Why direct air carbon capture and storage (DACCS) is not scalable and 'net zero' is a dangerous myth

Joseph Romm, Ph.D.
Rommj@sas.upenn.edu

EXECUTIVE SUMMARY

As global emissions have soared to 50 billion tons (Gt) of CO_2 equivalent, carbon dioxide removal (CDR) strategies have generated great interest. The three most widely analyzed and modeled are direct air carbon capture and storage (DACCS), which pulls CO_2 directly out of the air and stores it underground; planting trees; and bioenergy with carbon capture and storage, whereby growing biomass removes CO_2 from the air and a CCS system on the bioenergy plant could permanently bury it.

In theory, by combining deep emissions cuts (achieved by substituting carbon-free energy for fossil fuels) with a scaled-up CDR effort, we could bring total emissions down to "net zero." But as other white papers in this series have explained, **scaling tree planting faces major challenges, and scaling BECCS is impractical and would speed up global warming this century**.

This paper focuses on DACCS and the growing body of research casting doubt on its scalability. If we don't "drastically reduce emissions first," CDR "will be next to useless," argues a 2023 *Nature* article. **"We must be prepared for CDR to be a failure."** In its 2023 *Net Zero Emissions by 2050 Scenario*, the International Energy Agency has under 0.7 Gt CO_2 /year of DACCS removal by mid-century. The Intergovernmental Panel on Climate Change envisions far less DACCS than that in its 2900-page mitigation report from 2022. And that report notes we still haven't proven CCS by itself is scalable: "**Implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers**."

DACCS systems generally use enormous fans to push large volumes of air over either a liquid solvent or solid sorbent that absorbs CO_2. Then a large amount of energy is needed to release the CO_2 and regenerate the sorbents. The overall efficiency of this process is very low (5% to 10%) and the price very high because CO_2 in the air is so diluted—it's 300 times more diffuse than the CO_2 in a coal plant's flue gas, and the entire Houston Astrodome contains only about 1 ton of CO_2.

"**Capturing CO_2 from the air is the most expensive application of carbon capture**," explained the International Energy Agency in its 2022 DAC report. Per ton of CO_2 captured and stored, current DACCS costs range from several hundreds of dollars to $1000 or more. A 2018 "techno-economic assessment" of DAC concluded, "CO_2 **separation from air is unable to economically**

compete with CCS." So, if CCS does ever prove to be commercially scalable, it makes much more sense to put such systems on existing coal or gas plants than on DAC systems.

At a June 2023 Direct Air Capture Summit hosted by industry leader Climeworks, the company's co-CEO Jan Wurzbacher "told the crowd his company could see its prices remain as high as $300 by 2050." In 2021, Microsoft found that "at more than 50 times the cost per metric ton of most natural climate solutions, long-term solutions [like DACCS] today are both limited in availability and practically cost prohibitive." **Two experts noted in 2022, "Even if we succeed in reducing the cost of permanent carbon removal to $100 a ton, which would be a major technical achievement, it would cost around $22 trillion to reverse warming by one-tenth of one degree Celsius."** But recent studies suggest it will be very difficult to get prices anywhere near that low.

These prices for carbon removal assume DACCS is powered entirely by carbon-free power such as solar and wind. Yet a 2023 analysis found that "**Coupling DACS to intermittent renewables is typically not favorable for low costs**." And powering DACCS system by natural gas, "increases costs for the negative emissions by 250%, making it impractical," a 2022 book chapter on DAC explains.

DAC is an expensive and inefficient way to use vast amounts of renewables (or nuclear power). That carbon-free power could have been used to directly replace the CO_2 emissions from fossil fuel plants and cars cheaply and efficiently. A 2021 analysis of DACCS explained, "**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 finds using renewables to power electric vehicles is far more cost-effective at reducing CO_2 than using them to power DAC.**

A 2019 study concluded "DACC is unfortunately an energetically and financially costly distraction in effective mitigation of climate changes at a meaningful scale." DACCS requires a lot of energy. For instance, a 2020 review of lifecycle analyses of CCS and DACCS reported that "**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 Gt of CO_2**." A 2020 *Nature Climate Change* article raised concerns that DAC "could exacerbate demand for energy and water," and that this "could result in staple food crop prices rising" sharply "in many parts of the Global South, raising equity concerns."

A 2019 analysis noted, "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 [1.4°F].**" The affordability, scalability, and wisdom of running DACCS on carbon–free power are likely to remain problematic for decades. Yet, tree planting also has limited scalability, and scaling up BECCS increases

CO_2 in the air for several decades. **Other CDR strategies are being proposed but whether the CO_2 removed is permanent, quantifiable, monitorable, and scalable has not been demonstrated**.

So, we must not plan on substantial CDR saving the climate. But since CDR will very likely be a bit player for decades, "net zero" is a dangerous myth. And **the idea we can overshoot a temperature target by mid-century and then turn global emissions massively negative to quickly cool back down is magical thinking.** So, while we do have the technological capability to meet the Paris climate targets, the policies and actions of virtually every major emitting country as of now are insufficient to keep warming below 2°C. So, the choice is clear: Either we rapidly deploy carbon–free energy in every sector or the Paris targets will be overshot irreversibly on a century timescale.

THE CDR SCALABILITY CHALLENGE

In Paris in 2015, the world's nations unanimously agreed to reduce greenhouse gas emissions to a level that would avoid dangerous climate impacts. That required "holding the increase in the global average temperature to well below 2°C [3.6°F] above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C [2.7°F]"—a goal that was reaffirmed in Glasgow in 2021.

