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Engineered CO_2 Removal, Climate Restoration, and Humility

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Over the past 200 years, humans have dramatically altered our global environmental envelope accidentally through uncontrolled greenhouse gas emissions. Humans have also developed the technology to both stop emitting greenhouse gases and ultimately to *remove* them from the atmosphere through a combination of natural and engineered pathways. Ultimately, humanity must practice CO_2 removal in addition to maximal reduction in greenhouse gas emissions through conventional mitigation to achieve net-zero greenhouse gas emissions and ultimately net-negative emissions. To accomplish this task will require enormous sums of money and substantial cooperation between groups of people who commonly do not work together: technical experts, financiers, and government officials. In addition to heightened and accelerated ambition, humility is required as well. The task requires frequent and extended achievement in arenas that many scientists and engineers commonly understand only tangentially (e.g., lawmaking, regulatory enforcement, and project finance).

Keywords: CO_2 removal, negative emissions technologies, climate policy, climate finance, public acceptance, CCS, CDR

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The map is not the territory.
-Alfred Korzybski

We have reached a startling moment in human history. Over the past 200 years, humans have dramatically altered our global environmental envelope accidentally through unbridled greenhouse gas emissions, what Roger Revelle and Hans Seuss called a grand, unplanned geophysical experiment (Revelle and Suess, 1957). Perhaps more audacious still, in the past 10 years we've developed the technology to both stop the experiment and ultimately to *undo* it.

Specifically, we've developed enough technology and learned enough through scientific inquiry to remove greenhouse gases from the air and oceans—carbon dioxide removal or CDR (National Academies of Science Engineering and Medicine, 2018). Engineered approaches to CDR include direct air capture of CO_2 (Ishimoto et al., 2017; Sandalow et al., 2018), accelerated weathering of rocks (Schuiling and Krijgsman, 2006) and bioenergy plus carbon capture and storage or BECCS (Sanchez et al., 2018; Vaughan et al., 2018). Ultimately, in order to remove the dose of combustion-related pollution from the air and oceans, humanity must practice CDR in addition to maximal reduction in greenhouse gas emissions through conventional mitigation, such as efficiency and conservation measures, deployment of near-zero carbon emitting power sources such as solar, wind, or nuclear (Smith and Friedmann, 2017).

Combined, conventional mitigation and CDR can achieve net-zero greenhouse gas emissions and ultimately net-negative emissions. This will almost certainly require both natural approaches like restoring ecosystems and reforesting large areas (Griscom et al., 2017). It will almost certainly involve engineered systems, which have the advantage of dramatic rate improvements compared to nature and dramatic footprint reductions—both of great value on a finite earth.

Recent scholarship has underscored both the magnitude of the task and the rates required to achieve net carbon removal and negative emissions (Fuss et al., 2014). Estimates for the rate of CDR range from 10 to 20 Gt/y by century end, and many gigatons by mid-century (Gasser et al., 2015; Fuss et al., 2018). The IPCC's 1.5°C report (IPCC, 2018) places the integral estimate of CO_2 removal to be from 100 to 1,000 gigatons total by the century's end. This would be additional to full global economy-wide mitigation of 85% emissions reduction by 2050, a number substantially larger than all power sector emissions.

To accomplish this task will require enormous sums of money and substantial cooperation between groups of people who commonly do not work together, namely technical experts, financiers, and government officials, each of whom sees their role and mission very differently. It behooves the scientific, environmental, and policy communities to not be cavalier about this—either the level of difficulty or the cost and how that affects other human endeavors. Two responses seem appropriate simultaneously: ambition and humility.

The harsh arithmetic of climate change demands ambition and extraordinary response, demanding innovation, research, and investment in whole new fields of knowledge (Carbon180, 2018). However, the task is much greater than the technical work alone—it requires frequent and extended achievement in arenas that many scientists and engineers only tangentially understand. Specifically, four arenas stand out: policy design and implementation, markets for products and services, project finance, and social acceptance. These additional dimensions should prompt humility and (ideally) additional ambition, given the scope of the work.

