SCALING-UP NEGATIVE EMISSIONS: THE POWER OF LEVERAGING POLICY, PHILANTHROPY, PURCHASING AND INVESTMENT

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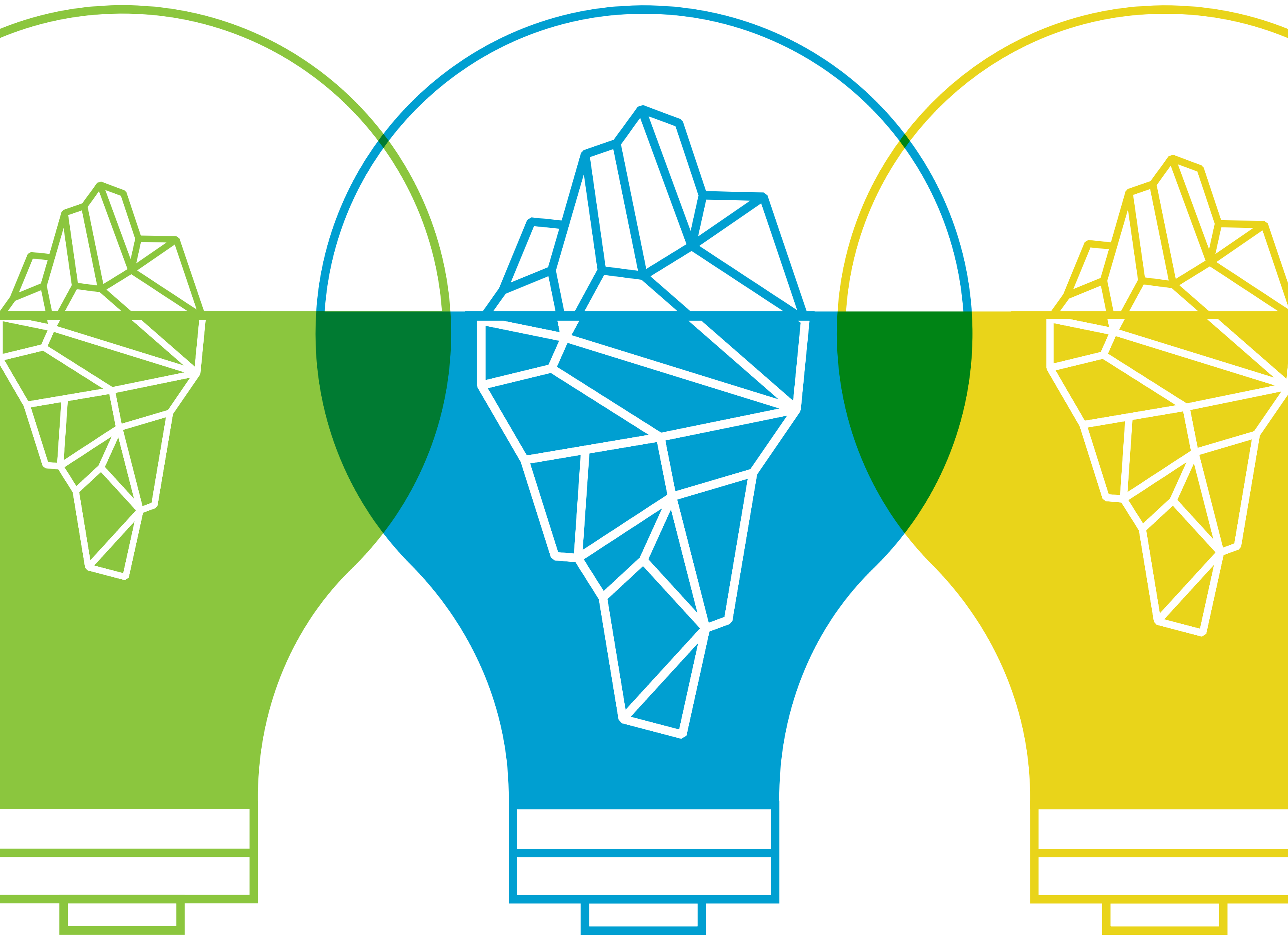
PUBLISHED IN: Frontiers in Climate



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ISSN 1664-8714
ISBN 978-2-83250-337-9
DOI 10.3389/978-2-83250-337-9

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Citation: Deich, N., Dipple, G. M., Paustian, K., Renforth, P., Wilcox, J., eds. (2022). Scaling-Up Negative Emissions: The Power of Leveraging Policy, Philanthropy, Purchasing and Investment. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-83250-337-9

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frontiers in Climate

PERSPECTIVE
published: 07 April 2021
doi: 10.3389/fclim.2021.636657

Carbon Purchase Agreements, Dactories, and Supply-Chain Innovation: What Will It Take to Scale-Up Modular Direct Air Capture Technology to a Gigatonne Scale

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Natural and engineered carbon dioxide removal have become regular features of climate models which limit warming to 1.5°C or even 2°C above pre-industrial levels. This gives rise to an assumption that solutions, for example direct air capture (DAC)—involving the direct removal of carbon dioxide from ambient air—can be commercialised and deployed at the necessary speed and scale to have a material impact, in the order of gigatonnes, by mid-century. Modular, solid-sorbent DAC on a gigatonne scale will require the mass mobilisation of supply chains to manufacture millions of modular DAC units—20 million of the present state of the art 50 tonne/year modules to deliver 1 gigatonne per year, as well as the large-scale production of novel chemical sorbents. To achieve a climate relevant DAC industry will demand innovative procurement models, for example carbon purchase agreements (CPAs), and dedicated DAC manufacturing facilities or dactories. In addition, insight is offered through the work of DAC start-up Carbon Infinity into the industry supply-chain position, adopting lessons from computing, and energy technologies. In particular, we look at approaches to drive demand and scale-up DAC module production, and opportunities presented in the development of an integrated DAC manufacturing industry.

Keywords: carbon purchase agreements, direct air capture policy, dactories, supply-chain innovation, manufacturing innovation, government procurement, modular direct air capture

OPEN ACCESS

Edited by:
Keith Paustian, Colorado State University, United States

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Dilip Khatiwada, Royal Institute of Technology, Sweden
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Specialty section:
This article was submitted to Negative Emission Technologies, a section of the journal Frontiers in Climate

Received: *01 December 2020*
Accepted: *12 March 2021*
Published: *07 April 2021*

Citation:
Izikowitz D (2021) Carbon Purchase Agreements, Dactories, and Supply-Chain Innovation: What Will It Take to Scale-Up Modular Direct Air Capture Technology to a Gigatonne Scale. Front. Clim. 3:636657. doi: 10.3389/fclim.2021.636657

TACKLING THE TRILLION TONNES

In conjunction with economy-wide decarbonisation, carbon dioxide removal (CDR) has shifted from a desirable component to an invaluable element in the formula of addressing runaway global temperature rise. The Intergovernmental Panel on Climate Change's (IPCC) 2018 Special Report found a remaining carbon budget of 420 gigatonnes of carbon dioxide ($GtCO_2$)—further depleted to <350 $GtCO_2$ by the start of 2020—to have a likely (>66%) chance of limiting warming to 1.5°C above pre-industrial levels (IPCC, 2018; Le Quéré et al., 2018; Friedlingstein et al., 2019). Increasingly broad consensus exists within the scientific community with respect to the necessity of widespread carbon removal to limit temperature rise within "safe" levels, aligned with the purview of the Paris Agreement. This is evidenced in models reviewed by the IPCC where all pathways that limit global warming to 1.5°C with limited or no overshoot project the use of CDR on the order of up to 1,000 $GtCO_2$, that is 1 trillion tonnes of carbon dioxide, over the twenty-first century

(IPCC, 2018). Ambition on such a scale candidly demands the development of a globally consequential carbon removal industry.

Engineered approaches to CDR include direct air capture of CO_2 or DAC (Breyer et al., 2019; Hou et al., 2019), bio-energy with carbon capture and storage or BECCS (Fridahl and Lehtveer, 2018; Hanssen et al., 2020), and enhanced rock weathering (Strefler et al., 2018; Beerling et al., 2020), alongside more widely recognised nature-based solutions including reforestation, afforestation, soil carbon sequestration, and peatland restoration (Seddon et al., 2020). Regardless of individual perspective concerning the respective merits and limitations of engineered or nature-based carbon removal pathways (land-use, permanence, energy requirements, cost), a comprehensive suite of CDR solutions will be necessary to achieve carbon removal resembling anything close to a climate consequential scale; although the scope of this perspective is centred on scaling-up modular DAC technology.

There are two dominant technical approaches to conduct DAC. One uses a solid chemical sorbent to capture CO_2 and the other uses a liquid solvent. Commercial liquid solvent-based systems typically resemble a large-scale industrial plant and the technology has been pioneered by the Canadian firm Carbon Engineering. Solid sorbent-based systems are more modular in nature, involving a standardised and highly-scalable manufacturing process to produce air capture modules. This approach is therefore the technical focus of this paper, as well as the Swiss firm Climeworks, Global Thermostat in the US, and the China-based Carbon Infinity.

While DAC is not without its sceptics, the technology has garnered increasing policy, investor, and media attention for its potential to scale-up to become a valuable carbon removal solution (Scott and Geden, 2018; Cox et al., 2020; Sekera and Lichtenberger, 2020). The scale of the scale-up challenge however should not be underestimated. Alongside the IPCC's findings of up to 1,000 $GtCO_2$ of cumulative CDR over the twenty-first century, complementary literature estimates 10–20 Gt/year of CDR by 2100, and multiple gigatonnes from now to 2050 (Gasser et al., 2015; Fuss et al., 2018; National Academies of Sciences, Engineering and Medicine, 2019). Assuming solid sorbent-based modular DAC technology accounts for a conservative 1 gigatonne of this suite of global CDR capacity, this would represent a "wartime level of effort" in the mobilisation of human, energy, material, financial, and importantly, supply-chain capacity.

There are 15 DAC facilities operating worldwide capturing a meagre 9,000 tCO_2/year or 0.000009 $GtCO_2$/year (IEA, 2020), while an unbuilt plant has ambitions to capture 36,500 tCO_2/year (Malo, 2019), and another industrial-scale plant with the intention to capture 1 $MtCO_2$/year (Carbon Engineering, 2020)—or only 0.001 $GtCO_2$/year—are currently in the design phase. To put the scale of the challenge further into perspective, to scale-up from 9,000 tonnes of CO_2/year in 2020 to a capture capacity of 1 billion tonnes (Gt) of CO_2/year in 2050, i.e., to grow by 111,111 times in 30 years, will represent a compound annual growth rate (CAGR) of 47.3%. To take one of the most successful examples of "blitzscaling" growth from the technology industry, Instagram took nearly 10 years to acquire 1 billion users (Constine, 2018). Although the comparison between developing an additional tonne of DAC capacity to an additional user of a social network is extreme, the "wartime" analogy for DAC deployment appears appropriate for the level of ambition the science suggests is necessary.

While numerous studies have focused on the techno-economic feasibility of DAC technology (Socolow et al., 2011; Smith et al., 2016; National Academies of Sciences, Engineering and Medicine, 2019; Realmonte et al., 2019), we do not aim to replicate such research. Rather, this perspective explores the fundamental considerations around what it will take in practise to scale-up DAC to the gigatonne scale. For example, Realmonte et al. (2019) discuss how deployment at such a scale "requires a major refocusing of the manufacturing and chemical industries for sorbent production," however they fail to mention the monumental manufacturing capacity needed to deliver ∼20 million DAC modules of the current state of the art 50 t/year. Put simply, the DAC industry will need to develop the cumulative manufacturing capacity of a year of the combined output of Ford, Toyota, Daimler, and Tesla, through dedicated DAC factories, or dactories.

There are three crucial pillars to addressing the inherent questions of scaling-up DAC technology to the gigatonne scale by mid-century:

- Lessons from the laws: potential for DAC cost and performance improvement using examples of historical innovation and "learning by doing" to move down the cost-curve;
- Chicken or egg: the barriers to scaling-up manufacturing and supply-chain capacity in the absence of demand-side drivers for DAC technology; and
- REAP rewards: resilience and efficiency aligned policies (REAP) developing integrated yet resilient supply chains, addressing resource constraints, and supporting the scale-up of a globally consequential DAC industry.

LESSONS FROM THE LAWS

Quantifiable technological progress has been recorded for decades, if not centuries. The most well-known is arguably Moore's law, documenting that the capacity of transistors on microprocessors doubles every 2 years. More recently, Swanson's law observes that for every doubling of cumulative production volume, the price of solar PV modules declines by 20% (**Figure 1B**). Both are grounded in lessons from the lesser-known Wright's law, outlined in Theodore P. Wright's 1936 paper *Factors affecting the costs of airplanes* (Wright, 1936). While Moore's law describes technological change as a function of time, and observations for solar are a reflection of experience, Wright's law combines innovation and economies of scale in a "we learn by doing" approach.

The evolution of the DAC industry will need to embrace the characteristics of all three laws. Variables from chemistry governing carbon capture efficiency, development of advanced nanomaterials (metal-organic frameworks, zeolites), and the

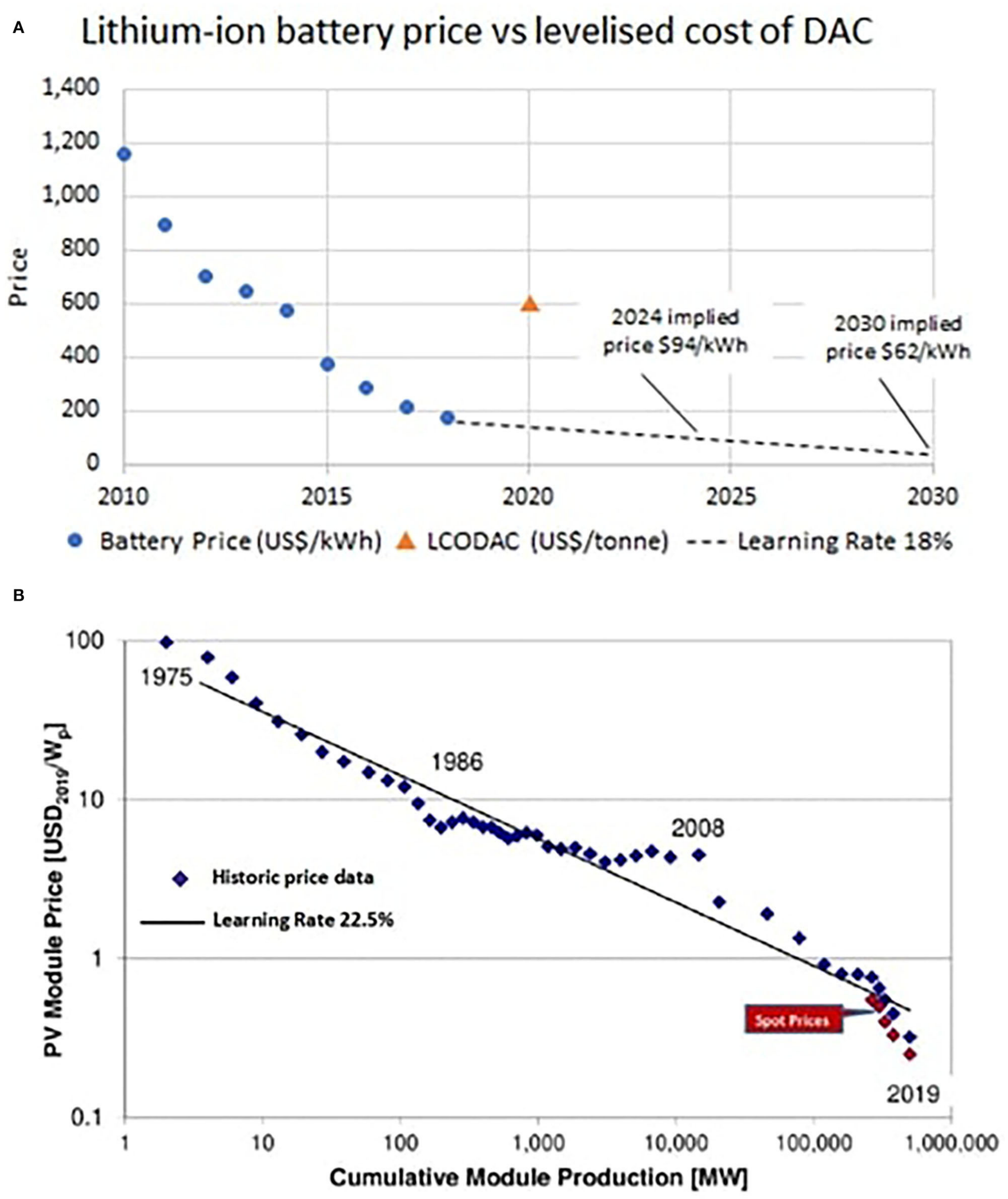

FIGURE 1 | (A) Lithium-ion battery cost-curve and forecast alongside levelised cost of DAC. Graph by Carbon Infinity, based on Bloomberg New Energy Finance (Goldie-Scot, 2019) Graph and BloombergNEF Data. **(B)** Solar PV module cost curve illustrating Swanson's law and the corresponding learning curve for solar PV. Graph by Carbon Infinity, based on European Commission's PV Status Report (Jäger-Waldau, 2019) Graph and BloombergNEF and PV News Data.

physics governing air flow through a contactor will—through continuous R&D, advanced design, and manufacturing—need to reflect some of the dynamics seen in the laws. For example, material science and thermodynamic advances resulting in a doubling of carbon capture capacity per square metre of sorbent material every 5 years, with the subsequent capital and operating cost implications on the levelised cost of direct air capture (LCODAC). Although the learning rate of DAC is uncertain given the lack of meaningful deployment, the economies of scale and cumulative experience elements of Swanson's and Wright's laws for the scale-up of modular DAC are potentially pronounced—especially drawing lessons from lithium-ion battery and solar module production as illustrated in the cost-curves in **Figure 1**.