In a 2018 *Special Report*, the Intergovernmental Panel on Climate Change (IPCC) stated, "**Limiting global mean temperature increase at any level requires global CO_2 emissions to become net zero at some point in the future**."[1] Net zero means that whatever emissions can't be mitigated must be offset by carbon dioxide removals (CDR). To limit warming to 1.5°C requires global net zero by 2050. The IPCC's 2022 mitigation report looked at a great many emissions pathways in the scientific literature and concluded, "**CDR options in pathways are mostly limited to BECCS, afforestation and direct air CO_2 capture and storage (DACCS)**."[2]

Yet even though many models include substantial amounts of CDR from these three approaches, none of them appears to be particularly scalable in the real world. In a November 2023 White Paper, "Why scaling bioenergy and bioenergy with carbon capture and storage (BECCS) is impractical and would speed up global warming," I review the recent literature and present new results from Climate Interactive's En-ROADS model to explain why "Policies to scale up bioenergy and BECCS would *increase* global warming for several decades, with net cooling not occurring until 2100 or beyond."[3] Other findings include "**Scaling up BECCS to 2 to 3 Gt CO_2/yr would require a land area the size of India" (which is 800 million acres), and "The best bioenergy strategy right now would be to let bioenergy plants retire without replacement, rather than putting CCS systems on them**." **Since**

biomass power increasingly relies on harvesting trees, scaling up BECCS is not carbon removal and is much more like deforestation.

That report, and a June one on carbon offsets,[4] as well as other publications,[5] make clear that afforestation is also not scalable. In part, that's because we must plant a staggering number of trees over huge tracts of land to make a difference as En-ROADS modeling has revealed. And in part the world simply doesn't have anywhere near that much land to devote to tree planting today—let alone in 2050—for afforestation, let alone afforestation plus BECCS.

As an August piece I wrote with Climate Interactive Executive Director Andrew Jones explained, En-ROADS "found that planting 1 trillion trees, under optimistic conditions, would remove only 6% of the needed CO_2 reduction [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**."[6] And if BECCS is aggressively pursued that would be another 800 million acres or more.

The first question to ask anyone advocating massive tree planting or BECCS is where will the trees be planted? Not on good cropland. Several models project we need over a billion new acres of agricultural land to feed the world in 2050.[7] 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.[8] "Our results suggest these grassy ecosystems with very few trees are also important for storing carbon in soil." But we 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 did and so would "have a warming effect that exceeds the cooling effect of reducing GHGs," as the National Academy of Sciences explained in 2019.[9] Finally, **most of the supposedly empty, unclaimed land targeted for tree planting is actually claimed and used by indigenous peoples and local communities. Simply seizing it to plant trees would perpetuate 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 is a potential advantage of DACCS, which is far less land intensive.

An introduction to the two main types of DACCS systems—those that use a liquid sorbent and those that use a solid sorbent—can be found in the Appendix.

LESSONS FROM CARBON CAPTURE AND STORAGE (CCS)

"**DACC energy needs appear to be 6x-10x higher than traditional CCS energy estimates, a process which itself is stuck in neutral**," noted JP Morgan in its *2021 Annual Energy Paper*.[10] This sums up one of the challenges DACCS faces. Regular systems recover CO_2 from industrial facilities—particularly power plants—and sequester it. They use much less energy and cost much less than DACCS, yet for the past two decades CCS has been "stuck in neutral."

So, a central question for DACCS is whether CCS is by itself going to be commercially practical and scalable by 2050. "Implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers," concludes the IPCC's 2022 mitigation report *Summary for Policymakers*.[11] This finding was signed off on by all the nations of the world.

The scale of the CCS challenge is enormous. Sequestering just 3 billion tons of carbon dioxide ($GtCO_2$) a year would mean capturing, transporting, and storing a volume of compressed CO_2 greater than the more than 90 million barrels of oil a day extracted by the global oil industry, which took a century to develop. As one expert put it, "Needless to say, such a technical feat could not be accomplished within a single generation."[12]

WHAT DOES DACCS COST?

DACCS is at a much earlier stage than CCS—pilot plants and prototype demonstration. The 18 existing DACCS systems capture only some 10,000 tons of CO_2 a year—4000 times less than the amount captured by the existing CCS systems. So long-term DACCS cost estimates and projections remain a "contentious issue," the National Academy of Sciences wrote in their 2019 report on negative emission technologies.[13]

The Congressional Research Service noted in 2021 that "generally, the more dilute the concentration of CO_2, the higher the cost to extract it, because much larger volumes are required to be processed."[14] Costs range from USD $15-25 per ton of CO_2 for industrial processes that produce "pure" or very concentrated CO_2 streams (such as natural gas processing) to $40-120 per ton of CO_2 for processes with "dilute" gas streams, like power generation, cement, and steel.[15] DAC is the most expensive—currently several hundred dollars per ton of CO_2—because CO_2 is so diffuse in the atmosphere, with a concentration of about 0.04%. The flue gas of a coal-fired power plant is about 14% CO_2 by comparison, 350 times greater.[16] An analysis in CleanTechnica points out that you must filter a Houston Astrodome's worth of air to get just 1 ton of CO_2—if the system were 100% effective at capturing CO_2.[17] A 2018 "techno-economic assessment" of DAC concluded, "CO_2 **separation from air is unable to economically compete with CCS**."[18] For the foreseeable future, it makes more sense to put CCS on an existing coal plant than to build a DACCS system.

A leading DACCS company, Climeworks, has said it is selling CO_2 removal for $600 to $1200 a ton. **At a June 2023 DAC Summit hosted by Climeworks, the company's co-CEO Jan Wurzbacher "told the crowd his company could see its prices remain as high as $300 by 2050."**[19]

In July 2020, Microsoft "issued a request for proposals to source our first carbon removals." In 2021, the tech giant published a report on the results.[20] It received proposals for 189 projects and chose to purchase from 15 suppliers. Only one was DACCS, from a Climeworks facility in Iceland. Microsoft concluded that "at more than 50 times the cost per metric ton of most natural climate solutions, long-term solutions [like DACCS] today are both limited in availability and practically cost prohibitive." Most of the projects Microsoft selected were so-called natural climate solutions like reforestation and improved forest management, which typically cost far less than $50 per ton of carbon removed.

