution to remove carbon dioxide requires that air be pushed through a liquid to absorb it or a solid nano-sponge device that captures the molecules. But getting the CO_2 out to sequester it then requires heat, and a lot of it.

Global Thermostat's solution uses Corning sorbents and requires hot steam to release the carbon dioxide. Carbon Engineering's proposal pushes air through dripping liquid with a solution of carbonate ions, hydroxide, and potassium ions, then turns the carbon ions into calcium carbonate. But this process too requires huge amounts of heat to then remove and sequester the carbon, energy that has to come from somewhere.

Remember the scale of the problem. A million tons of carbon dioxide is only 0.0025 percent of a single year's global emissions. It's only 0.0001 percent of the excess CO_2 in the atmosphere. Capturing even 10 percent of a single year's worldwide emissions would require 8,000 kilometers of high walls of fans, sufficient to stretch a third of the way around the equator. Every direct air capture solution runs into this fundamental barrier of scale.

It is much less expensive to keep the stable door closed on those tiny, invisible winged horses than to try to herd them back in. Accelerating energy from wind, water, and solar, plus storage and transmission, is not only a much cheaper way to eliminate net tons of carbon dioxide, but it actually delivers something of real value, electricity that can power our vehicles, heat our homes, and run our data centers.

And for the long, slow carbon drawdown from the atmosphere we do need to do in addition to eliminating fossil fuels, nature-based solutions, including planting trees, rewilding grasslands, restoring wetlands, and shifting to low-carbon tillage agriculture are much more scalable, much more quickly. Even so, they will take most of the century to have a meaningful effect.

report the costs as dollars per *gross* ton of CO_2 removed, whereas, in the real world, you must subtract out the CO_2 emissions created by the energy used to build and power the DACCS system—and subtract the CO_2 emitted to compress, transport, and store the gas. According to Herzog, it is far from clear that most DACCS systems will be run solely on zero-carbon power, such as nuclear or renewables, by 2030. His conclusions: "The assessment suggests that the low range of cost estimates in the literature," which range from $100-300 per ton of CO_2 removed, "will not be reached anytime soon, if at all."

A 2019 analysis of advanced fossil fuel plants in the *International Journal of Greenhouse Gas Control* concluded, "Experience teaches us that cost estimates for early-stage technologies tend to be optimistic and poorly predict the actual cost of those technologies that reach commercialization." Some expect DACCS to decline in price rapidly as more plants are built, economies of scale are achieved, and people gain experience operating the plants. But not all complex energy systems do that: The price of new nuclear power has risen in the past two decades.

The authors of a 2020 study in the journal *Joule* found they could "explain systematic differences in technologies' experience rates by distinguishing between technologies on the basis of (1) their design complexity and (2) the extent to which they need to be customized." The more complicated the system designs and the more they need to be adapted and customized to their specific use environments, the slower the rate that costs declined as sales volume increased. Solar cells are both technologically simple and easy to standardize. That's a key reason prices have been dropping sharply for so long. But like nuclear power, a DACCS system running on renewables has both high system complexity and high customization for each deployment.

Like nuclear power, a direct air capture system running on renewables has both high system complexity and high customization for each deployment

DACCS systems also have major siting challenges. As noted, they must be powered almost entirely by zero-carbon power to make environmental and economic sense. So, these systems must be sited in places with abundant access to carbon-free power, like solar and wind plants, which vary in output depending on weather and other factors and likely need energy storage to run DACCS. A 2023 analysis in the journal *One Earth* found, "Pairing [DACCS] to intermittent renewables is expensive." Indeed, it is especially challenging because the inefficiency of DACCS means it requires vast amounts of renewable energy just to achieve a relatively modest amount of CO_2 capture and storage. A 2020 review of CCS and DACCS in *Biophysical Economics and Sustainability* reported that "according to one estimate, renewables-powered DAC would require all of the wind and solar energy generated in the U.S. in 2018 to capture just 1/10th of a [billion tons] of CO_2."