DAC industry practitioners are largely in consensus on the economies of scale and learning effects from ramping up DAC deployment. Christoph Gebald, one of the founders and directors of Climeworks, in 2017 indicated his company's aspiration to bring costs down three-fold in 3-5 years through a combination of "purchasing higher volumes, professionalising our production infrastructure and automation of production steps" (Evans, 2017). Presumably in conjunction with that cost reduction target, Climeworks set an ambitious goal of capturing 225 $MtCO_2$/year by 2025—or nearly 1% of global CO_2 emissions. As Climeworks' modular DAC collector units have a capture capacity of 50 t/year (Beuttler et al., 2019), 4.5 million collector modules would need to be produced. Given that the production line in 2017 had an annual capacity of a mere 600 units—which has likely since been scaled-up—Climeworks and other aspiring DAC technology start-ups have some way to go before experiencing anything resembling the "production hell" famously associated with ramping-up manufacturing capacity to the necessary millions of DAC modules. Experience in moving down the cost-curve by the likes of solar and battery technologies, and the associated lessons of the laws, should be front and centre in the minds of DAC scientists, engineers, and entrepreneurs, while upholding the words of wisdom offered by Friedmann (2019): to embrace the necessary ambition to make progress and wield it with humility.

THE CHICKEN AND EGG CONUNDRUM

While it appears Climeworks is well-behind the necessary deployment schedule to capture 225 $MtCO_2$/year by 2025—illustrated by its August 2020 announcement of its biggest facility to date capturing 4,000 tCO_2/year (or 80 modules worth of the necessary 4.5 million) (Climeworks AG, 2020), this is somewhat due to commercialisation factors beyond its direct control: demand.

What comes first: an increase in affordability promoting demand, or demand driving down costs which increases affordability? In 1962, the first year that semiconductors shipped, the US government purchased every single one of them. In fact, from 1955 to 1977, government procurement accounted for 38% of all semiconductors produced in the US (The Engine, 2020). This supported the semiconductor industry in its infancy as a first and major customer, and created a demand environment in which companies had incentives to advance the state of the art. These advancements, alongside the economies of large-scale production, subsequently contributed to the rapid cost decline from US$32 for a single chip in 1961, to US$1.25 just a decade later (Kaplan, 2009). The US may no longer be in the midst of a space or arms race, however a world war in carbon removal against the slow-moving enemy that is climate change is surely worth waging.

To date, North American businesses have pioneered interest and advance-purchasing of DAC-derived carbon removal. Funds from technology companies including Stripe (Stripe, 2020), Microsoft (Smith, 2020), Shopify (Kauk, 2020), and Amazon (Amazon, 2020) have kickstarted what needs to be a concerted effort to achieve the scale of DAC the science suggests is necessary. While DAC shares its origins in space with computing and solar technologies, coupling DAC to CO_2 utilisation—whether in diamonds, concrete, vodka, or remote fuel synthesis—will accelerate deployment today, support its downward cost-curve trajectory, and further expand commercial applications. Climeworks' upcoming 4,000 tCO_2/year facility resulting from demand for a consumer carbon offset subscription, alongside some fiscally modest initiatives from the Federal US and United Kingdom governments to directly subsidise and fund DAC technology, and New York State legislation incentivising the procurement of low-carbon concrete utilising CO_2 capture and utilisation technologies are some promising signs (US Senate, 2017; Johnson, 2020; New York State Senate, 2020).

Meanwhile, the UK government has projected it will exceed its own legally binding carbon budget for the period 2023–2027 by between 70 and 230 $MtCO_2e$ (UK Department for Business, Energy and Industrial Strategy, 2019). The UK is certainly not unique in their faltering trajectory towards a net-zero goal. Much like what US government procurement of early computing technologies did for the technology industry, governments, and businesses in this carbon conundrum can make a significant contribution to the emergence of a climate consequential carbon removal and DAC industry with mechanisms like carbon purchase agreements (CPAs). Similar to the power purchase agreements (PPAs) which have become ubiquitous in the deployment of renewable energy, CPAs can offer demand-side certainty for start-ups in the field to invest in R&D, develop the supply-chain capacity, and manufacturing process innovation to provide for the nascent carbon removal industry what Germany's solar PV gift delivered for the world.

Irrespective of sufficient demand-drivers and adoption of CPAs, scaling-up manufacturing capacity from the hundreds to the millions of DAC modules will be a monumental task. The principal components of a solid sorbent-based DAC module involve a contactor and adsorbent array, industrial fan/blower, vacuum pump, and a heat exchanger, as highlighted in **Figure 2**. While most of these are technologically mature components, the contactor array—including the novel sorbent material—is the area with the most potential for capital and operating cost improvement, alongside optimisation of supply chains, and manufacturing innovation. Furthermore, the highly integrated nature of DAC module systems can enable quick capital and operating cost wins through industrial design innovation of novel

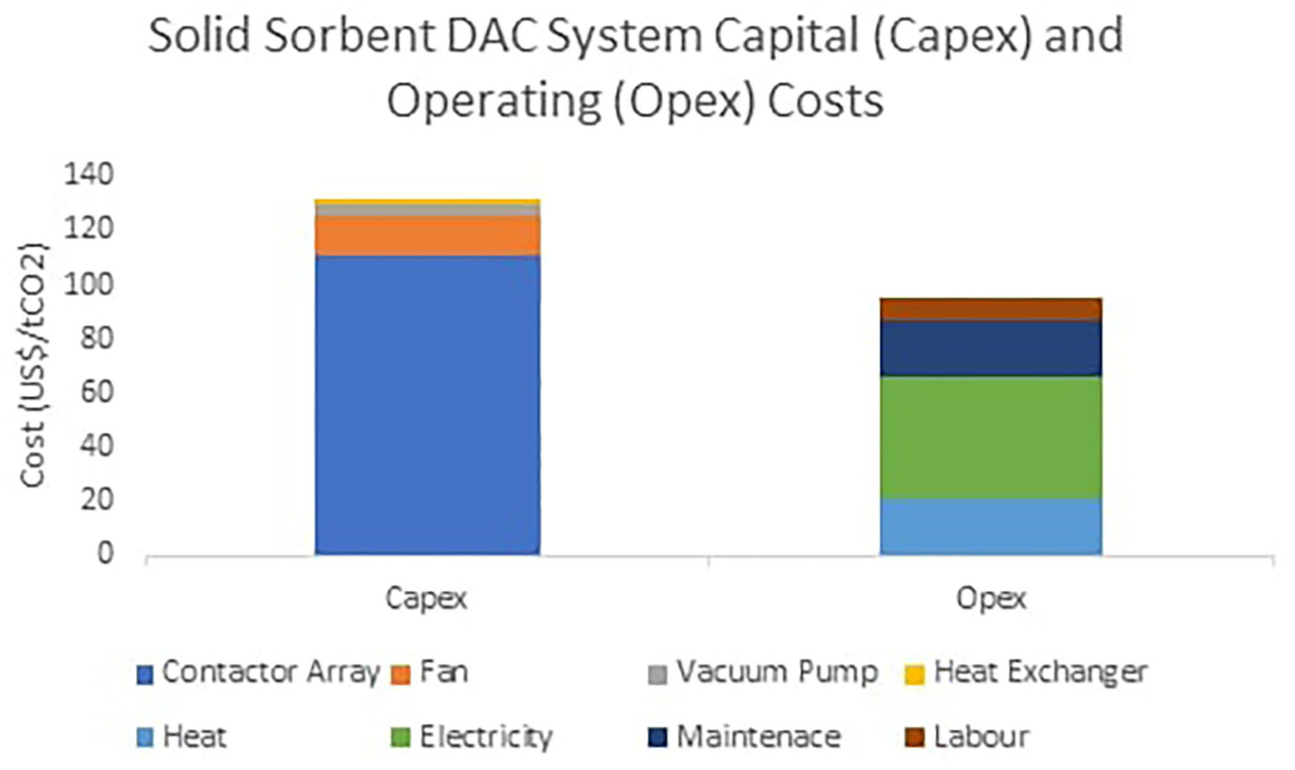

FIGURE 2 | Estimated annualised capital (Capex) and operating (Opex) costs for a solid sorbent direct air capture system with a capacity of 1 Mt/year of CO_2 removal. Graph by Carbon Infinity, based on Wilcox (2019) Graph and National Academies of Sciences, Engineering and Medicine (2019) Data.

(sorbent) components working alongside more mature (fan, pump) equipment.

In the meantime, the chemical engineering innovation and retooling of production for dedicated sorbent manufacturing ought not to be derided. Gigatonne-scale DAC deployment will require upwards of five million tonnes of specialist sorbent production, evidenced by a recent life cycle assessment of Climeworks' facilities (Deutz and Bardow, 2021). While not unprecedented, the utilisation of "spare capacity" is simply out of the question for chemical manufacturing at such a scale; especially for relatively new metal-organic framework (MOF)-based sorbent technologies that Carbon Infinity, Climeworks, and Global Thermostat (among others) are developing. The chemical industry therefore ought to be on notice for the chemical synthesis demands in the millions of tonnes required—from around 700,000 tonnes of ethanolamine production in the US in 2019 for more traditional monoethanolamine (MEA)-based sorbents (Garside, 2020)—to achieve gigatonne-scale DAC deployment.

REAP REWARDS

The efficient and continuous improvement of resource utilisation, encompassing energy, financial capital, material, and human resources will be critical to enable the rapid scale-up of DAC technology and reap the associated climate stabilisation rewards. Resilience and efficiency aligned policies (REAP) around supply chains are seeing renewed interest, not least due to the vulnerabilities exposed by the COVID-19 pandemic. The theoretical resilience of DAC supply chains have relatively strong foundations. Global chemical production is well-distributed globally, with BASF (Germany), the Dow Chemical Company (USA), and Sinopec (China) among the three largest chemical producers which could feasibly expand into mass MOF or MEA-based sorbent production. These countries also represent developed industrial hubs from where strong regionalised, rather than globalised, DAC supply chains should be established, alongside dedicated DAC module manufacturing to initially serve the European, Americas, and Asia-Pacific markets.

The efficient evolution and scale-up of the DAC industry can again benefit from models pioneered by the computing industry. The emergence of specialised semiconductor fabrication facilities enabled the division and specialisation of skills and supply chains which can be replicated in the DAC industry. For example, Apple now designs the architecture of their chips with fabrication contracted out to Taiwan Semiconductor Manufacturing Company (TSMC). We could conceivably see R&D labs and universities focused on developing specialised sorbents and components for a contract manufacturer with dedicated dactories to fabricate; further enabling the DAC industry to develop the specialisation, economies of manufacturing scale, and deployment know-how to move down the cost-curve.

These foundations can be further developed by highly resource-efficient and innovative financing mechanisms, blending public R&D funding with private capital, and future procurement of air captured CO_2. NASA's pioneering Commercial Crew Program, initiated in 2010 and leading to the first crewed space operation by a private company (SpaceX) just a decade later, offers a valuable case study into cost-effective blended-finance routes for the mass scale-up of DAC deployment. The program offered progressively greater funding while simultaneously whittling down prospective suppliers based on achieving certain milestones—culminating in awarding the crew transportation contracts to two companies—Boeing and SpaceX. This fixed-cost, public-private model incentivised commercial partners to reduce delivery costs—forecast by NASA to have saved US$20–30 billion in taxpayer money (McAlister, 2020). Such a model can undoubtedly be replicated for DAC. For example, a fixed-cost, government procurement process, through a government or group of governments with fiscal capacity—potentially via Mission Innovation or the Clean Energy Ministerial. This would take the form of CPAs for the purchase of 100 $MtCO_2$ in 2027 for US$100/tonne (US$10 billion contract)—a price within the realm of possibility, especially if complemented by a structured investment program. Such a program, like that adopted by NASA or the XPRIZE competitions could catalyse the mobilisation of private capital, the acceleration of innovation, and a wartime-like scale-up of dactories, kickstarting the development of a climate consequential global DAC industry.

CONCLUDING THOUGHTS

We must wake up to the unfortunate reality that we are not doing enough, nor at the necessary speed, to both transition away from our fossil-fuelled economic systems and develop a portfolio of solutions to draw down carbon dioxide from the air and prevent the worst effects of climate change. The COVID-19 pandemic has illustrated our ability to mobilise trillions of dollars in public capital, and use advance purchase agreements to repurpose and retool supply chains to develop vaccines, masks, and ventilators in the face of an invisible enemy. Developing carbon removal capacity needs to be approached in a similar vein: future generations will not excuse today's inconsequential action.

While net-zero goals are valuable signals, this needs to be accompanied by a carbon purchasing and investment agenda today to advance carbon removal solutions—in particular DAC technology, if they are to be available at a material scale by mid-century. Scientists, engineers, and entrepreneurs are assembling in increasing numbers to accelerate innovation and develop cutting-edge air capture technologies. However, this must be complemented by sufficient demand-side certainty, led by governments' or conscious corporations' balance sheets and purchasing power, for DAC technology to benefit from the economies of scale and manufacturing innovation dotted across the recent history of computing and energy technology deployment.

The science suggests we need a wartime-like mobilisation of supply chains, manufacturing capacity, and innovation. It is time we start listening and rekindle that spirit of ambition.

DATA AVAILABILITY STATEMENT

The original contributions generated for the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication. Any opinions and calculations presented in this article are the views of DI only and are not necessarily shared by his affiliations.

ACKNOWLEDGMENTS

The author would like to thank the editors of this journal, the reviewers of this article, and Stripe Inc., for sponsoring this important research topic.

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Conflict of Interest: The author is the Founder and a Director of Carbon Infinity.