A 2021 paper on "Future Prospects of Direct Air Capture Technologies," tried to gauge future prices by soliciting the judgment of 18 experts in DAC technologies and negative emissions. The study reported: "Experts project CO_2 removal costs to decline significantly over time but to remain expensive (median by mid-century: around 200 USD/t CO_2)."[21]

A 2022 book chapter by MIT CCS expert Howard Herzog "assesses estimates for DAC costs going forward."[22] **Herzog is skeptical the price in 2030 will be below $600 *per net ton* of** CO_2 **removed.** He explains that most studies report the costs as $ *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 DAC system—and by the CO_2 emitted to compress, transport, and store the CO_2. It is far from clear that most DAC systems will be run solely on zero-carbon power such as renewables by 2030.

If the DACCS system were powered by natural gas, then "the negative emissions are only 0.4 tCO_2 for every tCO_2 removed from the atmosphere," he explains. "This increases costs for the negative emissions by 250%, making it impractical." Thus, "**The assessment suggests that the low range of cost estimates in the literature, $100-300/tCO2, will not be reached anytime soon, if at all**."

Carbon Engineering founder David Keith disputed Herzog's analysis at a May 2022 MIT seminar entitled "Affordable Direct Air Capture: Myth or Reality?" where they both participated.[23] Keith said the current cost was $300-425/$tCO_2$. Keith noted that it is "much cheaper to do a post-combustion capture on a cement plant." He also said that "getting under $100 is really hard." But as two experts explained in 2022, "Even if we succeed in reducing the cost of permanent carbon removal to $100 a ton, which would be a major technical achievement, it would cost around $22 trillion to reverse warming by one-tenth of one degree Celsius."[24]

A July 2023 analysis of "four case study DAC technologies" and "four sources of low-carbon electricity" as well as grid power concluded, "**First, it is unlikely that the costs of DACS will reach the aspired $100 t/CO2 target**."[25] And the mean cost projections in these cases are quite high, around $300 a ton in two cases and much higher in the other two.

A 2019 analysis of advanced fossil fuel plants 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."[26] Some expect DACCS to decline in price rapidly as more plants are built, economies of scale are achieved, and people gain experience operating them. But not all complex energy systems do that: The price of new nuclear power has risen since 2009.[27]

The authors of a 2020 study of energy systems 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."[28] The more complicated the system design and the more they needed 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 so sharply for so long.

But a DACCS system is much more like nuclear power than solar cells. A DACCS running on renewables or nuclear power has relatively high system complexity and relatively high customization for each deployment. So, it is likely to see at best a slow rate of price decline. In the case of CCS, "there are studies that have shown that there has not been a lot of interproject learning."[29] The Climate Council, which is comprised of some of Australia's leading climate scientists and policy experts, pointed out in 2021: "There is not a single carbon capture and storage project in the world that has delivered on time, on budget, and captured the agreed amount of carbon."[30]

SITING DACCS

At the 2022 MIT seminar on DAC, Herzog discusses what he calls a key "cost myth"—that "since DAC uses air as a feed stream, DAC plants can be sited anywhere." In fact, he says, "siting is a very complex problem" because "items like land availability, access to low-carbon energy and other utilities like water, permitting issues, acceptable meteorological conditions …. and accessibility of carbon-storage options … all put constraints on the siting of DAC … especially when we start getting to large scale." He says, "all of these can be handled, but it just adds money." Keith agreed with Herzog: "you're absolutely right to say siting's real hard."

Let's look at the siting issue more closely. DACCS systems must be powered almost entirely by zero-carbon power like renewables or nuclear power to make environmental and economic sense, as discussed above. 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 DAC. Yet the 2023 analysis of four DAC technologies found, "**Pairing DACS to intermittent renewables is expensive**."[31] So this is another potential siting constraint.

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's *2021 Annual Energy Paper* notes, "just to sequester an amount equal to 15% of current US GHG emissions, would require infrastructure whose throughput volume would be higher than the volume of oil flowing through US distribution and refining pipelines, a system which has taken over 100 years to build."[32]

The current climate is uniquely unwelcoming for new pipelines, due in large part to public concern. In the face of organized opposition, major oil and gas pipelines have been delayed, driving up costs, or canceled outright, like the 1100-mile, $9 billion Keystone XL oil pipeline. 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?"**[33] And those battles have already spread to CO_2 pipelines, as **the *Wall Street Journal* detailed in a September 2023 article, "A New Nimbyism Blocks Carbon Pipelines."**[34] *Greenwire* reported on October 20, 2023 that "the developer planning a 1,300-mile network of carbon dioxide pipelines through the farm belt said Friday that it's scrapping the project."[35] The company cited the "unpredictable nature of the regulatory and government processes" in two out of the five states the pipeline had to cross. This is why DACCS systems will need to be sited as close to the storage as possible, with both pipeline and storage site far away from population centers.

Solid sorbent DAC systems have another potential constraint. To power the system, they may need low-grade waste heat from industrial facilities, which are often close to population centers.[36] And they may be a source of political opposition, especially if they were also near the CO_2 storage site. But again, the system really needs to be near the storage facility to avoid the pipeline siting problem.

Liquid DAC systems also have siting constraints especially since they can use a great deal of water—4.7 tons of water per ton of CO_2 captured from the air at 20°C (68°F) and 64% relative humidity.[37] In hotter and drier climates, substantially more water would be needed. "DAC in particular could exacerbate demand for energy and water," explains a 2020 *Nature Climate Change* article.[38] So it would be challenging to site the system in any region prone to high temperatures, aridity, and drought—doubly so because climate change is heating up and drying out more and more parts of the world. Yet, as noted, the system needs to be cited near renewables like solar, while the best solar energy opportunities are in places where it is very sunny most of the time, places that tend to be relatively hot and dry.