THE LIMITS OF WIZARDRY

In his book, "The Wizard & the Prophet," Mann (2018) describes two approaches to the challenge of restoring balance between man and nature, and two individuals who embodied each approach. Wizards are innovators (like Norm Borlaug, the inventor of dwarf wheat), and are prone to engineering solutions. Prophets are conservationists (like William Vogt, founder of modern environmentalism) and are prone to social solutions (e.g., regulation).

Mann asserts that wizards and prophets represent distinct approaches and tribes, commonly with very different world views and value systems. Understanding this axis of contention is essential to acknowledging the difficulty of the task of climate restoration and widespread deployment of CDR. Each tribe, wizards and prophets, believe that they are right, believe facts support them, and believe the other tribe to be naïve, foolhardy, or reckless. Despite their common goals, wizards, and prophets sometimes view each other with contempt.

Success, however, will likely require extraordinary measures wherein these tribes cooperate. The dimensions to large-scale CO_2 removal and climate restoration are daunting.

- *Net zero by 2050*: A robust finding of many integrated assessment modeling groups is that a 2°C climate stabilization trajectory requires net-zero emissions by mid-century. This extraordinary and unprecedented outcome will require a complete turnover of capital stocks for all power and heavy industry, dramatic improvements in vehicle and end-use efficiency, and immense capital deployment (IEA, 2018). Unfortunately, the long residence time for CO_2 in the atmosphere and the build-up of heat in the oceans makes this outcome insufficient to avoid the worst impacts of climate change (IPCC, 2018).
- *A trillion tons*: The 1.5°C report discussed above estimates that by century end, 100 billion−1 trillion tons of CO_2 must be removed from the air and oceans to stabilize at that target. For the great majority of these scenarios, existing natural carbon sinks lack sufficient rate, and volume to accomplish this task without augmentation or engineered CDR (Smith et al., 2016; National Academies of Science Engineering and Medicine, 2018).
- *Restoring climate*: In the Papal encyclical *Laudato Si*, Pope Francis (2015) argues the moral responsibility for climate stewardship extends beyond abatement and mitigation. To reduce human suffering and minimize global ecosystem damage, humanity must attempt to restore climate as much as practicable, requiring both exertion of technical faculties, and moral sensibilities—a case for accelerated CDR through engineered systems. To be clear, there are many potential states that could be considered "restoring climate" (e.g., just a return to pre-industrial level of atmosphere CO_2 vs. surface albedo reconstruction vs. a restoration of sea level through continental ice volumes reconstruction). Even then, some ecosystems and species are already lost or irretrievably damaged, begging the questions as to what restoration state is sufficient or required.
- *Any failure requires more CDR for success*: At present, the global economy is not on track for any of these outcomes. If mitigation is slowed for any reason (e.g., technical complexity, lack of investment), or if climate impacts accelerate and stimulate positive feedbacks (e.g., rapid polar ice collapse reducing albedo, elevated temperatures increasing wildfire impacts), the climate math demands additional CDR beyond the initial immense scale requirements. This also begs the question regarding the potential role for solar radiation management and its potential Relationship to and interaction with CDR—a topic not discussed here.

Technical success is necessary but insufficient to achieve climate stabilization. Most obviously, technical success (through government, private, and philanthropic investment) would lead to demonstrated cost reductions, making policies easier to enact since the public cost burden and level of disruption are minimized. Cost reduction alone, however, won't drive CDR. To remove CO_2 from the air and oceans at the multi-gigaton scale requires creation of new markets, trillions of dollars of investment, and global deployment (Smith and Friedmann, 2017; Sandalow et al., 2018). Policy, market forces, and wide-spread acceptance are indispensable components to achieving stabilization enabled and augmented by engineered CDR approaches.