TECHNOLOGY AND CODE
published: 06 May 2021
doi: 10.3389/fclim.2021.656108

Scaling CO_2 Capture With Downstream Flow CO_2 Conversion to Ethanol

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To prevent the global average temperature from increasing more than 1.5°C and lower the concentration of greenhouse gases (GHGs) in the atmosphere, most emissions trajectories necessitate the implementation of strategies that include both GHG mitigation and negative emissions technologies (NETs). For NETs, there are unique research challenges faced by both CO_2 capture and utilization to scale in an economically feasible manner. Starting with incumbent methods, wherein CO_2 is recovered from a high concentration source, and moving toward CO_2 capture from more widely available dilute sources, we outline how CO_2 capture systems interface with downstream utilization in flow reactors. To provide a real-world point of comparison, we analyze CO_2 sourcing for Air Company's CO_2-to-alcohols pilot and demonstration scale deployments in Brooklyn, New York, USA and Calgary, Alberta, Canada as case studies. The degree of reduction in atmospheric CO_2 depends on product alcohol usage; for example, use as a fixed chemical feedstock provides longer term emissions reduction than as a fuel, which is eventually oxidized. Lastly, we discuss the barriers that are present for economic scale-up of CO_2 capture and utilization technologies broadly.

Keywords: carbon dioxide utilization, direct air capture, carbon recovery, carbon capture, solar fuels, emissions to liquids, ethanol, flow chemistry

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Specialty section:
*This article was submitted to
Negative Emission Technologies,
a section of the journal
Frontiers in Climate*

***Received:** 21 January 2021*
***Accepted:** 06 April 2021*
***Published:** 06 May 2021*

Citation:
*Pace G and Sheehan SW (2021)
Scaling CO_2 Capture With
Downstream Flow CO_2 Conversion to
Ethanol. Front. Clim. 3:656108.
doi: 10.3389/fclim.2021.656108*

INTRODUCTION

Anthropogenic climate change is perhaps the most significant existential challenge that humanity faces today (Mora et al., 2018; Gills and Morgan, 2020). A rapid increase in utilization of fossil fuels since the industrial revolution has increased the concentration of greenhouse gases (GHGs) in the atmosphere at a faster rate than has been observed previously (Peng et al., 1983; Etheridge et al., 1996; Lacis et al., 2010). The overwhelming majority of scientific evidence points to this increase in atmospheric GHGs, specifically carbon dioxide, being the cause of the changing global climate (Oreskes, 2004; Hartmann et al., 2013). Historically, there has been an equilibrium between CO_2 sequestration via photosynthesis and CO_2 emissions by biodegradation and other natural mechanisms that gradually removed CO_2 from the atmosphere, transforming Earth's atmosphere into the habitable one that we now rely on (Des Marais, 2000; Gonzalez Hernandez and Sheehan, 2020). Burning fossil fuels to power today's society introduces a new, rapid flux of CO_2 into the atmosphere that natural photosynthesis can no longer compensate (Grace, 2004; Le Quéré et al., 2018).

Renewable technologies must be developed and deployed to bring equilibrium back to the global carbon cycle (Holdren et al., 1980; Goreau, 1990; Gielen et al., 2019). There are several renewable approaches to CO_2 emissions mitigation, and ultimately the planet will require a diversified portfolio as no single technology could reasonably abate global CO_2 emissions alone (Moriarty and Honnery, 2012; Fasihi et al., 2019; Realmonte et al., 2019). Many viable solutions rely on the increased utilization of renewable (wind, solar, hydroelectric, and others) energy with low lifecycle CO_2 emissions intensity (Sims, 2004). Displacing fossil fuel-based electricity generation with renewables indirectly reduces GHG emissions by preventing them from being emitted in the first place. Carbon capture and storage (CCS) technologies, on the other hand, provide direct CO_2 emissions reduction by sequestering CO_2 from anthropogenic sources or from the air (Snæbjörnsdóttir et al., 2020). Lastly, carbon capture and utilization (CCU) affords both direct and indirect emissions reduction by directly utilizing captured CO_2 as a reactant to make a product, which in turn displaces the product's fossil-derived counterpart. Together, the latter two technologies are known as carbon capture, utilization, and storage (CCUS). CCUS is a subset of negative emissions technologies (NETs), which is defined for the purposes of this article as technologies that reduce atmospheric GHG concentrations below the concentration that would occur without the technology (McLaren, 2012).

The utility of NETs increases over time as we implement measures to reduce global GHG emissions. In today's world where coal is still burned for electricity, it is in many cases more advantageous to replace these most polluting emitters with renewable energy to prevent their CO_2 emissions in the first place (Gaffney et al., 2020). Once the "lowest hanging fruit" is taken by removing the worst emitters, the relative difficulty of mitigating CO_2 increases. At this intermediate point, the utility of NETs to capture CO_2 from clean emitters is comparable to deploying additional indirect CO_2 emissions reduction measures. Ultimately, when most electricity generation is done renewably (which introduces additional energy storage challenges that further enable several CCU technologies) there will still be substantial CO_2 emissions in several areas, such as the chemical and aerospace industries, agriculture, aviation, and cement production (Fasihi et al., 2019). At this point, NETs will be required to maintain equilibrium in the global carbon cycle. As of 2020, we need to remove more than 170 gigatons of CO_2 from the atmosphere to remain under the target of 1.5°C of warming by 2100 (Johansson et al., 2020). This is the equivalent of more than 5 times the total amount of CO_2 emitted globally in 2019 (Friedlingstein et al., 2020).

Currently, the most widely commercialized systems that capture CO_2 recover it from a high-purity source, such as hydrogen production or sugar fermentation (de Assis Filho et al., 2013). These CO_2 recovery (CR) systems utilize feed streams with typically >95% CO_2 concentration, requiring minimal impurity removal to increase the concentration to >99%, while compressing to provide a liquefied CO_2 product for ease of transport and use. In contrast, point source CO_2 capture (PSC) uses a more dilute feed stream, such as natural gas flue gas which is ∼4–16% CO_2 in N_2 and O_2 from the air (Jiang et al., 2019). A testament to the energetic implications of CO_2 concentration on NET efficiency, much PSC research focuses on source gases with higher CO_2 concentrations (Li et al., 2011; Baker et al., 2017). Lower concentration feed streams necessitate use of a higher volume sorption system, and typically uses the industry standard monoethanolamine (MEA) CO_2 scrubber. Direct air capture (DAC), on the other hand, captures CO_2 from the air at ∼416 ppm which is much more energetically challenging than either CR or PSC (Ren et al., 2021). A key differentiator between these technologies is the concentration of CO_2 in their source material, which dictates the feedstock mass and energy required for separation.

In this article, we present an analysis of CO_2 capture technologies as they interface with downstream continuous flow CO_2 utilization systems. We provide an industrial perspective by discussing the advantages and challenges to deploying flow reactors downstream from CR at high-purity point sources in the Air Company pilot reactor in New York, as compared to PSC from the flue gas of a natural gas-fired power plant using an amine absorption-based system at the Air Company demonstration reactor in Calgary. In doing so, we highlight the trajectory for deployment of CO_2 capture technologies more broadly, when coupled with utilization as these emerging fields and respective technologies scale. Lastly, we discuss the lessons learned from these deployments as they relate to integrated CO_2 capture and utilization systems and their associated technological and infrastructural barriers.

TECHNOLOGIES THAT CAPTURE CO_2

All three major categories of CO_2 capture technologies are subject to the same development constraints as other chemical processes. To progress from conceptual idea, to a proof of concept, followed by a benchtop prototype, then pilot, demonstration, and small commercial plant is highly capital intensive and requires research and development infrastructure of its own. As they are both still the subject of heavy R&D, the economics for both PSC and DAC do not reach the low cost point that CR has achieved. Given the long chemical scale-up and development cycles and the fundamentally higher energy requirement for PSC and DAC, CR is the lowest hanging fruit today as a CO_2 source to provide suitable feedstock for CO_2 utilization. On the other hand, CR has the lowest potential for scale and long-term CO_2 emissions reduction since there are limited sources; many are dependent on industries powered by fossil fuels that can be replaced with renewable alternatives, such as H_2 production (**Table 1**).

CR acts on CO_2-rich gases produced during processes such as fermentation and is fully commercially available (Haszeldine et al., 2018). Due to its source gas containing >90% CO_2, it can function without high thermal energy input to capture and release CO_2 from a sorbent and is typically fully powered by electricity. This gives it the best economics of all the CO_2 capture technologies today, as evidenced by its widespread use to produce CO_2 for sale. Due to its high concentration feedstock, CR is

TABLE 1 | Typical reported energy consumption and potential scale for CO_2 capture technologies as defined by their source concentration.

	CO_2 Recovery	CO_2 Capture	DAC
Source concentration	>90%	4–16%	>416 ppm
Sorbent phase	Liquid	Solid, Liquid	Solid, Liquid
Reported output temperatures	−18°C	30–130°C	80–900°C (Sadiq et al., 2020)
Reported output pressures	20–57 bar (liquid)	0.1–2 bar	1–100 bar
Example sources	Fermentation, H_2 Refining	Coal and natural gas power generation	Ambient air
Reported energy cost (kWh/ton)	120 kWh/ton (Möllersten et al., 2003)	666–2,650 kWh/ton	1,470–3,803 kWh/ton
Electrical energy cost range (kWh/ton)	120 kWh/ton	136–189 kWh/ton (Fitzgerald et al., 2014)	200–775 kWh/ton (Goeppert et al., 2012)
Thermal energy cost range (kWh/ton)	N/A	530–2,500 kWh/ton	994–3,030 kWh/ton (Broehm et al., 2015)
Potential scale (GT CO_2/year)	<1	~6 (Olivier et al., 2017)	>33

TABLE 2 | Summary of technologies under R&D to improve the economics of PSC, including their current stage of development and reported technology readiness level (TRL).

Point Source CO_2 capture technology	Stage of development	TRL
Monoethanolamine (MEA) (Jiang et al., 2019)	Commercialized	9
Solid sorbent (Svante)	Commercialized	9
Ammonia absorption (Shirmohammadi et al., 2018)	Commercial demonstrations	6–9
Vacuum swing adsorption (Divekar et al., 2020)	Lab	3–5
Metal-organic frameworks (MOFs) (Witman et al., 2017)	Lab	3–5
Clathrate-based (Lim et al., 2018)	Lab	3–5
S-EGR membranes (Baker et al., 2017)	Lab	3–5
Nonaqueous amine absorbent (Guo et al., 2019)	Lab	3–5
Two-membrane system (Turi et al., 2017)	Theoretical	2–3
Activated carbon adsorption (Jiang et al., 2019)	Theoretical	2–3
Photoresponsive MOFs (Park et al., 2020)	Theoretical	2–3

TABLE 3 | Selected technologies under R&D to improve the economics of DAC, including current stage of development and reported TRL.

Direct air capture technology	Stage of development	TRL
Amine adsorbents (Broehm et al., 2015)	Commercial demonstrations	8–9
Solid adsorbents (Ishimoto et al., 2017)	Commercial demonstrations	8–9
MOFs (Lee et al., 2014)	Lab	2–5
Electrochemical absorption (Voskian and Hatton, 2019)	Lab	2–3
Resin (moisture swing) (Lackner, 2013)	Lab	2–3
$NaOH/Na_2CO_3$-$Ca(OH)_2/CaCO_3$ (Broehm et al., 2015)	Theoretical	2–3

the most entropically and energetically favorable CO_2 capture technology by a large margin as shown in **Table 1**. However, because CR has the lowest potential for scale for global CO_2 removal, it is insufficient to meet decarbonization goals over the long term if not used in tandem with PSC and DAC. Due in part to its low potential for scale and need for future technological improvements, there is a dearth of scientific literature and policy-based focus on CR. For this reason, it makes the most pragmatic sense to prioritize deployment of CR in locations where there are concentrated CO_2 streams being emitted as the lowest-hanging fruit in the NET portfolio. These deployments can be done rapidly while simultaneously continuing to scale PSC and DAC technologies.

PSC predominantly acts on post-combustion point sources, such as natural gas combined cycle (NGCC) plants with CO_2 concentrations of 4–16% (Jiang et al., 2019; see **Table 1**). Currently, PSC is operating at industrial scales, but its poor economics prevent widespread deployment, prompting further R&D in laboratories and pilot plants to reduce capital and energy costs (**Table 2**). Several PSC pilots show significant promise to further these goals, with innovations such as corrosion inhibitors helping to reduce heat duty from 5.0 to 1.8 GJ/ton CO_2 and with projected return on investment within 2.5 years (Idem et al., 2015; Shirmohammadi et al., 2018). Current challenges are centered around optimizing adsorbent capacity at the high temperatures and low CO_2 concentrations present in flue gas streams (Divekar et al., 2020). Unfortunately, many otherwise promising improvements in PSC (including selective membranes in combined cycles reaching 90% capture rates) require expensive retrofitting of plants, which may deter commercial deployment (Turi et al., 2017).

PSC typically uses the byproduct gas of fossil fuel combustion as a source of CO_2, raising concerns that overreliance on PSC may enable continued fossil fuel dependence. In contrast, DAC has been proposed as a mechanism that minimizes the need for infrastructural change or fossil fuel dependence from its inception (Lackner et al., 1999). As DAC removes CO_2 from air, with a concentration that is orders of magnitude lower than that of CR and PSC, it requires the highest energy input of the technologies studied (Breyer et al., 2019). One of its strengths as a component of a diversified portfolio of NETs is in offsetting distributed emissions, such as those from aviation and agriculture. Areas for improvement of DAC technology primarily focus on decreasing energy requirements for CO_2 desorption (see **Table 3**). Of the high temperature and low temperature DAC systems, low temperature thus far achieves lower heat supply costs (Fasihi et al., 2019). Thicker absorbent films, thinner monolithic walls, and adsorbents with higher efficiency at ambient air conditions can decrease the required energy of temperature vacuum swing adsorption (Sinha et al., 2017).

Critics argue that both PSC and DAC delay an inevitable transition to renewables, and thus increase the societal costs associated with pollution (Jacobson, 2019, 2020). There are scenarios in which this concern is understandable; some DAC deployment trajectories require a quarter of global energy demand by the end of the century (Realmonte et al., 2019). However, the warming targets in the Paris Agreement can only be met if NETs are part of the portfolio of climate solutions deployed (Haszeldine et al., 2018), making it imperative to deploy both low-carbon energy generation and NETs. The timing and trajectory of NET deployment is critical to reconcile both sides of the discussion. In the near term, NETs have the most impact by displacing the processes that are both most CO_2 intensive, thereby maximizing both direct and indirect CO_2 emissions, and have no renewable replacement in the foreseeable future.