Powering DAC with a natural gas plant that has CCS is problematic. There is not currently one commercial scale gas-fired power plant with CCS in the world.[39] In part, that's because adding CCS to a natural gas system sharply increases both its capital and operating costs.[40]

Also, the extraction and transportation of gas is associated with significant greenhouse gas emissions before the gas gets to the CCS system.[41] In particular, natural gas is mostly methane, and natural gas production and delivery is leaky. As a result, a significant amount of methane escapes in the process, studies show. Methane has more than 80 times the global warming potential of CO_2 over a 20-year period. So, this leakage is a major contributor to near-term global warming. Stanford researchers noted in 2014, "A review of more than 200 earlier studies confirms that U.S. emissions of methane are considerably higher than official estimates. Leaks from the nation's natural gas system are an important part of the problem."[42] Until such leaks are sharply reduced, simply capturing the carbon at a natural gas power plant would still leave high lifecycle GHG emissions for gas plants with CCS.

The idea of building hundreds of new natural gas plants—each with a carbon capture and storage system—to power DAC raises a key question: **Wouldn't it be much cheaper and a better use of resources to simply put CCS systems on existing natural gas plants**? After all, DAC systems are very expensive, and building hundreds of new gas plants means significantly increasing natural gas production and hence natural gas leaks.

This raises a crucial question when looking at DACCS: What are the opportunity costs?

OPPORTUNITY COST

Under what circumstances would DACCS be a good use of carbon-free power? There will be a huge 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. **That carbon-free power could be**

used to directly replace the CO_2 emissions from fossil fuel plants or from vehicles much more cheaply and efficiently. But full decarbonization of the grid and ground transportation is unlikely to be completed before 2050, and so scaling up DACCS before then would be counterproductive.

Because CO_2 in the air is so diluted, the overall efficiency of this process is quite low. And that's a key reason why the costs and energy consumption for DACCS are so high. In a 2019 report on negative emissions technologies, a committee of the National Academy of Sciences calculated that the efficiency of a solid sorbent system is 7.6%-11.4% and of a liquid system is 4.1%-6.2%.[43]

The Academy "held a series of public workshops and meetings to inform its deliberations." Their report notes **"the committee repeatedly encountered the view that NETs will primarily be deployed to reduce atmospheric CO_2 after fossil emissions are reduced to near zero."** A 2021 analysis 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."[44]

Further a 2021 analysis published by the American Institute of Chemical Engineers, "Renewable Power for Carbon Dioxide Mitigation," found that using renewables to power electric vehicles (EVs) 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 EVs 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 ICEV" [internal combustion engine vehicle].[45] So EVs will have a far lower cost per ton of CO_2 reduced than DAC systems. And by the time DAC might seriously start scaling up, it is likely that EV costs will be equal to if not lower than ICEVs, especially on a lifecycle basis.[46]

A 2022 review by the European Academies' Science Advisory Council—the "collective voice of European science"—noted that "**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**."[47] A 2019 study concluded "DACC is unfortunately an energetically and financially costly distraction in effective mitigation of climate changes at a meaningful scale before we achieve the status of a significant surplus of carbon-neutral/low-carbon energy." Scale is a key issue for DACCS because the process is so energy intensive. Using the liquid sorbent DAC system to remove 10 gigatons (Gt) of carbon dioxide a year from the air (20% of total greenhouse gas emissions), could require 15% to 24% of Total Global Energy Supply (TGES). Using the solid sorbent could require 37% to 63% of TGES.[48]

Even on a much smaller scale, DACCS requires a lot of energy. A 2020 review of CCS and DACCS 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 Gt of CO_2."[49]

Besides consuming a great deal of energy, DACCS systems use a great deal of materials and liquid DAC systems use lots of water. A 2020 *Nature Climate Change* article concluded that the energy and water usage of DAC, "could result in staple food crop prices rising" sharply "in many parts of the Global South, raising equity concerns" about deploying negative emissions technologies.[50]

Significantly, the United States (and many other countries) will be spending billions of dollars on DACCS over the next decade. The 2021 Bipartisan Infrastructure Law devotes $6.5 billion "largely for direct air capture and carbon dioxide storage."[51] The 2022 Inflation Reduction Act ramps up and extends a major tax credit for CCS and DACCS.

In 2008, the U.S. Congress launched the corporate income tax credit for CCS (including DACCS), which is known as 45Q. In 2018, the Congress expanded it. In the 2022 Inflation Reduction Act, they expanded it again. As a result, the tax credit for CCS by power plants and industrial facilities is rising to $85 per metric ton if the CO2 is stored in geologic formations and $60 if the CO_2 is either utilized beneficially (to make a commercial product) or used to extract more oil from an oil field (enhanced oil recovery). The Inflation Reduction Act also made a separate tax credit for DACCS for projects that start construction before 2033—$130 a ton if the CO_2 is either utilized beneficially or stored in oil and gas fields and $180 if the CO2 is stored in geologic formations.

The prices above 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.[52] It will be very important for the federal government to ensure that any lifecycle analysis is comprehensive, so that only net tons are subsidized, not gross tons.

CONCLUSION

"**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 IPCC chair, in a 2021 article, "Climate scientists: concept of net zero is a dangerous trap."[53] He added, "Why are we willing to gamble the lives and livelihoods of millions of people, the beautiful life all around us, and the futures of our children?"