THE ROOM WHERE IT HAPPENS

Today, the policy support for engineered CDR approaches is surprisingly robust and evolved. The US has the largest overt support through the 2018 passage of the FUTURE Act, which expanded and amended a small, existing tax credit for capture and storage of CO_2. The amendments, among other changes, explicitly included direct air capture (Energy Futures Initiative, 2018). This policy was the first to provide a government approved value of CO_2 from the air in the form of a transferable tax credit. The State of California has a separate mechanism in the form of the Low Carbon Fuel Standard, first passed into law in 2006. In 2019, it was amended in 2018 to include two provisions relevant for direct-air capture (California Air Resources Board, 2018). The first allowed synthetic fuels made from air-derived CO_2 to qualify as novel fuels for carbon crediting (strictly speaking not CDR). The second allowed for any plant that captured CO_2 from the air and stored it permanently *anywhere in the world* to qualify for carbon crediting. These policies have created new and rapidly expanding markets within the US for CDR.

Market and valuation policies can and have been augmented by additional policy support. For example, the governments of the United Kingdom (UK Natural Environmental Research Council, 2017) and Japan have created a distinct R&D program to support development of CDR technologies. In the US, several state governments are considering creating or amending "buy clean" policy mandates, which give government purchasing agencies mandates or latitude to buy low-carbon products (defined by life-cycle analysis). Some proposed legislation explicitly require states to purchase a fraction of fuels or build materials made with air-captured CO_2. Should they become law, these provisions would create markets, stimulate investment, and provide new grants for innovators, investors, and entrepreneurs.

Despite this recent progress, most nations lack policy mechanisms necessary to deploy engineered solutions to CDR. Central is the absence of a proper market for CDR services, necessary to pay engineers, or the companies that hire them. Key unresolved questions in this undefined market: who pays (e.g., tax payers, rate payers, or consumers) and how (e.g., direct govt. procurement, trading schemes, or feed-in-tariffs on goods and services).

Importantly, this lack of policy is commonly not due to an information deficit—many policy makers have received briefs on CCS, BECCS, CO2U, and even direct air capture and are versed on the viability and importance of the subject. The lack of policy mechanisms reflects in large part an inability of scientists, engineers, and practitioners to frame policy support in a context politicians can use. Overall, engagement is minimal, and communication is often laden with jargon and unduly complex. In some cases, points that scientists and engineers believe are political winners (e.g., showing leadership, creating jobs, maintain competitiveness) are not couched in sensible politics or do not differentiate themselves from similar requests from other constituents (e.g., organized labor, justice advocates, medical researchers). The community of innovators and practitioners must improve their engagement with political decision makers if they want to expand, create, or propagate technology into markets.

OTHER PEOPLE'S MONEY

Those seeking deployment of engineered CDR approaches must recognize that this will ultimately be done through a market. It is unlikely that governments will underwrite the costs completely or mandate public expense. Private capital and public & private companies will deliver solutions to these evolving markets, competing with each other for market share. The business model could be similar to the services provided by waste management and pollution control firms—following mandates and regulations, companies would offer CDR services for a fee.

Thankfully, the appetite for "impact investing," meaning investment vehicles that deliver social benefits in general and environmental benefits in specific, has grown substantially in the last few years (USSIF, 2018). Pension funds, equity firms, hedge funds, and philanthropic investment has increased substantially the amount of money and has expanded the kinds of projects that merit consideration (Global Impact Investing Network, 2016). Overall, these investors still seek substantial capital returns on investment in short time frames (3–5 years) and some investors, like pension funds, carry firm, and well defined fiduciary responsibilities. Many investors require substantial returns (10–30%) in order to merit investment, and they have many competing options for investment. As such, most investment has remained in fields like biomedicine, high technology, or conventional infrastructure. Some clean energy investments have moved only into fairly safe vehicles (e.g., guaranteed renewable power offtakes), while other opportunities such as efficiency or geothermal power have received much less focus (Reicher et al., 2017).

For these reasons and others, substantial challenges remain for CDR to receive large capital flows despite real increased interest in and enthusiasm for impact investment. The largest of these is discussed above—the lack of a market that values CDR services. However, an adequate market signal or carbon price equivalence is not necessarily sufficient. In addition, the technologies and markets are heterogeneous and complex, making it difficult for potential investors to understand the potential technical or market risks. Overcoming these challenges requires patience and dedication, and may require additional policy support to stimulate large-scale investment and capital flows into engineered CDR.