We propose a trajectory for deployment of CO_2 capture technologies that follows this approach, and examples on the pilot and commercial demonstration scales using continuous flow CO_2 conversion systems are described below. The stranded sources of concentrated CO_2 are urgent to capture, but not as important in the long-term as our ability to remove CO_2 from the air. Correspondingly, the energy and capital intensity of DAC make it more economic to first pursue lower-hanging fruit, especially when today's renewable energy infrastructure does not provide adequate heat to power DAC systems without burning fossil fuels (Holmes et al., 2013; Keith et al., 2018), but it is critical

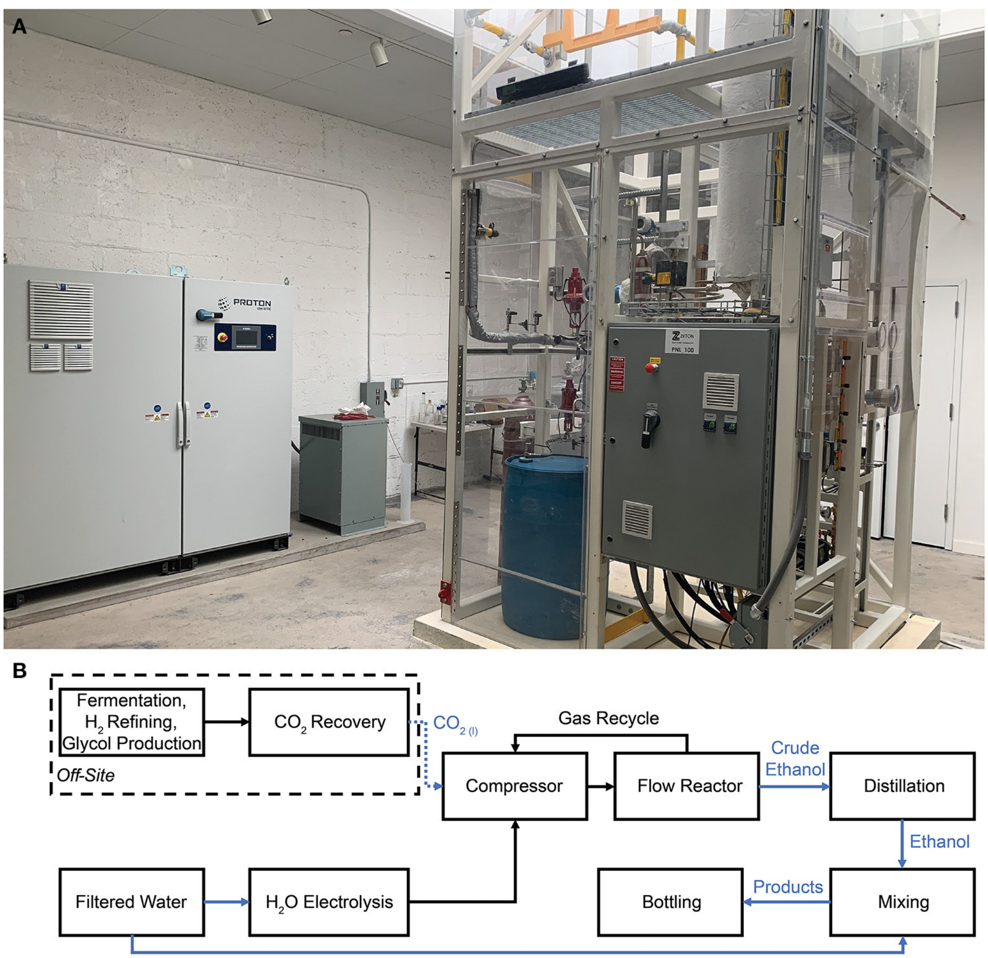

FIGURE 1 | Air Company pilot plant in New York that utilizes CO_2 sourced from CR, **(A)** photograph of the electrolyzer for H_2 production (left) and CO_2 hydrogenation system (right), and **(B)** block flow diagram of the processes taking place in the facility.

that large-scale R&D efforts lower these expenses in the future. Proper timing for both renewable electricity and NETs is critical to maximize societal benefit.

AIR COMPANY EXAMPLES

Air Company's CO_2-to-alcohols commercial pilot plant in Brooklyn, New York is a distillery that utilizes CO_2 delivered from CR-sourced sites, including fermentation facilities, to produce ethanol. The ethanol is distilled, mixed, and bottled on-site to produce spirits and hand sanitizer. The facility is powered by a mixture of offsite wind turbines and utility-scale solar photovoltaics, enabling ethanol production from CO_2, H_2O, and renewable electricity. **Figure 1A** is a photograph of Air Company's CO_2 conversion pilot plant in the facility, with a NEL H-series H_2O electrolysis system and a fixed bed flow reactor for CO_2 hydrogenation. A flow chart of the process can be seen in **Figure 1B**; in brief, CO_2 and H_2 are compressed, heated, and fed into the 16-foot fixed bed flow reactor. The reactor is filled with a novel and proprietary heterogeneous catalyst that has not yet been reported in literature and is developed and synthesized on the kg-scale in Air Company's facilities, enabling stable and continuous conversion of CO_2 and H_2 into ethanol. The gaseous products are passed through a condenser assembly, which separates the room-temperature crude ethanol aqueous liquid and gases (Sarp et al., 2021). Room temperature gases are recycled into the reactor for further conversion. The facility and systems are further adaptable to accommodate CO_2 electrolysis when that technology is at an appropriate commercial stage of development (Chen et al., 2018).

After the CO_2 conversion process, the crude ethanol is filtered and distilled to produce a neutral spirit that is ∼95% ethanol by volume, the remaining 5% being water with <300 ppm net of all impurities by gas chromatography (GC), and meets all requirements for United States Pharmacopeia (USP) grade. In this facility, the CO_2 fed into the reactor is captured offsite via CR powered by renewables, which typically requires 120 kWh/ton, together with ∼30 kWh/ton for transportation. CR is a continuous flow system that delivers CO_2 as a liquid

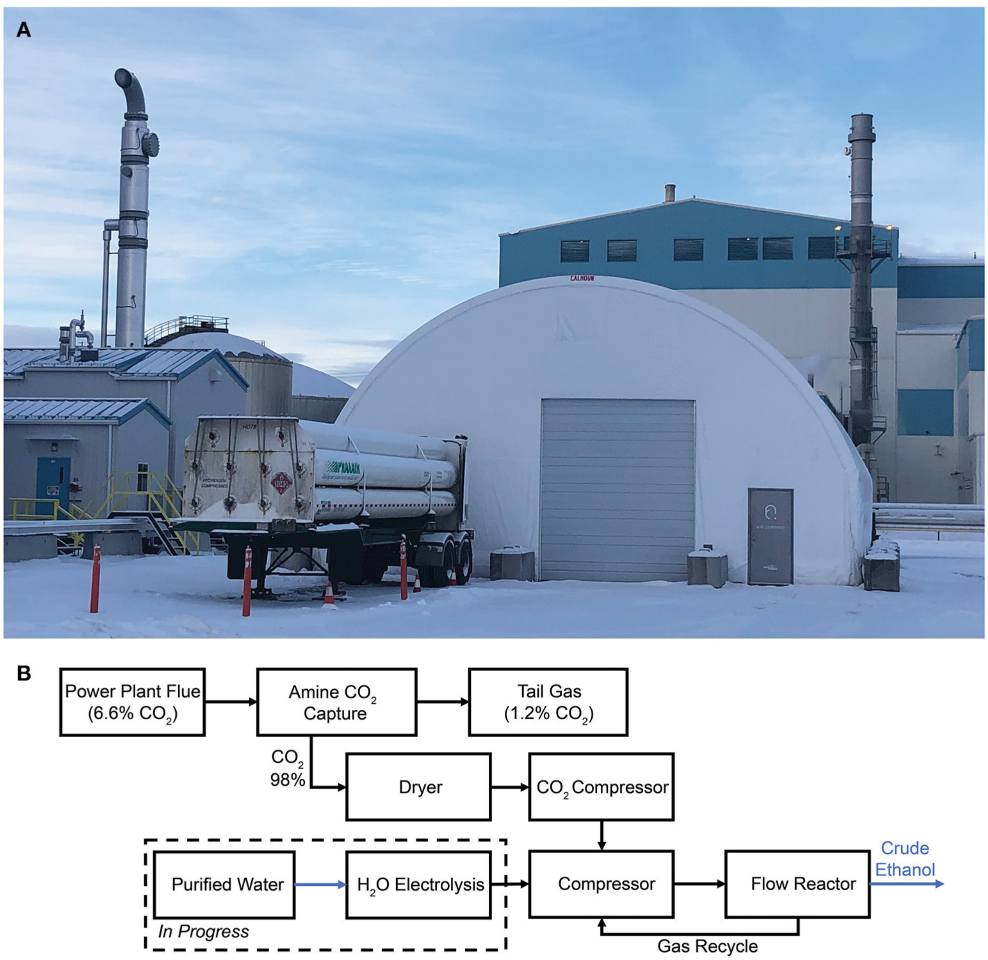

FIGURE 2 | Air Company plant in Calgary utilizing CO_2 sourced from PSC at a NGCC power plant, **(A)** photograph of the CO_2 conversion system, and **(B)** block flow diagram of the processes taking place in the facility.

TABLE 4 | Summary of inlet parameters and approximate energy cost for CO_2 capture coupled with pilot and production scale downstream flow reactors.

Parameter	Brooklyn pilot	Calgary demonstration
CO_2 emitter concentration	95%	6.6%
CO_2 capture electricity required	120 kWh/ton CO_2	136 kWh/ton CO_2
CO_2 capture heat required	n/a	2,405 kWh/ton CO_2
Transportation fuel required	30 kWh/ton CO_2	n/a
CO_2 product concentration	>99%	98%
Delivery pressure	57 bar (liquid, 21 °C)	0.2–1 bar
Water content (weight %)	<0.1% (Dry)	2%
Electrolysis energy required	11 MWh/ton CO_2	8.9 MWh/ton CO_2

at high pressure, ensuring consistent supply and eliminating concern about the rate or variability of CO_2 use in flow reactors downstream.

Defining NETs as technologies that reduce atmospheric GHG concentrations below that which would occur without the technology, lifecycle assessment is based on a cradle-to-gate analysis (McLaren, 2012). Under optimal production conditions and operating at capacity, to produce 1 kg of ethanol as a functional unit, a minimum of 1.91 kg of CO_2 and 0.26 kg of H_2 is required. Depending on the lifecycle analysis methodology, a reasonable carbon footprint for the captured CO_2 is ~ -1.78 kgCO_2e given that the CO_2 used in the process would otherwise be emitted to the atmosphere (Müller et al., 2020). The primarily wind and solar power for the facility has average lifecycle emissions of 10 gCO_2e/kWh (Sovacool, 2008). Water electrolysis consumes 81 kWh/kg H_2, which equates to 0.21 kgCO_2e (NEL Hydrogen, 2020). Compression, heating, cooling, and distillation are all powered by electricity or waste heat and net ~8 kWh/kg ethanol. Amortized material of construction emissions over production lifetime averages 40 gCO_2e/kg ethanol, accounting for unoptimized system mass (Sheehan, 2021). This results in an estimated carbon footprint of ~-1.45 kgCO_2e/kg ethanol, though a more detailed and thorough lifecycle analysis that includes cradle-to-grave considerations is the subject of a future study that is currently underway.

Especially when transportation GHG emissions are minimal as to keep the net CO_2e <100 kg per ton of CO_2 captured, CR is an ideal capture medium for downstream flow CO_2 conversion. The CO_2 is delivered as a liquid, which has a constant vapor pressure. This is helpful in flow systems if there are one or more stages of compression prior to introduction of CO_2 to other reactants. The suction pressure of these compressors must remain constant for optimum operation and to ensure adequate compressor lifetime, and severe variation in inlet CO_2 pressure or temperature can cause challenges that prompt plant shutdown. CR eliminates these operational variables and is economic without substantial subsidy, which makes it a model system for integration with flow CO_2 conversion systems in the near-term despite its limited long-term utility.

Unlike fermentation processes, NGCC power plants release flue gas streams with CO_2 concentrations of 4–16%. In this case, CO_2 is a harmful byproduct of electricity production. PSC from NGCC power plants takes place today using a commercial monoethanolamine (MEA) process, in which CO_2 is absorbed by liquid MEA at high pressure and low temperature and stripped from the MEA at low pressure and high temperature. Air Company's Calgary commercial CO_2-to-alcohols demonstration plant is deployed at the Shepard Energy Center, an 860 MW NGCC power plant. The NGCC byproduct flue gas containing 6.6% CO_2 is fed into the MEA adsorption system operated by the Alberta Carbon Conversion Technology Center (ACCTC), shown in the left on the photograph in **Figure 2A**. The product from the capture system, water-saturated CO_2 (98%), is then pumped into the Air Company building. Tail gas is typically emitted from amine CO_2 capture systems, which contains ~1.2% CO_2 that is not captured because it is too energy-intensive to do so. The water content of the captured CO_2 could have implications for the efficacy of the system, and a knockout drum dryer is used for its removal. After compression, the CO_2 is combined with H_2 and introduced into a reactor similar to, but significantly larger than, the Air Company pilot plant. While H_2 was supplied via tube trailer in the interim, construction of an integrated facility with a H_2O electrolyzer powered by renewable electricity is nearly complete. **Table 4** shows a summary of the gas inlet parameters between the pilot and demonstration facilities.

DISCUSSION AND CONCLUSIONS

For the Air Company pilot and commercial demonstration facilities as well as deployments for larger CO_2 utilization systems by us and others in the future, plant economics will play a major role in the technology used for CO_2 capture. Our experiences suggest that the hypothesis to target the high-concentration CO_2 emitters first is valid, but the GHG reduction of these sources is limited. This calls for research to reduce the capital costs, energy requirements, and improve product characteristics (e.g., temperature, pressure) for PSC and DAC at-scale. In our case, using a CR-sourced pilot reactor and PSC-sourced commercial demonstration reactor, the biggest barrier to use of DAC was the large capital expenditure for small units (on the order of 1–10 tons per day of CO_2). Innovations in materials science and sorbent materials that drive down the capital cost of small DAC units would be hugely beneficial for distributed deployment, especially in industries where customers are willing to pay a substantial premium for modular and distributed DAC, thus offsetting its comparably larger operational expense.

Beyond capital expenditure and operational considerations, the necessity of retrofits for certain PSC technologies could represent key barrier to PSC deployment and receives little academic attention (Koelbl et al., 2014). Due in part to the costs of retrofits and the abundance of non-retrofittable power plants, DAC has surprisingly been identified as the less expensive option compared to PSC in one third of NGCC plants.

Further select cases (e.g., microalgae cultivation) also make DAC energetically competitive despite being the furthest from commercial availability (Mangram, 2012; Wilcox et al., 2017; Azarabadi and Lackner, 2020; Hirsch and Foust, 2020). There is no fundamental reason why both DAC and PSC systems also cannot deliver product CO_2 with the same consistency, pressures, and temperatures as CR to optimize integration with downstream flow reactors. Beyond facilitating retrofits, research that improves the feedstock input and CO_2 output tolerances of DAC and PSC technologies could further accelerate commercialization.

Locations for geological storage and measures to mitigate leakage also represent key barriers to scaling NET outside CR, PSC, and DAC technologies themselves that must be addressed (Koelbl et al., 2014; von Strandmann et al., 2019). Since CCS does not produce a physical, saleable end product, exploration into further profitable NET opportunities, mass production and innovative infrastructural development, financial incentives, and international policy will be necessary to reach emissions targets (Honegger and Reiner, 2018; Hirsch and Foust, 2020; Olfe-Kräutlein, 2020). The high startup costs associated with early CCU deployment may potentially be overcome by following successful disruptive innovation models in electric vehicles (EVs) and EV infrastructure that move from high-end to mass markets to scale pragmatically, for example, as Tesla has done (Chen and Perez, 2018).

Ultimately, widespread CO_2 capture and utilization will be needed to meet emissions targets, but these technologies alone will not save us. Real infrastructural change to facilitate an economic trajectory of CO_2 capture deployment is required. Similar to the way the hardware and software for EVs existed prior to its currently accelerating adoption due to cultural and political changes, these fundamental pieces exist for CO_2 capture. CO_2 utilization technologies now provide an additional incentive to build the required infrastructure on local and global scales.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

GP performed research on CO_2 capture technologies, compiled information in **Tables 1**, **2**, and drafted the main body of the article. SS conceptualized the research, the facilities in **Figures 1**, **2**, and supervised the work. Both authors wrote and revised the manuscript.

FUNDING

GP acknowledges the New York State Energy Research and Development Authority (NYSERDA) for their Clean Energy Internship Program. SS acknowledged the Ontario Centre of Innovation for Phase 1 and 2 awards under their Solutions 2030 Challenge (Nos. 29828 and 31826), and NASA Centennial Challenges for a Phase 1 award from their CO_2 Conversion Challenge.

ACKNOWLEDGMENTS

We thank the Air Company operations team, Gregory Constantine, Jackson Constantine, Morgan Sparkes, Nicholas Steinke, Jodi Taylor, Joshua Anderson, Santiago Gonzalez Hernandez, Dr. Chi Chen, and Dean Pawulski, for their work on the facilities described in this article. We also acknowledge Dr. Marcius Extavour and the NRG COSIA Carbon XPrize team, Dr. John Sirman, and Dr. Aref Najafi for their discussions and support of CCUS technologies.