How big a role could DACCS play in addressing climate change, in dealing with the 50 billion tons of greenhouse gasses (GHGs) humans emit each year? In its September 2023 *Net Zero Emissions by 2050 Scenario*, the International Energy Agency has less than 0.7 Gt CO_2/year of DACCS removal by mid-century. The IPCC envisions substantially less DACCS than that in its 2022 mitigation report. Carbon Engineering founder, Dr. David Keith, would not speculate on an answer to this question. He did say in 2022, "we should focus on cutting emissions," and "**there is so much overhype around air capture. The public discussion is disconnected from reality**."[54]

Perhaps a more germane question is: When will it even makes sense to start significantly scaling up DACCS? As we've seen, the answer is post-2050 at the earliest—and even that assumes a much more rapid replacement of fossil fuels with carbon free energy in power generation, buildings, industry, and transportation than the world has yet embraced. 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**."[55]

A 2019 analysis 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."[56] Yet scaling tree planting faces major challenges and scaling bioenergy with CCS is impractical and would 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 tons of GHGs. If we don't "drastically reduce emissions first," then CDR "will be next to useless," argued CDR expert, David T. Ho, an oceanography professor, in an April 2023 *Nature* article.[57] Ho, who was a reviewer for the $100-million XPRIZE Carbon Removal competition, concludes, **"We must be prepared for CDR to be a failure."**

So, planning on substantial CDR saving the climate would be unwise and dangerous. The idea we can "overshoot" a temperature target by mid-century and then turn global emissions massively negative to cool back down in a timeframe that would matter is magical thinking. In a 2018 *Special Report*, the IPCC explained, "Limiting global mean temperature increase at any level requires global CO_2 emissions to become net zero at some point in the future." 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. They wrote, **"In private, scientists express significant skepticism about the Paris Agreement, BECCS, offsetting, geoengineering and net zero."** This paper and the two others in this series make clear offsetting, BECCS, and net zero deserve such significant skepticism.

Finally, the Climate Action Tracker[58] notes that, as of now, the "policies and action" of the top 10 GHG-emitting countries (including land-use change and forestry emissions)—**China, the U.S., India, Russia, Indonesia, Brazil, Japan, Iran, Canada, and Saudi Arabia**[59]—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 targets, so that is where we should focus our energy and resources.

ABOUT THE AUTHOR

Dr. Joseph Romm is Senior Research Fellow at the University of Pennsylvania Center for Science, Sustainability, and the Media (PCSSM). His work focuses on the sustainability and scalability—and the scientific underpinnings—of the major climate solutions, as well as the media coverage of them. His first PCSSM white paper, "Are carbon offsets unscalable, unjust, and unfixable—and a threat to the Paris Climate Agreement?" *was has been cited in the New York Times, The Cleveland Plain Dealer, Inside Climate News, and Bloomberg. Auden Schendler, SVP for sustainability at the Aspen Ski Co. called it "one of the most important papers ever published in the climate movement."*

Romm spent 5 years in the 1990s working on climate and clean energy solutions at the US Department of Energy. For 3 years, he helped to run the Office of Energy Efficiency and Renewable Energy ultimately serving as Acting Assistant Secretary, where he oversaw a $1 billion budget for R&D, demonstration, and deployment of climate solutions, including biofuels, biopower, and hydrogen.

In 2008, Romm was elected a Fellow of the American Association for the Advancement of Science for "distinguished service toward a sustainable energy future." In 2009, Time magazine named him "Hero of the Environment" and "The Web's most influential climate-change blogger" for his work at Climate Progress. Rolling Stone named him one of "100 people who are changing America." Romm has 10 books in the areas of climate change, clean energy, and communications, including an Oxford University Press book that NY Magazine called "the best single-source primer on the state of climate change." His 2004 book, "The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate," was named one of the best science and technology books of 2004 by Library Journal. He has written extensively on bioenergy for more than 15 years. He holds a PhD in physics from M.I.T.

APPENDIX: INTRODUCTION TO DACCS

Direct air carbon capture and storage (DACCS) pulls carbon dioxide directly out of the air and sequesters it underground. DACCS is a multipart process:

1. Large fans blow ambient air over a liquid solvent (or solid sorbent) that absorbs (or adsorbs) the CO_2;
2. Then a high-temperature process releases the CO_2 as a highly concentrated stream while regenerating the sorbent;
3. The CO_2 is compressed to more than 1,000 pounds per square inch to transport it, typically via pipeline, to the storage site; and

4. The CO_2 is then injected underground—either to extract more oil (enhanced oil recovery) or simply to be stored in a non-production reservoir—and, ideally, constantly monitored to verify the ongoing integrity of the storage system.

It's worth looking a little closer at the two main types of DACCS, since they have different energy, water, and material requirements. The "most technically mature method for capturing atmospheric CO_2" uses a solvent—a strong liquid base, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH)—which dissolves the CO_2 and forms a carbonate solution (see Figure 1 below).[60] That solution is then mixed with a calcium hydroxide ($Ca(OH)_2$) solution in a "precipitator" to regenerate the liquid base while also forming $CaCO_3$—solid calcium carbonate (also known as chalk).

The solid precipitate goes into an industrial oven (a "calciner") where it is reacted with oxygen at temperatures up to 900°C (1650°F). That creates pure CO_2 along with CaO (also known as quicklime) which is mixed with water in a "slaker" to form calcium hydroxide (also known as slaked or caustic lime) for reuse. The liquid base is also regenerated at the same time.