At the same time, DACCS systems probably need to be sited near permanent geological storage. Otherwise, a long, expensive CO_2 pipeline system would have to be built. JP Morgan noted, "Just to sequester an amount equal to 15 percent of current U.S. GHG emissions would require infrastructure whose throughput volume would be higher than the volume of oil flowing through U.S. distribution and refining pipelines, a system which has taken over 100 years to build."

The current climate is uniquely unwelcoming for new pipelines due in large part to public concern. In the face of organized opposition, major pipelines like the Keystone XL oil pipeline have been delayed, driving up costs, or canceled outright. In 2020, the Atlantic Coast natural gas pipeline was canceled "after environmental lawsuits and delays had increased the estimated price tag of the project to $8 billion from $5 billion," the *New York Times* reported in a 2020 article headlined "Is This the End of New Pipelines?" And those battles have already spread to CO_2 pipelines, as the *Wall Street Journal* detailed in a 2023 article titled, "A New Nimbyism Blocks Carbon Pipelines." In October 2023, the developer of 1,300 miles of CO_2 pipelines scrapped the project because of the permitting challenge in some of the states it had to cross. This is why DACCS systems need to be sited as close to the storage as possible, with both pipeline and storage sites far away from population centers.

Continued on page 44

SIDEBAR

Climate Battle Requires Carbon Removal

Antti Vihavainen
Chief Executive Officer
Puro.earth

"Scaling carbon dioxide removal will not only impact the climate crisis but will also contribute to the required transformation to a prosperous, more sustainable world economy, including in the Global South"

Reducing carbon dioxide emissions is an unavoidable must, but to mitigate the worst impacts of climate change and reach the Paris Agreement goals, we also need to remove as much CO_2 from the atmosphere as possible, without delay. The Intergovernmental Panel on Climate Change has said the deployment of carbon dioxide removal is necessary if net-zero emissions are to be achieved. At this pivotal juncture for the planet, scaling long-term and durable CDR through voluntary corporate action needs renewed emphasis.

Besides bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS), which lock up carbon in geological formations, durable carbon removal includes varied and innovative solutions that sequester carbon for hundreds, and even thousands of years. Some of these methods are CO_2 incorporated into building materials, biochar produced from waste biomass, and enhanced rock weathering. Due to its technological characteristics, (compared to nature-based removal) in these methods it is possible to accurately quantify the amount and permanence of carbon dioxide physically removed from the atmosphere.

Scientists estimate that 5 to 10 billion tons of CO_2 will need to be removed annually from the atmosphere by 2050 to meet the Paris goals, depending on our success at reducing emissions, and CDR processes not only can help but will provide added environmental and economic benefits. The scaling challenge, however, amounts to trillions of dollars of investment capital needed to deploy and grow these durable carbon removal technologies.

How do we reach sufficient growth to reach this number? First, since there is no silver bullet to solving the climate crisis, we need to make many different kinds of investments, both for scaling renewable energy sources and defossilization of industries as well as innovation and deployment of carbon removal processes. It is not the same investors in these varied endeavors and thus it is not a zero-sum game between these different approaches.

Currently, the best tool we have is voluntary climate finance through carbon credits. Neutralizing residual emissions with removal credits provides a critical mechanism to direct financial flows toward credible climate change mitigation. We need to tackle the issues to get climate finance into the right hands, because scaling CDR will not only impact the climate crisis but will also contribute to the required transformation to a prosperous, more sustainable world economy, including in the Global South.

Significant progress is already being made to address the scaling challenge. We have just issued the largest quantity of CDR ever in the voluntary carbon market: 157,000 CO_2 Removal Certificates (CORCs), which came from a BECCS project called Red Trail Energy in North Dakota. This major milestone shows the scale being achieved in the supply side of the market at the moment. We will be issuing credits from three further processes for the first time this year. The ball is well and truly rolling in scaling up supply to meet the 10 billion ton annual removal goal.