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Conflict of Interest: All authors are employees of Air Company.

frontiers in Climate

ORIGINAL RESEARCH
published: 26 May 2021
doi: 10.3389/fclim.2021.630893

Future Prospects of Direct Air Capture Technologies: Insights From an Expert Elicitation Survey

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Direct air capture (DAC) technologies are promising but speculative. Their prospect as an affordable negative emissions option that can be deployed in large scale is particularly uncertain. Here, we report the results of an expert elicitation about the evolution of techno-economic factors characterizing DAC over time and across climate scenarios. This is the first study reporting technical experts' judgments on future costs under different scenarios, for two time periods, for two policy options, and for two different DAC technologies. Experts project CO_2 removal costs to decline significantly over time but to remain expensive (median by mid-century: around 200 USD/tCO_2). Nonetheless, the role of direct air capture in a 2°C policy scenario is expected to be significant (by 2050: 1.7 [0.2, 5.9] GtCO_2)[1]. Projections align with scenarios from integrated assessment model (IAM) studies. Agreement across experts regarding which type of DAC technology might prevail is low. Energy usage and policy support are considered the most critical factors driving these technologies' future growth.

Keywords: negative emission, expert elicitation, cost, uncertainty, policy, direct air capture

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Specialty section:
This article was submitted to Negative Emission Technologies, a section of the journal Frontiers in Climate

Received: 18 November 2020
Accepted: 28 April 2021
Published: 26 May 2021

Citation:
Shayegh S, Bosetti V and Tavoni M (2021) Future Prospects of Direct Air Capture Technologies: Insights From an Expert Elicitation Survey. Front. Clim. 3:630893. doi: 10.3389/fclim.2021.630893

1. INTRODUCTION

According to the Special Report on Global Warming of 1.5° C (SR1.5) by the Intergovernmental Panel on Climate Change (IPCC), achieving climate targets such as those outlined in the Paris agreement, requires a fast transition of energy and economic systems to renewable, clean, and sustainable alternatives as well as substantial deployment of carbon dioxide removal (CDR) technologies (Allen et al., 2019). Across future socioeconomic pathways and models, most scenarios staying well below 2°C by the end of the century require net-zero greenhouse gas (GHG) emissions mid-century and negative aggregate emissions after that (Rogelj et al., 2018). Carbon dioxide removal, which is essential to achieve these objectives, includes a wide range of terrestrial and ocean-based technologies from bio-energy with carbon capture and storage (BECCS) (Azar et al., 2010), to direct air capture (DAC) (Socolow et al., 2011), and indirect ocean capture (IOC) (de Lannoy et al., 2018).

However, the technologies' effectiveness in permanently removing GHG emissions from the atmosphere depends on how system boundaries are defined and differ substantially across different negative emission technologies (Tanzer and Ramirez, 2019). Furthermore, the scale of carbon

[1]Throughout this paper, we report the median estimate and the uncertainty range for the estimated values as M $[L, U]$ where M is the median and L and U are the 10th and 90th percentiles, respectively.

dioxide removal required to achieve climate targets of 1.5° and 2°C is currently unproven. There is a wide range of technical, environmental, social, and ethical risks associated with such massive deployment (Fuss et al., 2014; Intergovernmental Panel on Climate Change, 2018; Lenzi, 2018) with the required spending estimated to reach up to a third of government general expenditure in developed countries (Bednar et al., 2019). This adds to existing uncertainties about the future cost and capacity of CDR technologies (Waisman et al., 2019).

In recent years, DAC has attracted investors and policymakers' attention to the point that it is now considered an appealing CDR strategy. This is because of its potential capability of reversing the increase in atmospheric CO_2 concentrations by directly removing CO_2 from the atmosphere without substantial interference in the energy, food, and water infrastructure (Smith et al., 2016; Wilcox et al., 2017). There are currently two types of DAC technologies in the commercial stage using either solid sorbent or liquid solvent materials for capturing CO_2 from the ambient air.

DAC plants can be installed anywhere and can use various types of energy input, making them an attractive solution compared to other CDR methods such as BECCS, which face stricter geographical constraints (Fridahl and Lehtveer, 2018). However, to achieve net negative emissions, DAC technologies need to be coupled with renewable energy sources such as solar and wind (Breyer et al., 2019), limiting the feasibility of DAC projects.

The National Academy of Sciences (NAS) report on negative emissions technologies has provided the latest and most reliable estimates for DAC technologies' cost and capacities (National Academies of Sciences Engineering and Medicine, 2019). Further assessment of DAC technologies reveals that achieving net-zero emissions by mid century in the US alone would require between 560 and 1,850 $MtCO_2$ to be removed by DAC technology and then permanently stored underground annually (Larsen et al., 2019). However, there are only few studies on techno-economic assessment of DAC technologies (Keith et al., 2018; Azarabadi and Lackner, 2019; Fasihi et al., 2019) and their potential contribution to mitigation efforts (Realmonte et al., 2019; Fuhrman et al., 2020). These studies have highlighted the sensitivity of DAC on techno-economic assumptions and the pace and extent of capacity addition. All of these assumptions are highly speculative, given the early stage of technological development.

A structured expert elicitation can help narrow key parameters and quantify uncertainties in the form of probabilistic distributions that can be used in subsequent modeling analysis of decarbonization pathways. Furthermore, the evolution of the cost and capacity factors over time and across policies is missing in DAC technologies' current techno-economic assessments. Although insightful, the quantitative results of expert elicitation studies should be treated with caution. For example, between 2008 and 2011, several expert elicitation studies were conducted to project the future solar photo-voltaic systems' future costs in 2030 (Curtright et al., 2008; Baker et al., 2009; Bosetti et al., 2012; Verdolini et al., 2015). However, a recent study showed that the actual price in 2017–18 was lower than the median projections for 2030 (Nemet, 2019). Therefore, in addition to providing the median projections, we have emphasized on identifying the range of uncertainties in experts' judgements and have presented the results in the context of their background policy scenarios.

In this paper, we report the results of an elicitation of 18 experts in negative emissions and direct air capture technologies and the economic and policy issues. Expert elicitation studies have been widely used to gauge uncertainty surrounding the future costs of various energy technologies (Wiser et al., 2016; Anadon et al., 2017; Thomas et al., 2017; Baik et al., 2020). Our survey was designed to elicit information about DAC technologies' future in two future scenarios of climate change policies; policy as usual (PAU) and a stringent climate policy consistent with the 2°C target (2DC).

Under each scenario, experts were first asked to choose a technology that they thought will be the dominant DAC technology in 2050. Then they provided the 10th, 50th, and 90th percentiles of the cost and annual installed capacity of the chosen DAC technology in the present (year 2020) and in the future (year 2050). The current cost estimates of DAC technologies vary based on the material used in the capturing process and other assumptions about the capturing and regeneration units' design. Therefore, they are subject to a wide range of uncertainty (Socolow et al., 2011; Keith et al., 2018; Tollefson, 2018; National Academies of Sciences Engineering and Medicine, 2019). For all additional questions, experts were asked to provide further information referring only to the PAU scenario and DAC technology choice under this scenario.

1.1. DAC Technologies

Every DAC technology achieves the objective of capturing carbon from the ambient air through two distinct phases: carbon dioxide capture, and regeneration. First, a chemical is used to capture carbon from ambient air and binds with it in a contactor. The choice of the carbon capturing material is the key determining factor in designing a DAC plant at this phase, as it can be either a solid sorbent or a liquid solvent. During the regeneration phase, captured carbon is separated from the binding chemical. The regeneration process requires a substantial amount of energy in the form of heat, electricity, pressure, or a combination of them depending on the type of the material used in the capturing process. After the removal of the CO_2, the material will be regenerated for reuse. At the same time, the captured CO_2 is sent out for storage or utilization (Sanz-Perez et al., 2016). **Figure 1** represents the general setup of a DAC process with capture and regeneration phases.

There are currently two main DAC technologies available at the commercial stage, one liquid and one solid. The liquid solvent system uses a hydroxide solution (NaOH or KOH) that is highly binding and reacts quickly with the CO_2 from the air to form water and carbonate in the contractor. In the regeneration unit, the carbonate is heated to about 900°C to release a high-purity CO_2 gas that can be further processed for sequestration and/or utilization (Socolow et al., 2011; National Academies of Sciences Engineering and Medicine, 2019). Several designs and materials have been proposed for this process (Baciocchi et al.,

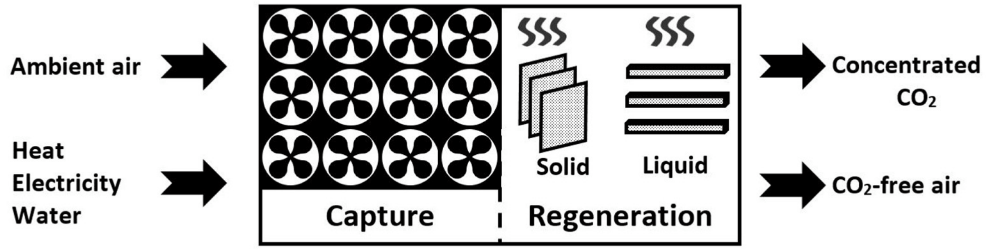

FIGURE 1 | A schematic DAC facility consists of two main phases: Capturing CO_2 from the ambient air and then releasing it through the regeneration process.

2006; Zeman, 2007; Holmes et al., 2013; Li et al., 2015). Currently, the only commercial liquid solvent-based plant uses potassium hydroxide (KOH) and its techno-economic assessment has been published in Keith et al. (2018).

The second technology uses solid sorbent materials that require lower temperatures in the regeneration process (Beuttler et al., 2019). Another advantage of this setup is its flexibility, allowing a modular design to be scaled up easily. Like the liquid solvent system, many different setups and materials have been proposed for the literature's solid sorbent system (Choi et al., 2012; Kulkarni and Sholl, 2012; Sinha et al., 2017). However, currently, only two companies are developing this technology at a commercial scale (Gambhir and Tavoni, 2019).

Regardless of the type of the material used for capturing carbon, the key factor in ensuring the successful *net* removal of CO_2 is integrating the DAC system with low-carbon energy sources such as solar and wind for electricity and natural gas for heat (Gambhir and Tavoni, 2019).

1.2. Future Climate Scenarios

The future growth of DAC technologies depends on the type of climate change mitigation and adaption policies adopted by the international community. These policy options range from minimum efforts to curb greenhouse gas emissions to aggressive decarbonization pathways that ensure the increase in global mean temperature remains under 1.5° or 2°C as outlined in the Paris agreement (Rogelj et al., 2018). As climate policies become more stringent and carbon budget becomes tighter, the need for negative emission technologies increases (Anderson and Peters, 2016). In this survey, we consider two climate change scenarios with different implications for the development and deployment of DAC technologies:

1. Policy as usual (PAU): under this scenario future climate policies would be coherent with efforts planned in the Intended Nationally Determined Contributions (INDCs) (Levin et al., 2015). Under the INDC commitments, and excluding the climate neutrality targets which have been announced after the elicitation took place, the global mean temperature is likely to rise by 2.6–3.1° C by 2100 (Rogelj et al., 2016). Future development of DAC technologies under the PAU scenario will be mainly driven by factors outside the direct government policy interventions, including private sector R&D investments, emerging demand for carbon utilization, and other market mechanisms.
2. Stringent climate policy consistent with the 2°C target (2DC): under this scenario coordinated international efforts will reduce emissions in line with the long-term Paris agreement goal of keeping global temperature rise well below 2°C. According to the IPCC 1.5SR, this requires achieving global carbon neutrality by 2050–60 (Intergovernmental Panel on Climate Change, 2018). The 2DC scenario requires deployment of negative emissions technologies especially to achieve the climate targets after 2030 (Rogelj et al., 2016). Future development of DAC technologies under this scenario is therefore, directly affected by climate policies aimed at reaching the 2°C target and by competition with other negative emission technologies or mitigation options.

Presenting the experts in our survey with these two very different policy scenarios, has allowed us not only to provide a median estimate of future cost and capacity of DAC technologies under each scenario but also to compare these estimates and to draw some insights from on how the experts foresee the role of DAC technologies in shaping future climate policies.

2. MATERIALS AND METHODS

In our survey, we asked experts to provide judgements about the future costs and capacity of these DAC technologies, how their technical specifications will evolve, and what non-technical barriers could prevent their diffusion. The survey was designed, developed, and conducted according to expert elicitation guidelines developed in the last few decades (Cooke and Goossens, 2000).

Elicitation is a structured procedure of collecting scientific data in the form of expert judgment (Cooke, 1991; Morgan, 2014). The participating experts are asked to express their professional judgment about an uncertain quantity such as cost or capacity of an emerging technology by providing information about their subjective distribution over this quantity's possible values (Cooke and Goossens, 2000). If more than one expert participates in the elicitation, a procedure of aggregation will be performed to synthesize their knowledge and express it in the form of a single probability distribution function (O'Hagan et al., 2006). While, elicitation is not a sampling exercise to statistically represent the population's view, the choice of experts

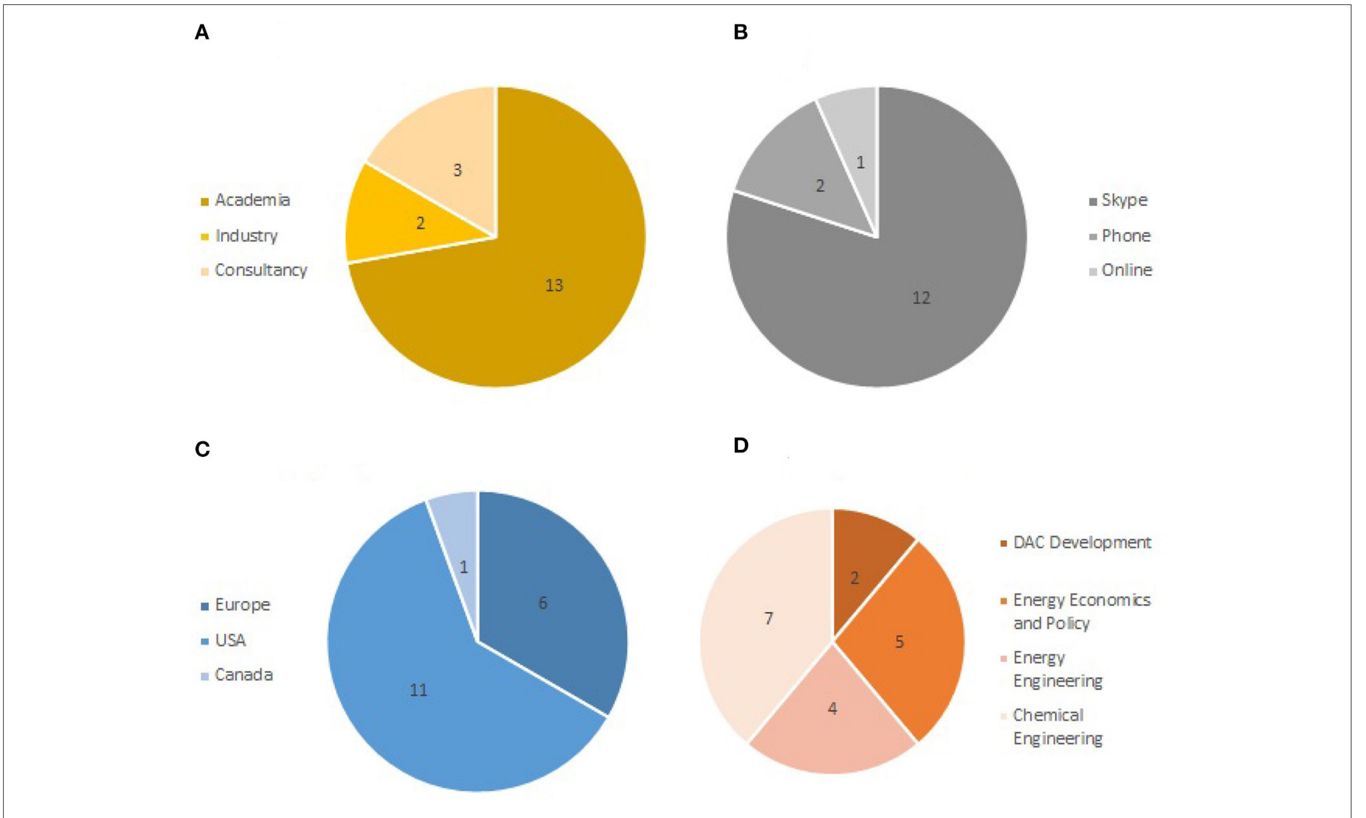

FIGURE 2 | Expert elicitation coverage in terms of **(A)** experts affiliation, **(B)** interview method, **(C)** experts location, and **(D)** experts background.

in the elicitation procedure should reflect the broad judgments and professional opinions that exist in the field. The required number of experts which should be included in an expert elicitation survey is indeed very subjective and depends on the characteristics of the subject matter (Morgan, 2014).