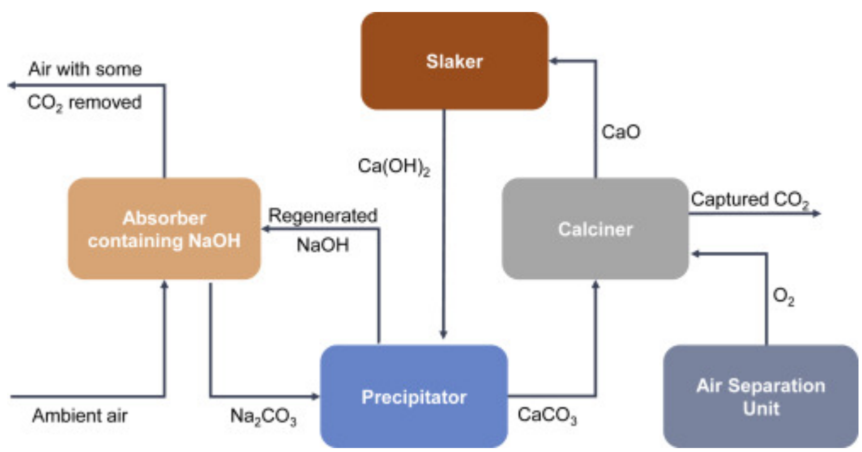

Figure 1: DAC Using a Strong Liquid Base, like Sodium Hydroxide (via Gambhir and Tavoni, 2019)

This liquid-based process is used by the DAC company Carbon Engineering, which was founded by David Keith, who is a geophysics professor at the University of Chicago and Director of their Climate Systems Engineering Initiative

The other method commonly used for capturing CO_2 from the air uses solid sorbents (called amines), which adsorb CO_2 from ambient air in the first step of a 2-step process (see Figure 2 below). In Step 1, adsorption, the CO_2 adheres to the surface of the sorbent (as opposed to absorption, where the CO_2 is dissolved into the liquid solvent). Adsorption creates a weaker bond with the CO_2 than absorption, so considerably less energy is needed to separate the CO_2 from the amine sorbent.

In Step 2, a pure stream of CO_2 is separated out with much lower-temperature heat—around 100 °C [212 °F] (Figure 3).

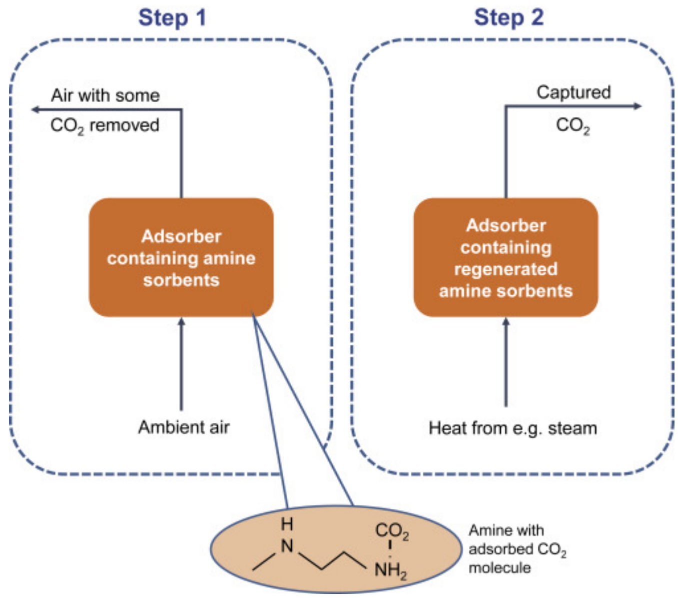

Figure 2: DAC Using Solid Sorbents (via Gambhir and Tavoni, 2019)

This solid sorbent process is used by a variety of DAC companies, including Climeworks and Global Thermostat.

According to one analysis, this DAC process actually uses considerably more energy than the liquid-based process does because it’s “based on amine-modified solid sorbents such as monoethanolamine (MEA).”[61] The synthesis of MEA from ammonia (NH3) and ethylene oxide requires a tremendous amount of energy.[62] Amines degrade over time, which means, as one analysis put it, “Currently, the sorbent needs to be replaced after about 24 months and represents a significant maintenance cost.”[63] Interestingly, “Both the solid sorbent and liquid solvent DAC approaches require roughly 80% thermal energy and 20% electricity for operation.”

Carbon Engineering is the first company to employ a liquid solvent system. In a 2018 journal article, David Keith and others at the company described in detail “A Process for Capturing CO_2 from the Atmosphere.”[64] Their design, which uses a liquid potassium hydroxide sorbent, describes “one possible configuration of plant equipment” that has “on-site combustion of natural gas to meet all plant thermal and electrical requirements.” For such a plant designed to capture 0.98 Mt-CO_2/year from the ambient air, the system would also capture all the CO_2 from the onsite natural gas combustion—another 0.48 Mt- CO_2/year. As a result, this DAC system design would deliver in total a 1.46 Mt- CO_2/year stream of high-pressure CO_2 so it can be transported to a site where the CO_2 is either stored or utilized. More recently, Keith has described this design as “extremely unlikely” and indicated actual systems would “use low-carbon renewables.”[65]

ACKNOWLEDGEMENTS

The contents of this report, including any mistakes, are the responsibility of the author alone. The author would like to thank the David Ho, Danny Cullenward, Auden Schendler, and Simon Bennett for their comments on the penultimate draft. And finally, the author is very grateful to Michael Mann and Heather Kostick of University of Pennsylvania's Center for Science, Sustainability, and the Media for their tremendous help in bringing this project to fruition.

CITATION: Joseph Romm, *Why direct air carbon capture and storage (DACCS) is not scalable, and 'net zero' is a dangerous myth,* A University of Pennsylvania Center for Science, Sustainability, and the Media White Paper, November 2023. https://web.sas.upenn.edu/pcssm

ENDNOTES

[1]IPCC, *Global Warming of 1.5 °C*, Chapter Two, 2018.

[2]IPCC, *Climate Change 2022: Mitigation of Climate Change, Technical Summary*, 2022.

[3]Climate Interactive, "En-ROADS June 2023: Bioenergy," June 1, 2023. This document presented preliminary results of the BECCS modeling.

[4]Joseph Romm, "Are carbon offsets unscalable, unjust, and unfixable—and a threat to the Paris Climate Agreement?" University of Pennsylvania Center for Science, Sustainability, and the Media, June 2023.