ALL THE RAGE

Even policy support and substantial investment does not necessarily guarantee uptake or propagation. Large-scale CO_2 removal will require public acceptance and support, in large part because of the scale of deployment and magnitude of capital required. Innovations, even ones that dramatically improved people's quality of life, faced substantial public, and governmental opposition (Juma, 2017). The case of CDR is harder, as it provides few immediate, tangible benefits to consumers, or citizens tied to operation. As such, acceptance and right to operate may play an outsized role in deployment.

The technical CDR community ignores the issue of public acceptance at their peril. For example, many teams are seeking pathways to increase soil uptake, BECCS yields and performance, and mineralization though genetic modification of microbial consortia or plant species. Public response to the application of GMOs has been decidedly mixed (Lucht, 2015) and in some cases has led to bans and limiting regulation. Similarly, public response to ocean fertilization experiments and solar radiation management studies has been strong and much of it negative (Abate and Greenlee, 2010; Cummins et al., 2017), greatly complicating future attempts to deploy these approaches.

An important case of social acceptance involves two geological carbon storage projects in Germany: Barendrecht & Schwartzepumpe. These two projects, one power, one industrial, were meant to herald in large-scale deployment of CCS in Europe and create new technologies (e.g., oxyfired coal boiler systems), provide international leadership, maintain jobs, and create green products for export. Both focused on CO_2 storage onshore, which became a focus for local opposition. Poor handling of public engagement at the Barendrecht project strengthened public opposition, and eventually the project was shelved. This led to further political liabilities in Germany, and the ultimate collapse of Schwatrzepumpe (Lockwood, 2017).

While there are many cases where poor public engagement led to failure, there are many stories where positive public engagement led to success (Forbes et al., 2010). In different fields and projects, lessons learned have become strategies for public engagement (Lockwood, 2017). In these cases, neutral technical arbiters (e.g., from universities or government research centers) have a key role in gaining public confidence. However, it is also the case that early engagement, listening and addressing public concerns, and creating processes for public engagement have proven important components of successful strategies.

All engineered CDR approaches are fundamentally new, leading to questions from the public. These could include cost, potential public value, local risk and safety, and ethical concerns. It is important to engage public stakeholders as scientists, practitioners, and engineers with "two ears and one mouth," so as to best address the core questions arising from public discourse.

WHY WE DO WHAT WE DO: CONCLUSIONS

In reviewing the work ahead, it's helpful to remember that the case for CDR is extremely compelling, founded in daunting and incontrovertible math and science. We do what we do first and foremost because it is necessary and because we value our progress, civilization, and the glory of the natural world. This is true regardless of how difficult the path or how vexing the societal circumstances of the undertaking. Cleaning our collective room may be unpleasant but is ultimately necessary and is the work of climate restoration.

In that context, engaging in policy, finance, markets, and society are equally necessary. The work of reducing and reversing greenhouse gas emissions is not like the work of developing a fast microchip or a new medical scanner—dealing with a tragedy of the commons involves engaging the commons.

Toward that end, scientists and engineers involved in engineered CDR should embrace the necessary ambition to make progress and wield it with humility.

They will need to listen carefully to politicians of all stripes to understand their needs and serve them in a way that's consistent with rapid deployment of CDR technologies. This requires perseverance as well as a willingness to postpone an optimal solution for an actionable one.

They will need to study and come to understand the needs of investors and business leaders. This will require trust and patience, and a certain amount of silence.

They will need to meet with public stakeholders who stand with inquiry or in opposition. This will require generosity of time and spirit, and a willingness to be positive at all times.

They will need to improve their skills at communicating with investors, policy makers, the lay public, and media. To do so will require creativity and wiliness to practice and to fail.

Because the challenge is both immense and urgent, it is essential to start today. While there may be opportunities to speed forward on a few key actions, it is most likely that most of the engagements will be slow and laborious. Ultimately, though, that's part of the work needed to succeed, and is demanded of our community. We have few choices—the work is the work.

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The author confirms being the sole contributor of this work and has approved it for publication.

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