On the demand side, the past year has seen the likes of Microsoft agree to purchase up to 315,000 metric tons of CO_2 removal via a carbon capture startup called Heirloom, and JP Morgan Chase agreed to invest more than $200 million in carbon removal companies. The Puro Registry, which lists all CORCs that have been retired, has recorded over 160,000 such certificates in the last three years.

But make no mistake, we need more investment and many more retirements of this scale if we are to reach the Paris goals. Scaling carbon removal will not only mitigate the worst impacts of the climate crisis but also will contribute to building an ultimately carbon net-negative economy globally. So now more than ever corporations need to get behind the voluntary carbon markets and scale durable CDR technology before it's too late.

At the same time, DACCS plants will very likely have to be close to prime land for building huge solar and wind farms to power them. But that means they will directly compete with projects that want to use that prime land to build renewables for directly replacing fossil fuels. This raises a crucial question when looking at DACCS: Under what circumstances would DACCS be a good use of carbon-free power? There is an opportunity cost to using vast amounts of renewables (or nuclear power or new natural gas with CCS) in an expensive and inefficient effort to pull CO_2 out of the air.

DETERMINING the best use of carbon-free power would require a comprehensive lifecycle analysis comparing the use of such power in a DACCS system with the use of such power to directly replace the emissions of existing fossil fuel plants or to power electric vehicles and thus replace gasoline. Yet the 2020 review article in *Biophysical Economics and Sustainability* that examined more than 200 studies, reports, and literature reviews on CO_2 removal and storage "found no analyses of a full-scale, renewables-powered DAC process based on a full life cycle and including embodied emissions and emissions from chemicals (e.g., sorbent) manufacture." As the authors point out, "yet, the major, but generally ignored, policy issue about subsidizing renewables-powered DAC is whether renewable energy should be channeled for carbon removal rather than used directly to reduce carbon emissions by powering homes, industry, businesses, and transport."

There is an opportunity cost to using vast amounts of renewables (or nuclear power or new natural gas with CCS) in an expensive and inefficient effort to pull CO_2 out of the air

For a 2019 report, the National Academy of Sciences "held a series of public workshops and meetings to inform its deliberations." Its report notes, "The committee repeatedly encountered the view that NETs [negative emissions technologies] will primarily be deployed to reduce atmospheric CO_2 after fossil emissions are reduced to near zero." A 2021 *Frontiers in Climate* study of DAC systems found, "Only when the region's electricity system is nearly completely decarbonized do the opportunity costs of dedicating a low-carbon electricity source to DAC disappear."

Further, a 2021 analysis published by the American Institute of Chemical Engineers found that using renewables to power electric vehicles is far more cost-effective at reducing CO_2 than using them to power DAC. The analysis concluded that displacing gasoline-powered vehicles with EVs powered by renewables reduces more CO_2 than the same renewables used to power DAC. The analysis notes electric vehicles have "significant advantages over DAC," including "the capital cost of DAC plants will be significant, while the cost of an EV is basically the difference in cost between an EV" and an internal combustion engine vehicle. So, EVs will have a far lower cost per ton of CO_2 reduced than DACCS systems. Also, by the time DACCS might seriously start scaling up, it is likely that EV costs will be equal to, if not lower than, gasoline-powered cars, especially on a lifecycle basis. Just as electrifying transportation and charging electric vehicles is a much more cost-effective way to use renewables to directly reduce CO_2 emissions than using them to power DAC, electrifying heat for buildings and industrial processes will inevitably also be much more cost-effective than natural gas. That's because new heat pumps are highly efficient and pay for themselves with energy savings.

The bottom line is that right now, for every ton of CO_2 removed by a DACCS system, we effectively raise ambient CO_2 levels by 10 to 20 tons since that's how much emissions we could have reduced if we had not misallocated the renewable energy along with all of the money and effort needed for DACCS. As Glen Peters, research director for the Climate Mitigation group at Norway's leading climate research center, wrote in August 2023, "If we are just reducing emissions a little bit, then CDR must be the most irrational mitigation option around."