However, even with a careful selection of the experts, elicitation surveys are subject to biases known to any human decision-making process (Walls and Quigley, 2001). To minimize the impacts of such biases, we carefully analyzed the potential biases. We followed the procedure outlined for eliciting the future prospects of renewable energy technologies to address the potential biases in our elicitation protocol (Bosetti et al., 2012).

We designed a two-stage procedure to eliminate the bias in expert selection and in choosing the uncertain parameters. In the first phase (exploratory phase) of the project, we interviewed 13 experts online from June to August 2019. The list of participants in the exploratory phase is provided in **Supplementary Material**. The main purpose of these interviews was, therefore to address the following two biases.

- *Expert selection bias:* we asked the participants in the exploratory phase to identify other experts that should be contacted in the main phase of the project, and
- *Parameter selection bias:* we asked the participants in the exploratory phase to identify the pressing issues that the experts believed could be addressed through a formal expert elicitation survey.

At the end of the exploratory phase, 30 experts were identified and contacted for the survey's main phase. Out of these 30 experts, 18 agreed to participate in the survey. We tried to choose the pool of experts with broad affiliation, geographical representation, and expertise background as shown in **Figure 2**. The experts represented both industry and academia with backgrounds in chemical engineering, energy engineering, energy economics and policy, and DAC development. Currently, there are only a few DAC plants in operation in Europe and North America. Our experts are similarly from these two geographical locations. Since DAC is still considered new technology, most research on DAC technologies is focused on optimizing the chemical properties of the absorbents/adsorbents and the chemical processes involved in capturing and regeneration phase. Therefore, it is not surprising to see that most of the experts in our study had chemical engineering or energy engineering background. However, we also included experts with economics and policy background and empirical experts and industry representatives to have a balanced mix of professional judgment opinions. **Table 1** shows the list of experts and their affiliation. All answers are anonymously reported in the rest of the paper.

The objective of the main phase of the survey was to assess the future technical developments and costs of

TABLE 1 | List of experts in the main phase in alphabetical order by last names.

Name	Expertise	Affiliation
Christoph Beuttler	DAC development	Climeworks
Stefano Consonni	Energy engineering	Politecnico di Milano
Michael J Desmond	Energy economics and policy	Independent consultant
Samuel Julio Friedmann	Energy economics and policy	Columbia University
Ajay Gambhir	Energy economics and policy	Imperial College
Matteo Gazzani	Energy engineering	Utrecht University
Chris Greig	Chemical engineering	Princeton University
Whitney Herndon	Energy economics and policy	Rhodium Group
Howard Herzog	Chemical engineering	MIT
Chris Jones	Chemical engineering	Georgia Tech
Ryan Lively	Chemical engineering	Georgia Tech
Marco Mazzotti	Chemical engineering	ETH Zurich
Sean McCoy	Chemical engineering	University of Calgary
Colin McCormick	Energy economics and policy	World Resources Institute
Jim McDermott	DAC development	Rusheen Capital Management
Matteo Romano	Energy engineering	Politecnico di Milano
Robert Socolow	Energy engineering	Princeton University
Jennifer Wilcox	Chemical engineering	Worcester Polytechnic Institute

The ordering is intentionally different from the one used in the figures.

available DAC technologies for removing carbon dioxide from the air. We particularly focused on liquid solvent and solid sorbent technologies as they are at different levels of development and commercial deployment. The experts were given an option to provide techno-economic estimates for any other DAC technology beyond these two types. However, none of the experts chose to discuss an alternative DAC technology. The questionnaire was divided into three sections:

1. Assessing the cost and capacity of DAC technologies under two future scenarios o climate change policy (i.e., 2DC scenario and PAU scenario);
2. Identifying the current and future technical requirements for DAC deployment in terms of required energy, temperature, land, etc.;
3. Evaluating critical non-technical factors including growth barriers and supporting policies that will have an effect on future deployment of DAC technologies

We surveyed through interviews to eliminate any misinterpretation of the questions and clarify the experts' answers where needed. The interviews included 12 via Skype, 3 in-person, and 2 via phone from November 2019 to March 2020 (see **Figure 2B**). Only one person used the link to the online survey without having an interview. At the beginning of each interview we provided experts with a set of practice questions unrelated to DAC technologies to help the experts get familiar with the elicitation procedure and gauge their uncertainty. In the main part of the survey, few experts responded partially or preferred not to answer one or more questions. The list of survey questions is provided at the end of **Supplementary Material**.

To identify uncertainty in experts' assessment, they were asked to provide low, median, and high estimates corresponding to the 10th, 50th, and 90th percentiles of the current and future costs, capacity, and performance of DAC technologies under 2DC and PAU scenarios. For each DAC technology, we report the results at the individual level for each expert and at an aggregated level for the group of experts. The quantitative approach to construct individual distributions from the 10th, 50th, and 90th percentiles are presented in **Supplementary Materials**. The "aggregated" values are obtained from combining the individual expert's probability distributions with equal weights. Combining the judgements of experts participating in the survey is also a very subjective issue. Some studies have recommended some additional pre-elicitation interviews to gauge the quality and performance of expert judgements (Cooke and Goossens, 2008). However, a review of several elicitation surveys using equal weights method and performance weights method shows that they produce similar medians and equal weights method has better accuracy (Clemen, 2008). Nevertheless, while averaging the expert judgments, we combine individual probability distributions and calculate the quantiles of the combined probability distribution instead of taking the average of the individual quantiles. This method has been shown superior in performance and producing more evenly spread combined distribution. The median of equally-weighted combinations of individual distributions is shown to be a better estimate than the average of equally weighted individual medians (Cooke et al., 2021).

3. RESULTS

3.1. Cost Estimates

Under each scenario (PAU or 2DC), experts were first asked to define which DAC technology (solid sorbent, liquid solvent, or another technology) is expected to become the dominant one by 2050. For the prevalent technology, respondents were then asked to give a probabilistic estimate for different economic and technical parameters. The first set of results is provided in **Figure 3** where the total net removal costs are calculated based on experts' estimates of high, medium, and low capital expenditure (CAPEX) and operating expenses (OPEX). Individual estimates of CAPEX and OPEX for each expert are provided in **Supplementary Material**.

A key factor to consider here is that net removal costs depend on the assumption that the experts have implicitly made about the DAC plants' energy source and potential storage or utilization of the captured carbon. Although we did not limit the experts to think about any specific energy source, most experts indicated that future DAC plants will use renewable energy sources for their operations (see **Figure 7**).

The experts' estimates provided in **Figure 3** are compared with the range provided by the most recent NAS report (National Academies of Sciences Engineering and Medicine, 2019). The

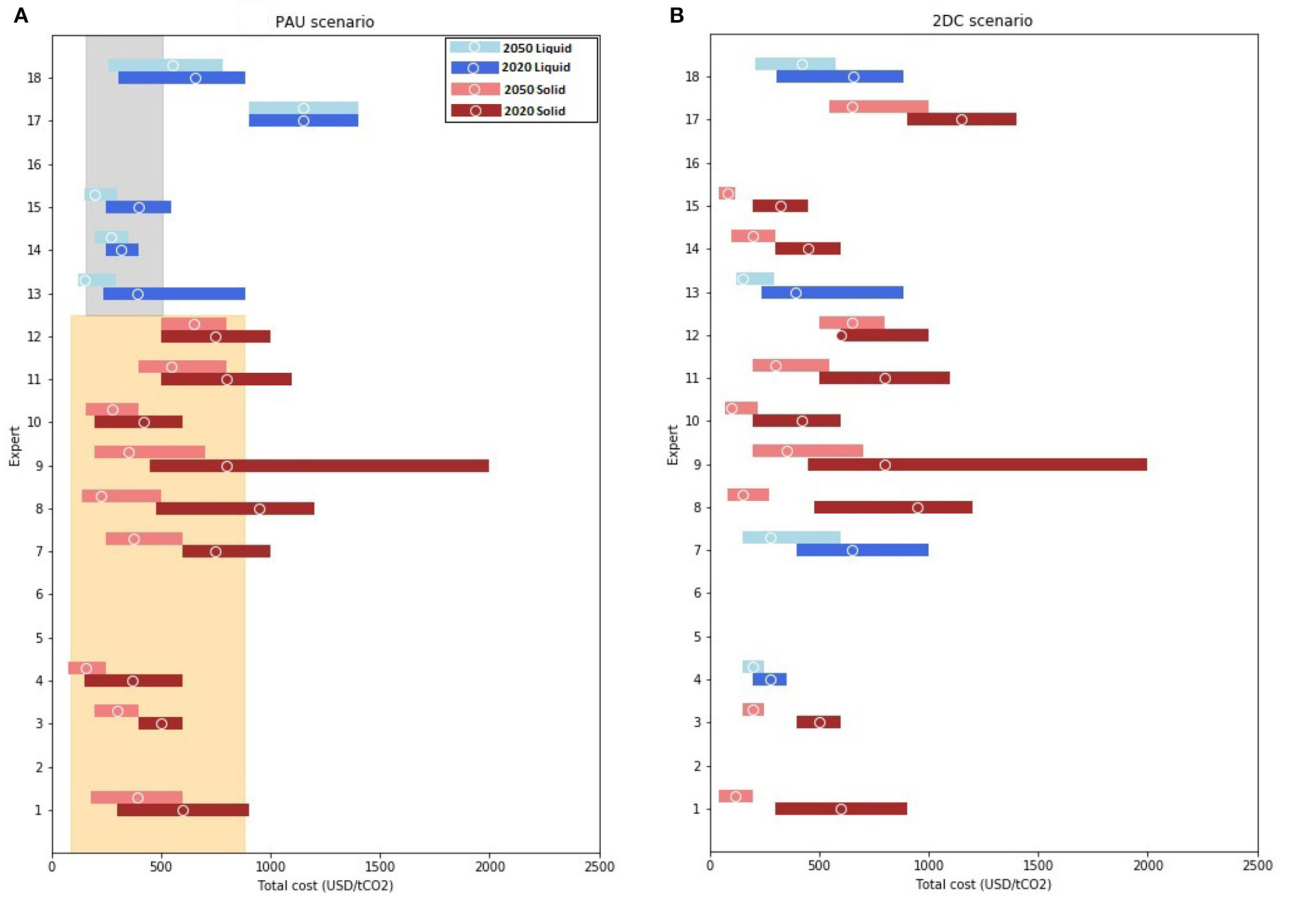

FIGURE 3 | Total net removal cost estimates (50th, 90th, and 10th percentiles) for solid sorbent (red bars) and liquid solvent (blue bars) technologies under **(A)** PAU scenario and **(B)** 2DC scenario. The results are reported for 2020 (dark colors) and 2050 (light colors) for each expert. The orange and gray boxes indicate the range of values reported in the National Academy of Sciences (National Academies of Sciences Engineering and Medicine, 2019) reports for solid sorbent and liquid solvent technologies respectively. Experts 2, 5, 6, and 16 did not provide answers to the cost estimate questions.

NAS report devises a cost correction factor, defined as $\frac{1}{1-x}$, where x is the amount of CO_2 emitted for every unit of CO_2 that is captured by DAC. If a DAC plant uses high carbon intensity fossil fuels, x approaches 1 and the cost grows. In contrast, when using renewable energies, x is approaching zero, making the net removal cost equal to the actual capture cost. The lower-bound and upper-bound of the NAS net removal cost estimates for liquid solvent DAC are 156 USD/tCO_2 for a system with high-efficient solar energy and 506 USD/tCO_2 for a low-efficient system with wind energy, respectively (gray shaded area in **Figure 3**)[2].

On the other hand, most cost estimates in the literature are only considering the capturing cost. Therefore, their net removal costs are highly dependent on the choice of energy source. The American Physical Society (APS) has estimated the capture cost for a realistic design using liquid solvent DAC to be around 550 USD/tCO_2, while the corrected cost (i.e. including emissions from energy sources) would be 780 USD/tCO_2 (Socolow et al., 2011). The optimized avoided cost of a similar design is as low as 518 USD/tCO_2 (Mazzotti et al., 2013). Alternative designs of liquid solvent DAC have been suggested where K^+ is used instead of Na^+ as cation (Keith et al., 2018). This new design's capture cost is estimated to be in the range of 94–232 USD/tCO_2. Assuming a 13% increase due to the electricity source's carbon intensity, the avoided cost will be in the range of 106–262 USD/tCO_2.

Our analysis outlined in the **Figure 3** shows that out of five experts who chose the liquid solvent DAC system in the PAU scenario, two reported median net removal cost estimates larger than the NAS upper-bound. They also reported a much smaller reduction in the future cost estimates compared to the other experts. The three other experts, however, not only reported a sharp decline in the median net removal cost in 2050 compared to 2020, but also expressed a considerably smaller uncertainty over the future cost values. The reduction in the median net removal cost is more evident when comparing the aggregate cost estimates

[2]In order to meet the high temperature heat requirements in liquid solvent systems, the NAS report contains calculations based on both burning fossil fuel and H_2 combustion, with H_2 produced through electrolysis with renewable sources.

in 2020 and 2050 in **Figure 4** where the aggregate median net removal cost goes down from 453 [251, 1,150] USD/tCO_2 in 2020 (**Figure 4C**) to 275 [135, 1,150] USD/tCO_2 in 2050 under PAU scenario (**Figure 4D**).

The cost reductions from 2020 to 2050 are even more profound in the 2DC scenario. In this case, all four experts who chose the liquid solvent DAC system indicated a reduction in the median cost and the uncertainty over it in 2050 compared to 2020. As shown in **Figure 4**, the aggregate median net removal cost goes down from 453 [222, 837] USD/tCO_2 in 2020 (**Figure 4G**) to 214 [124, 445] USD/tCO_2 in 2050 under 2DC scenario (**Figure 4H**).

Unlike liquid solvent DAC, only a few techno-economic studies have estimated the capture cost of solid sorbent DAC systems. The NAS lower-bound and upper-bounds for solid sorbent DAC are 89 USD/tCO_2 for a system with high-efficient solar energy and 877 USD/tCO_2 for a low-efficient system with coal energy, respectively (orange shaded area in **Figure 3**). A most recent study has put the capture cost of solid sorbent DAC in the range of 120–155 USD/tCO_2 (Fasihi et al., 2019).