[5]Maxine Joselow, "Republicans want to plant a trillion trees. Scientists are skeptical," *Washington Post*, August 2, 2023. See also Climate Interactive, "The Washington Post Shared Our Analysis of A Trillion Trees - Here's What's Behind the Numbers," August 2, 2023.

[6]Andrew P. Jones and Joseph Romm, "The Magical Thinking of McCarthy's Trillion-Tree Plan to Solve Climate Change," *The Messenger*, August 16, 2023.

[7]Timothy D. Searchinger, et al., "Europe's renewable energy directive poised to harm global forests," *Nature Communications*, September 2018.

[8]Stanford University news release, "Soils or plants will absorb more CO_2 as carbon levels rise – but not both, Stanford study finds," March 24, 2021,

[9]National Academies of Sciences, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, The National Academies Press, 2019.

[10]Michael Cembalest, *2021 Annual Energy Paper*, JP Morgan Asset and Wealth Management, 2021.

[11]UN IPCC, *Climate Change 2022: Mitigation of Climate Change, Summary for Policymakers*, Working Group III contribution to the Sixth Assessment Report, 2022.

[12]Vaclav Smil, "Energy at the Crossroads," OECD Global Science Forum, May 17-18, 2006. For a similar calculation, see also Niall Mac Dowell et al, "The role of CO2 capture and utilization in mitigating climate change." *Nature Climate Change*, April 2017.

[13]National Academy of Sciences, *Negative Emissions Technologies and Reliable Sequestration*, 2019.

[14]Congressional Research Service (CRS), "Carbon Capture and Sequestration (CCS) in the United States," October 5, 2022, Washington DC.

[15]Adam Baylin-Stern and Niels Berghout, "Is carbon capture too expensive?" International Energy Agency, February 17, 2021.

[16]Congressional Research Service (CRS), "Carbon Capture and Sequestration (CCS) in the United States," October 2021, Washington DC.

[17]Michael Barnard, "Air Carbon Capture's Scale Problem: 1.1 Astrodomes For A Ton Of CO_2," *CleanTechnica*, March 14, 2019.

[18]Daniel Krekel et al., "The separation of CO2 from ambient air—A techno-economic assessment," *Applied Energy*, May 2018.

[19]Brian Kahn, "Removing Carbon From the Air Enters Its Awkward Teen Years," *Bloomberg*, June 12, 2023.

[20]Microsoft, *Microsoft carbon removal: Lessons from an early corporate purchase*, 2021.

[21]Soheil Shayegh et al., "Future Prospects of Direct Air Capture Technologies, Insights From an Expert Elicitation Survey," *Frontiers in Climate*, May 2021.

[22]Howard Herzog, "Chapter 6: Direct Air Capture," in Mai Bui and Niall Mac Dowell, eds., *Greenhouse Gas Removal Technologies*, Royal Society of Chemistry, August 2022,

[23]Mark Dwortzan, "Affordable direct air capture: myth or reality?" MIT Climate Portal., June 8, 2022

[24]Zeke Hausfather and Jane Flegal, "We need to draw down carbon—not just stop emitting it," *Technology Review*, July 5, 2022.
[25]John Young et al., "The cost of direct air capture and storage can be reduced via strategic deployment but is unlikely to fall below stated cost targets," *One Earth*, July 21, 2023.
[26]Edward Rubin, "Improving cost estimates for advanced low-carbon power plants," *International Journal of Greenhouse Gas Control*, September 2019.
[27]Max Roser, "Why did renewables become so cheap so fast?" *Our World in Data*, December 1, 2020.
[28]Abhishek Malhotra and Tobias S. Schmidt, "Accelerating Low-Carbon Innovation," *Joule*, November 2020.
[29]Dave Roberts, "Which technologies get cheaper over time, and why? A conversation with Abhishek Malhotra and Tobias Schmidt about learning curves," Volts podcast, January 13, 2023. The quote is from Malhotra.
[30]The Climate Council, "What Is Carbon Capture and Storage?" 2021.
[31]John Young et al., "The cost of direct air capture and storage can be reduced via strategic deployment but is unlikely to fall below stated cost targets," *One Earth*, July 21, 2023. The paper notes, "pairing DACS to intermittent renewables is unlikely to be cost-effective unless the renewable power comes from installations with high-capacity factors, such as some offshore wind installations." A requirement for large amounts of high-capacity renewables would be a severe siting constraint.
[32]Michael Cembalest, *2021 Annual Energy Paper*, JP Morgan Asset and Wealth Management, 2021
[33]Hiroko Tabuchi and Brad Plumer, "Is This the End of New Pipelines?" *New York Times*, published July 8, 2020. The articles notes that 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."
[34]Benoît Morenne and Joe Barrett, "A New Nimbyism Blocks Carbon Pipelines," *Wall Street Journal*, September 30, 2023.
[35]Jeffrey Tomich, "Developer scuttles plans for Midwest CO2 pipeline," *Greenwire*, October 20, 2023.
[36]Sara Budinis, "Direct Air Capture," International Energy Agency, November 2021. This report notes, "recovered low-grade waste heat could power a solid DAC system." This strategy would work with high confidence only if the industrial facility or power plant was not at risk of being shuttered for the foreseeable future. You wouldn't want to design a system whose economics depended on waste heat from a plant that could be shut down in a few years.
[37]David Keith et al., "A Process for Capturing CO2 from the Atmosphere," *Joule*, August 2018.
[38]Jay Fuhrman et al., "Food–energy–water implications of negative emissions technologies in a +1.5 °C future," *Nature Climate Change*, August 24, 2020.
[39]Oliver Morton, tweet, October 14, 2021.
[40]Edward Rubin, John Davison, and Howard Herzog, "The cost of CO_2 capture and storage," *International Journal of Greenhouse Gas Control,* September 2015.
[41]Raw natural gas has a lot of impurities, and "CO2 normally has the largest contribution," explains one 2018 study. "In fact, in some raw natural gas streams, its volume fraction can be higher than 50%." But natural gas for use by homes and businesses delivered by pipeline must be no more than about 2% to 4% CO2. If the CO2 removal process vents the CO2—rather than capturing and storing it—then those emissions must count towards the total GHG emissions of burning the natural gas. See Margot A. Llosa Tanco et al., "Membrane Optimization and Process Condition Investigation for Enhancing the CO2 Separation From Natural Gas," Chapter 17 in *Current Trends and Future Developments on (Bio-) Membranes*, ed. by Angelo Basile and Evangelos Favvas, Elsevier, 2018.
[42]Mark Golden, "America's natural gas system is leaky and in need of a fix, new study finds," *Stanford Report*, February 21, 2014.
[43]National Academy of Sciences, *Negative Emissions Technologies and Reliable Sequestration*, 2019. The efficiency being calculated here is the "exergy efficiency" or the so-called "second-law" [of thermodynamics] efficiency. It is defined as "the ratio of minimum work to real work": Wmin/Wreal.
[44]Noah McQueen et al., "Natural Gas vs. Electricity for Solvent-Based Direct Air Capture," *Frontiers in Climate*, January 27, 2021.
[45]James Lattner and Scott Stevenson, "Renewable Power for Carbon Dioxide Mitigation," American Institute of Chemical Engineers, March 2021. The other significant advantage EVs have is that "DAC does not help balance variable supply with demand—the capacity of the DAC plant cannot be fully utilized on renewable supply alone."
[46]Just as electrifying transportation and charging an electric vehicle is a much more cost-effective way to cut CO_2 emissions with renewables than using them to power DAC, electrifying heat for buildings and industry will inevitably also be, too. That's because the heat pumps use for such heating are highly efficient and pay for themselves with energy savings.
[47]European Academies' Science Advisory Council (EASAC), "Forest bioenergy update: BECCS and its role in integrated assessment models," February 2022. The EASAC consists of the 27 national science academies of the EU Member States, Norway, Switzerland and UK. The report notes "Policy-makers should suspend expectations that BECCS can deliver significant CDR removals by 2050 until models have identified the sensitivity of atmospheric CO_2 levels to different feedstock payback times and can be confident that time-related targets can be achieved."