In addition, besides consuming a great deal of energy, DACCS systems use a great deal of materials, and liquid DACCS systems use lots of water.

A 2020 *Nature Climate Change* article concluded that the energy and water usage of DACCS "could result in staple food crop prices rising" sharply "in many parts of the Global South, raising equity concerns" about deploying negative emissions technologies.

Significantly, the United States (and many other countries) will be spending billions of dollars on DACCS over the next decade. The 2022 Inflation Reduction Act has a tax credit for DACCS for projects that start construction before 2033—$130 a ton if the CO_2 is utilized beneficially or stored in oil and gas fields and $180 if the CO_2 is stored in geologic formations. To date, most captured CO_2 has been used to squeeze more oil out of the ground, a dubious way at best to address the climate problem. As Internal Revenue Service guidance explains, these tax credits are per metric ton of "qualified" CO_2, where qualified means "based upon an analysis of lifecycle greenhouse gas emissions." So, these are not the "*gross* tons" of CO_2 pulled out of the air but rather "*net* tons," which are the gross tons minus "the full fuel lifecycle" emissions of the DACCS system. It will be very important for the federal government to ensure that any lifecycle analysis is comprehensive so that only net tons are subsidized.

"Relying on untested carbon dioxide removal mechanisms to achieve the Paris targets when we have the technologies to transition away from fossil fuels today is plain wrong and foolhardy," said Robert Watson, former Intergovernmental Panel on Climate Change chair, in a 2021 article, "Climate scientists: concept of net-zero is a dangerous trap."

How big a role could DACCS play in addressing climate change, dealing with the 50 billion tons of greenhouse gases humans emit yearly? In its September 2023 Net Zero Emissions by 2050 Scenario, the International Energy Agency has less than 0.7 billion tons per year of DACCS removal by midcentury. The Intergovernmental Panel on Climate Change envisions substantially less DACCS than that in its 2022 mitigation report. A 2019 analysis in *Nature Communications* explains, "The risk of assuming that DACCS can be deployed at scale, and finding it to be subsequently unavailable, leads to a global temperature overshoot of up to 0.8 °C." At the same time, unfortunately, scaling tree planting faces major challenges too, and scaling biomass BECCS is impractical and would additionally speed up warming. Also, there isn't enough land for either of them—let alone both at the same time—if the goal is to make a serious dent in those 50 billion annual tons of GHGs. If we don't "drastically reduce emissions first," then CDR "will be next to useless," argues David Ho in an April 2023 *Nature* article. He concludes, "We must be prepared for CDR to be a failure."

Ultimately, either we deploy carbon-free energy in every sector at an unprecedented scale and speed, or the Paris Agreement targets will be overshot irreversibly on a century timescale

SO, planning on substantial CDR to save the climate would be unwise and dangerous. It won't achieve the goals of the 2015 Paris Agreement. And the idea we can "overshoot" a temperature target by midcentury and then turn global emissions massively negative to cool back down in a timeframe that would matter is also magical thinking. But because CDR will very likely be a bit player for decades, the idea of net-zero is really a "dangerous trap," as Robert Watson and his co-authors argued in their 2021 article. "In private, scientists express significant skepticism about the Paris Agreement, BECCS, offsetting, geoengineering, and net-zero."

Finally, the policies and actions, including land use changes and forestry emissions, of the top 10 GHG-emitting countries—China, the United States, India, Russia, Indonesia, Brazil, Japan, Iran, Canada, and Saudi Arabia—are all insufficient to keep warming below 2°C. Ultimately, either we deploy carbon-free energy in every sector at an unprecedented scale and speed, or the Paris targets will be overshot irreversibly on a century timescale. The good news is the world does have the technological capability and investment dollars to do the former and meet the Paris Agreement targets, so that is where we should focus our energy and resources.