In our study, most of the 2020 net removal cost median estimates are consistent with the NAS report range as shown in **Figure 3**. Only one expert (expert 8) reported the median net removal cost larger than the NAS upper-bound. However, the 2020 net removal cost uncertainty ranges vary greatly among the experts while the uncertainty ranges are smaller for the 2050 net removal cost estimates. Similar to the liquid solvent DAC, both the median estimates and uncertainty ranges reduce under 2DC scenario. As **Figure 4** shows the median of the aggregate median net removal cost with solid sorbent technology goes down from 624 [336, 1,035] USD/tCO_2 in 2020 (**Figure 4A**) to 336 [158, 631] USD/tCO_2 in 2050 under PAU scenario (**Figure 4B**).

On the other hand, under 2DC scenario the aggregate median net removal cost with solid sorbent technology goes down from 591 [314, 1,143] USD/tCO_2 in 2020 (**Figure 4E**) to 207 [77, 691] USD/tCO_2 in 2050 under 2DC scenario (**Figure 4F**).

In summary, these graphs help us compare the results in terms of median net removal cost estimate and the uncertainty range around it across time, policy, and technology domains (see also **Supplementary Figure 5** and **Supplementary Table 3**).

- **Median estimate:** while the current solid sorbent technology has a slightly higher median removal cost estimate compared to the liquid solvent technology, the future median cost estimates for both technologies converge to a lower level in 2050 under both policies compared to 2020. However, the median of 2050 cost estimates is lower under 2DC scenarios than PAU scenarios for both technologies. Furthermore, the estimated 2050 median values under 2DC scenario (214 USD/tCO_2 and 207 USD/tCO_2 for liquid solvent and solid sorbent technologies, respectively) are in line with the range of 200 USD/tCO_2 to 350 USD/tCO_2 cost estimates used in integrated assessment models (IAMs) (Realmonte et al., 2019).
- **Uncertainty range:** the uncertainty over net removal cost is generally smaller in 2050 compared to 2020 for each expert and the aggregated results. More experts favored solid sorbent technology and the individual uncertainty ranges are generally smaller for this type of DAC technology. The aggregate uncertainty ranges under 2DC scenario are smaller for liquid solvent technology and slightly larger for solid sorbent technology.

3.2. Capacity Estimates

In addition to costs, experts provided information about expectations on the future deployment of DAC technologies. In **Figure 5**, elicited probabilities concerning annual installed capacity (AIC) are reported for both technologies under two scenarios. First, we note that currently, there are very few installed DAC facilities, and therefore, the experts provided near-zero estimates for 2020 values. Second, only five experts estimated that the median AIC of solid sorbent systems will be above 100 MtCO_2 in 2050 but none of them provided an AIC estimate above 1 GtCO_2. On the other hand, two respondents estimated that AIC of liquid solvent system will go beyond 1 GtCO_2 in 2050. This highlights the potential of a liquid solvent system in delivering high capacity removal in large scales. Under 2DC scenario, however, the median AIC estimates increase significantly for both technologies in 2050. However, the uncertainty ranges are wider in both groups for individual experts and aggregated estimates.

Figure 6 shows the fitted cumulative distributions under each scenario for a combined set of both technologies. Merging data for both technologies allows us to understand what experts think about the role of DAC in shaping the mitigation portfolio under each scenario regardless of the type of technology being used. In this case, the median of aggregate distribution for AIC in 2050 is 0.24 [0.05, 1.34] GtCO_2 under PAU scenario while it reaches to about 1.69 [0.19, 5.86] GtCO_2 under 2DC scenario (see also **Supplementary Figure 6**). Regardless of large uncertainties over the AIC estimates, the experts' collective judgments suggest that DAC could contribute to reaching the 2°C climate target by removing several GtCO_2 by mid century under 2DC scenario. These values are again in line with the estimated values reported in previous IAM studies. For example, the estimated values of around 3 GtCO_2 from a multi-model analysis of DAC scenarios (Realmonte et al., 2019) corresponds to the 70th percentile of the aggregate distribution in our survey. Another recent study has shown that given the current cost and performance characteristics, DAC should provide about 3 GtCO_2 annual negative emissions by 2035 to meet the climate target of 1.5° C (Fuhrman et al., 2020). Other studies have highlighted the interplay of mitigation ambitions and CDR requirements. They have shown that increasing mitigation efforts in short-term (e.g., limiting emissions from 18 to 31 GtCO_2 per year in 2030) could reduce the need for CDR for achieving the 2°C climate target from 8 to 2 GtCO_2 per year (Strefler et al., 2018).

Like the cost estimates, we can now compare the AIC median estimates and the uncertainty range around it across time, and policy for a combined set of both technologies (see **Supplementary Figure 7** and **Supplementary Table 4**).

- **Median estimate:** the future median AIC estimates converge for both technologies to higher levels in 2050 compared to 2020. Still, the median of 2050 AIC estimates are much higher under 2DC scenario compared to PAU scenario.

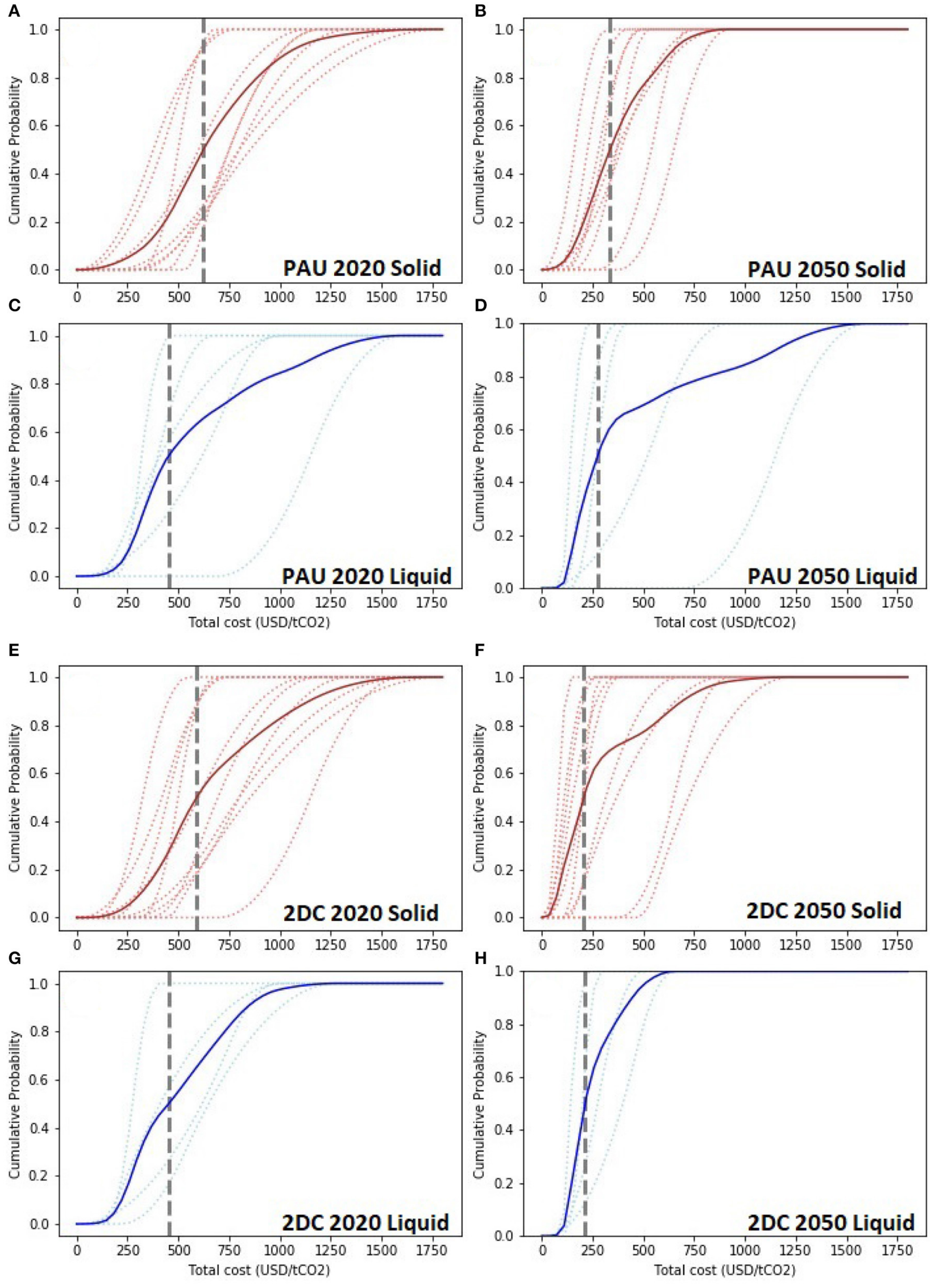

FIGURE 4 | Cumulative distribution functions (CDF) for net removal cost for the aggregate (continuous lines) and for each expert (dotted lines). The median of the aggregate distribution is indicated by gray dashed line. Cumulative distributions are triangular fit to 10th, 50th, and 90th percentiles for solid sorbent (red lines in **A,B,E,F**) and liquid solvent (blue lines in **C,D,G,H**) technologies under PAU scenario **(A–D)** and 2DC scenario **(E–H)**. The results are reported for 2020 **(A,C,E,G)** and 2050 **(B,D,F,H)** for each expert. The aggregated CDF is constructed by combining equally weighted individual probability distribution functions (PDF) as shown in **Supplementary Figure 5** (**Supplementary Material**).

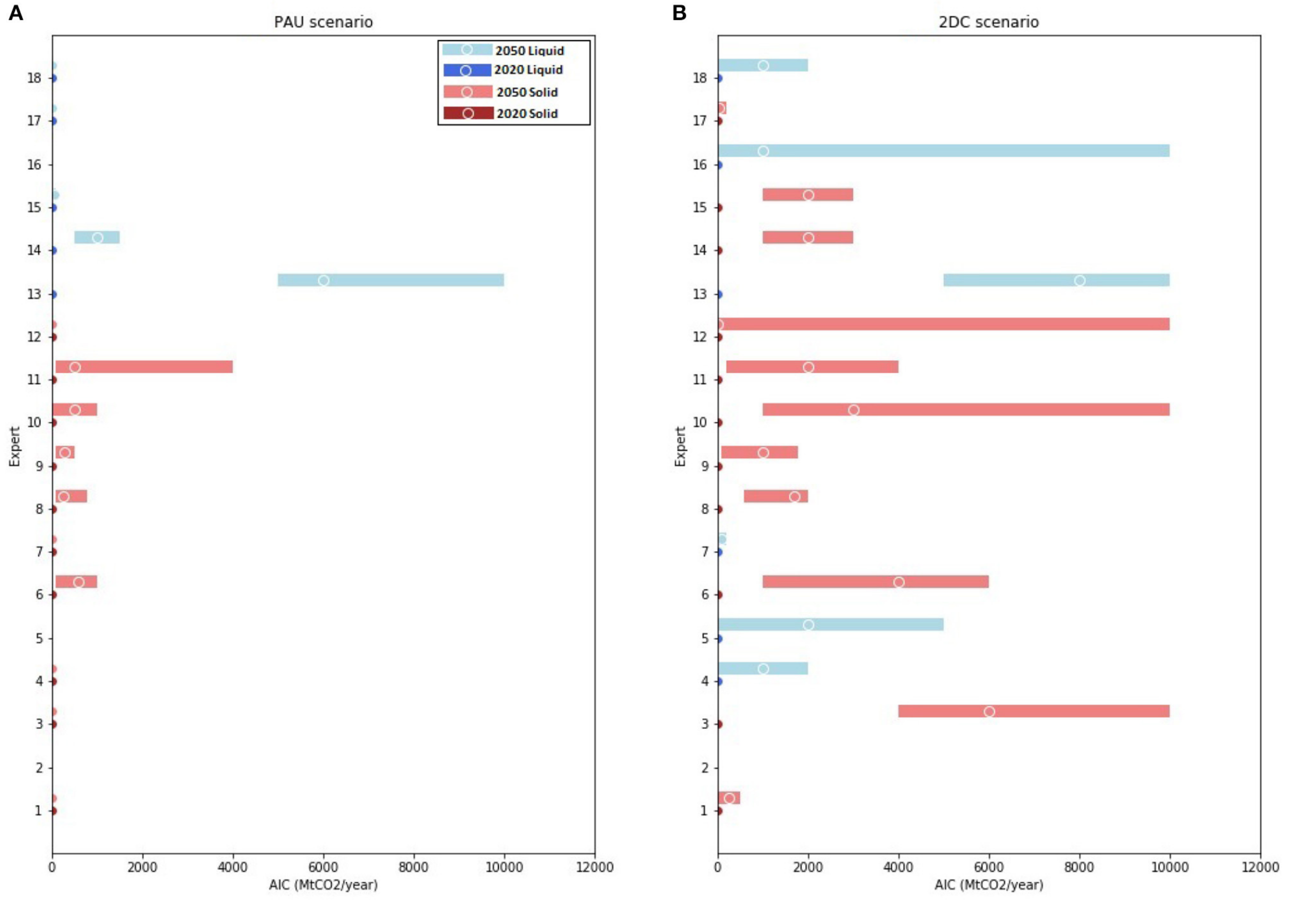

FIGURE 5 | Annual installed capacity (AIC) of DAC (50th, 90th, and 10th percentiles) for solid sorbent (red bars) and liquid solvent (blue bars) technologies under **(A)** PAU scenario and **(B)** 2DC scenario. The results are reported for 2020 (dark colors) and 2050 (light colors) for each expert. The 2020 values are near zero and negligible. The red bars show the solid sorbent technology and the blue bars represent the liquid solvent technology. Experts 2 did not provide answers for the AIC estimate questions. Experts 5 and 16 provided estimates only for 2DC scenario.

- **Uncertainty range:** the uncertainty over AIC is larger in 2050 compared to 2020 for each expert and the aggregated results mainly because the 2020 numbers are almost zero. The individual uncertainty ranges are generally wider for solid sorbent technology. The ranges under 2DC scenario are larger and the aggregated range is more spread.

3.3. Energy Requirement

The experts provided estimates for each technology's evolution in required energy, temperature, and land in addition to the cost and capacity estimates. The detailed results for these parameters are provided in **Supplementary Figure 8**.

Liquid solvent DAC technologies, in general, require more heat during the regeneration process. Processing solid sorbent DAC technologies, on the other hand, is less energy-intensive and it requires a lower temperature. Energy requirements estimates in this survey are generally higher than those reported by the NAS (National Academies of Sciences Engineering and Medicine, 2019). The median estimate for solid sorbent technologies is around 8 GJ/tCO_2 in 2020 while the NAS estimates range from 4 to 6 GJ/tCO_2. However, the experts estimated that the median energy requirements for solid sorbent systems will drop to about 6 GJ/tCO_2 by 2050 which falls at the upper-bound of the NAS' estimate range. On the other hand, the median estimate for liquid solvent technologies is around 10 GJ/tCO_2 in 2020, within the range of NAS estimates (8–12 GJ/tCO_2). The experts estimated that liquid solvent systems' median energy requirements will drop to about 8 GJ/tCO_2 by 2050. The 2020 estimates of energy requirements for both technologies are in the range of values used in the IAM studies. For example, Realmonte et al. assume two DAC technologies with an overall energy requirements ranging from 5.0 to 9.9 GJ/tCO_2 (Realmonte et al., 2019) while Fuhrman et al. assume a range of 6.6–9.9 GJ/tCO_2 for low- and high-cost DAC technologies respectively (Fuhrman et al., 2020).