[48]Sudipta Chatterjee1 & Kuo-Wei Huang, "Unrealistic energy and materials requirement for direct air capture in deep mitigation pathways," *Nature Communications*, July 2020.
[49]June Sekera and Andreas Lichtenberger, "Assessing Carbon Capture: Public Policy, Science, and Societal Need," *Biophysical Economics and Sustainability*, October 2020.
[50]Jay Fuhrman et al., "Food–energy–water implications of negative emissions technologies in a +1.5 °C future," *Nature Climate Change*, August 2020.
[51]U.S. Department of Energy fact sheet, "The Infrastructure Investment and Jobs Act," 2021.
[52]The "full fuel lifecycle" emissions of the DACCS system "includes all stages of fuel and feedstock production and distribution, from feedstock generation or extraction through the distribution and delivery and use of the finished fuel to the ultimate consumer."
[53]James Dyke, Robert Watson, and Wolfgang Knorr, "Climate scientists: concept of net zero is a dangerous trap," *The Conversation*, April 22, 2021.
[54]David Keith, August 18, 2022, Personal communications with the author.
[55]Glen Peters, Thread on the site formerly known as Twitter, Aug 18, 2023. The full text of the first post in the thread is, "I often [hear] 'we are not reducing emissions so we need CDR'. This is a complete misunderstanding of the role of CDR. If we are just reducing emissions a little bit, then CDR must be the most irrational mitigation option around. CDR has a function when emissions plummet."
[56]Giulia Realmonte et al., "An inter-model assessment of the role of direct air capture in deep mitigation pathways," *Nature Communications*, July 2019.
[57]David T. Ho, "Carbon dioxide removal is not a current climate solution— we need to change the narrative," *Nature*, April 4, 2023.
[58]For detailed discussions of the climate strategy of the world's major emitters compared to what is needed to achieve the Paris targets, see The Climate Action Tracker (CAT).
[59]The top 10 countries come from the "Climate Data Explorer" of Climate Watch, which is managed by World Resources Institute, as a contribution to the NDC Partnership. Of the next 10 countries--**Congo,** Germany, **South Korea, Mexico, Australia, South Africa, Türkiye, Vietnam, Thailand, and Pakistan—**Germany is the only one whose "policies and action" are "sufficient" to keep warming below 2°C. Congo and Thailand are not rated by CAT, and almost all the rest have "policies and action" insufficient to keep warming below 3°C.
[60]Ajay Gambhir and Massimo Tavoni, "Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation," *One Earth*, December 2019.
[61]Sudipta Chatterjee & Kuo-Wei Huang, "Unrealistic energy and materials requirement for direct air capture in deep mitigation pathways," *Nature Communications*, July 2020.
[62]Giulia Realmonte et al., "Reply to 'High energy and materials requirement for direct air capture calls for further analysis and R&D'," *Nature Communications*, July 2020. The authors of this reply write that if the sorbent is MEA, "We agree with the authors that this would make DAC2 [amine-based DAC] unlikely to be able to deliver multi-Gt scale CO2 removals." But they add, "We note, however, that there is still a high degree of confidentiality around the precise nature of the amine sorbents used in pre-commercial plants (such as those of Climeworks), so we would caution against basing any analysis solely on the MEA sorbents which the authors use as a reference."
[63]Howard Herzog, "Chapter 6: Direct Air Capture," in Mai Bui and Niall Mac Dowell, eds., *Greenhouse Gas Removal Technologies*, Royal Society of Chemistry, August 2022.
[64]David Keith et al., "A Process for Capturing CO2 from the Atmosphere," *Joule*, August 2018.
[65]David Keith, August 18, 2022, Personal communications with the author.