3.4. Utilization and Integration

The DAC process's output is CO_2 with high purity that can be either sequestered in geological storage sites or processed for utilization in the production of carbon-based fuels and other chemicals (Gambhir and Tavoni, 2019). Therefore, successful

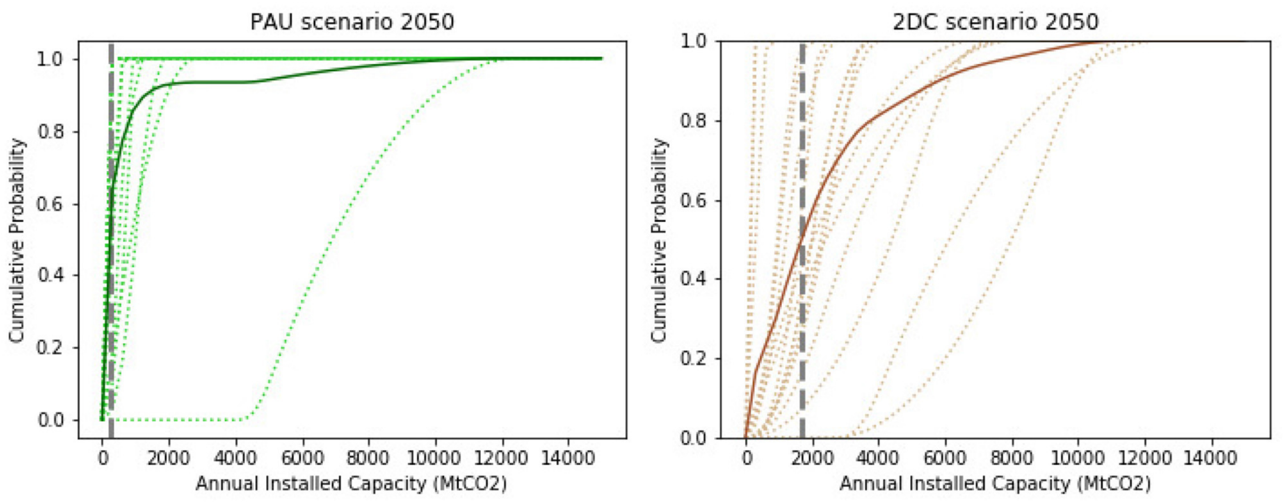

FIGURE 6 | Cumulative distribution functions (CDF) for annual installed capacity in 2050 for the aggregate (continuous line) and for each expert (dotted line). The median of the aggregate distribution is indicated by gray dashed line. Cumulative distributions are triangular fit to 10th, 50th, and 90th percentiles for both solid sorbent and liquid solvent technologies under PAU (green lines) and 2DC (brown lines) scenarios. The aggregated CDF is constructed by combining equally weighted individual probability distribution functions (PDF) as shown in **Supplementary Figure 7** (**Supplementary Material**).

deployment of DAC technologies in the future is highly dependent on the availability of carbon sequestration or utilization options. Half of the experts (50%) elicited in our study indicated "Geological storage" as the most likely option for sequestration of the captured CO_2 while only 39% of the experts chose "Enhance oil recovery" as the first option for utilization of the captured CO_2 followed by the utilization of the captured carbon in producing synthetic fuel and more generally, "air-to-chemicals."

To fully realize its climate benefits, DAC should be integrated into a low carbon energy system (Mac Dowell et al., 2019). But even when DAC facilities are powered with renewable energy sources, there is still a risk of higher health and social costs from upstream fossil emissions (Jacobson, 2019). In our survey, we asked experts about the type of facilities that need to be placed near DAC plants. Some studies have highlighted the long-term social and Although liquid solvent DAC requires substantial heat that makes it harder to completely rely on renewable sources, few experts rank fossil fuel related facilities above renewable energy sources. On the other hand, almost 40% of the experts highlighted the need to integrate DAC facilities with renewable sources of energy (wind and solar) or locating DAC facilities near geothermal reservoir. **Figure 7A** shows the ranking of supporting facilities that the experts believe should be placed near DAC facilities. The integration of DAC facilities with renewable energy sources is not only essential for meeting the electricity requirements but also for providing the necessary thermal energy for the regeneration process (Wohland et al., 2018). However, in the case of liquid solvent technologies with high temperature requirements, using renewable electricity directly for heating is not efficient. In this case, renewable electricity can be used for electrolysis to generate hydrogen which can be used in fuel cells for thermal heating (National Academies of Sciences Engineering and Medicine, 2019). Other studies have suggested the integration of DAC systems and renewable energy sources to produce methanol (Daggash et al., 2018; Bos et al., 2020; Liu et al., 2020).

In terms of limitations to DAC technologies' future growth, half of the experts (50%) indicated that lack of supporting "Policy and regulations" will hinder the expansion of DAC technologies. After policy, the need for innovation in reducing the DAC process's energy intensity and integrating it with renewable sources of energy has received support from 44% of the experts. One interesting outcome of this study is to show that "Social acceptability" and "Storage capacity" have received only about 22 and 17% of the experts' votes, respectively. This indicates that the experts believe that not only there is enough geological storage capacity for permanent sequestration of captured CO_2 but also general public is willing to accept DAC as long as there is a policy and regulatory support for that. Although the provision of chemical sorbent materials has been highlighted in previous studies as a potential constraint for DAC technologies' mass development, it (Realmonte et al., 2019), only 11% of the experts highlighted it as a potential critical obstacle in our study. **Figure 7B** shows the ranking of these limiting factors.

Finally as shown in **Supplementary Figure 9**, experts projected that most direct air capture projects will be developed in North America (27%), Europe (16%), and China (16%), identifying these regions are the early adopters of DAC technologies. They also projected that about one-fifth of future DAC installations will be in the Middle East. As the world economy is moving away from fossil fuel consumption, oil and gas producers could take advantage of their existing infrastructure to transition from processing fossil fuel to processing

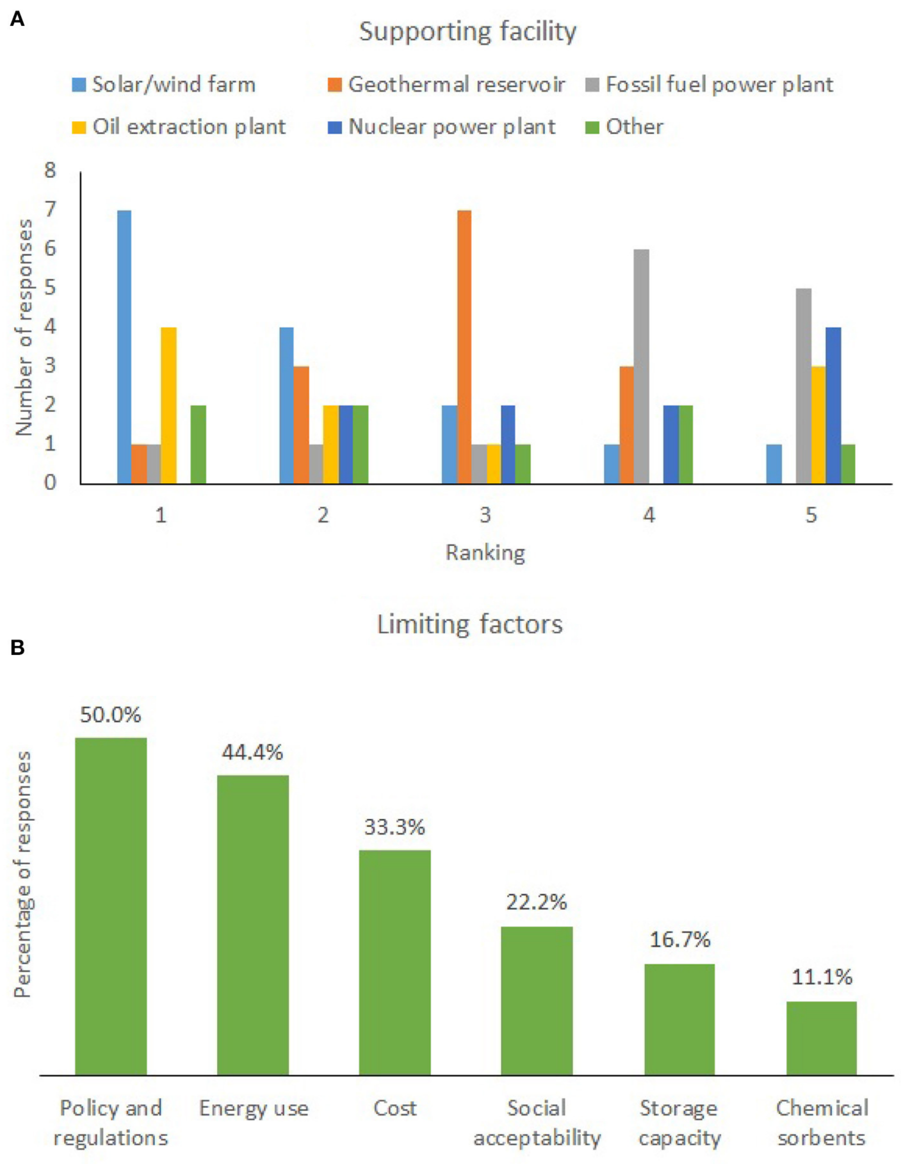

FIGURE 7 | Ranking of **(A)** supporting facilities required in the vicinity of future DAC plants with 1 indicating the highest rank and 5 indicating the lowest rank, and **(B)** limiting factors in developing DAC technologies.

synthesized fuel made from the captured carbon in DAC facilities.

4. DISCUSSION

This paper summarizes the results of an expert elicitation on direct air capture technologies and their prospects. To the best of our knowledge, we are the first to provide a summary of experts' judgment on how DAC technologies may evolve over time and across climate policy scenarios. Three key areas emerge from the results of our survey.

First, the experts' removal cost estimates show a wide range of uncertainty due to the lack of available, trustworthy information about the real costs of developing and operating DAC technologies. This calls for more transparency in reporting the cost and performance of existing DAC facilities. Although private companies operate the current DAC plants, such voluntary transparency in reporting their financial costs can benefit the whole field and help potential investors, policy makers, and technology developers to identify the key obstacles in developing new DAC projects. Despite high uncertainty in estimation of current removal costs, there was a strong consensus among the experts that the costs will fall sharply from their current levels (500–600 USD/tCO_2 removed) but will remain significant (about 200 USD/tCO_2 removed in 2050) under a strong climate policy regardless of the type of technology.

The second finding highlights the prospective deployment of direct air capture. Even the most optimistic experts were hesitant to provide median estimates of annual installed capacity of more than few $GtCO_2$. These estimates and those of the cost estimates are both in line with annual negative emissions capacity required to reach stringent climate targets according to integrated assessment models of climate change and economy (Strefler et al., 2018; Realmonte et al., 2019; Fuhrman et al., 2020). This highlights the challenges of developing a successful DAC program in the medium-term (Beuttler et al., 2019). Even under the best prospects, DAC should be considered part of a vast portfolio of mitigation strategies, most importantly renewables and gas with carbon capture and storage.

Third, although the science of capturing CO_2 from ambient air has been known over the past few decades, various technical and policy obstacles have hindered the adoption of DAC technologies in scale needed for tackling the growing carbon concentration in the atmosphere. Developing new absorbent/adsorbent materials, alternative process designs, and finally new energy sources can reduce the net removal cost of CO_2. Half of the experts indicated lack of supporting policy as a major obstacle in developing DAC projects (**Figure 7**). In terms of types of policy that will benefit DAC projects, more than half of the experts (56%) indicated establishing a carbon credit market such as "Low carbon fuel standard" that is currently in place in California will be the most effective way to support DAC technologies. Carbon tax and R&D policies were the second and the third favorite policies after carbon credit. In any case, government support is a key enabling factor for developing DAC at scale.

Finally, we should acknowledge some of the limitations of our study. First, we were not able to reach all of the 30 experts we wanted to talk to. Some refused to participate in this study and some were not comfortable providing projections about a new technology that they considered to be too uncertain. As a result, we were able to talk to only 18 exerts. Second, although we tried to cover the key technical, economic, and policy aspects of the DAC technologies, investigating the detailed technical aspects of their energy requirements and chemical processes was beyond the scope of this research and requires further investigation. As more DAC projects are being developed, more experts with direct expertise in different aspects of these technologies will be available. We hope our study provides the first step in collecting informed predictive judgments about DAC technologies and paves the way for future expert elicitation studies in this field.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SS carried out the interviews and wrote the manuscript. VB and MT supervised the process. All authors revised and improved the manuscript and contributed in designing the questionnaire.

ACKNOWLEDGMENTS

We would like to thank all the experts who contributed valuable time to this study in both phases of the projects. We specially thank Dr. Jennifer Wilcox and the NET Primer Workshop organiserz at Worcester Polytechnic Institute (Feb 10-11, 2020) for providing us with access to the attendees for conducting the interviews. We would like to thank Roger Cooke from RFF for providing useful insights and guidance on how to conduct the elicitation and analyze the results. VB and MT acknowledge support from the Italian Ministry of University and Research, PRIN project #201782J9R9 'Experimenting with climate change: a behavioral approach to foster cooperation'.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2021.630893/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Climate

PERSPECTIVE
published: 21 June 2021
doi: 10.3389/fclim.2021.686440

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Implementing the Soil Enrichment Protocol at Scale: Opportunities for an Agricultural Carbon Market

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OPEN ACCESS

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Specialty section:
This article was submitted to Negative Emission Technologies, a section of the journal Frontiers in Climate

Received: *26 March 2021*
Accepted: *27 May 2021*
Published: *21 June 2021*

Citation:
Jackson Hammond AA, Motew M, Brummitt CD, DuBuisson ML, Pinjuv G, Harburg DV, Campbell EE and Kumar AA (2021) Implementing the Soil Enrichment Protocol at Scale: Opportunities for an Agricultural Carbon Market. Front. Clim. 3:686440. doi: 10.3389/fclim.2021.686440

High-quality agricultural carbon credits that incentivize regenerative practices can help address climate change through greenhouse gas (GHG) abatement and CO_2 sequestration. Generating large volumes of such credits requires rigorous crediting methodologies. The Soil Enrichment Protocol (SEP) by the Climate Action Reserve (CAR) aims to unlock this type of crediting potential. The SEP includes new expert-driven standards for validating the use of soil biogeochemical modeling to generate credits. Technical experts at Indigo Ag participated in the SEP working group and are supporting implementation of the first project, CAR 1459_RP1, on hundreds of thousands of acres in the US. The authors share their thoughts on new approaches enabled by the SEP as both contributors to the theory behind and practitioners of these approaches. The SEP enables scalable, high-quality credits through four main advances: (1) allowing flexibility in the use of biogeochemical models that meet explicit performance requirements, (2) enabling a new approach to field-level, modeled baselines, (3) supporting a hybrid approach of credit generation using both soil measurement and modeling, and (4) requiring a new type of credit uncertainty quantification that accounts for multiple sources of uncertainty. Together these advances support agricultural credit quantification that enables payments to offset transitional costs for growers, at large enough scales to create a robust market, with a level of rigor that ensures any credited emission reductions have real climate impact. Innovations in soil analyses, advances in research, and improvements in data collection could further improve the potential for agricultural carbon credits to scale.

Keywords: negative emissions technology, agriculture, soil, carbon offset, carbon credit, regenerative agriculture

INTRODUCTION

To ensure long-term success at a global scale, carbon markets must be based on confidence in driving emissions reductions. This confidence requires rigorous and transparent protocol standards for greenhouse gas (GHG) mitigation and CO_2 sequestration to generate high-quality carbon credits, defined as being realistically baselined, additional, and permanent, among other criteria (see **Table 1**). Since the use of an offset credit involves the allowance of an equal emission elsewhere on Earth, offset credits that do not equate to equivalent amounts of emissions reductions (i.e., are not real) result in direct environmental harm. Confidence is critical; if credits are not rigorous, science-based, and transparent in their methods; if low-quality, unverified credits are transacted in the market, it can cast doubt on the entire market and the incentive structure can collapse.

Recently, multiple entities (including Indigo Ag) have either explored or actively launched programs to generate agricultural carbon credits due to the potential for regenerative practices, such as cover cropping and reduced tillage, to reduce GHG emissions and sequester carbon in soils (Paustian et al., 2016). To support large-scale practice change, growers need to be directly compensated for the carbon credits they generate on their operations. Implementing regenerative practices often involves transitional costs, such as changes to equipment to plant into heavier residue, or ongoing operational costs, such as annual purchases of cover crop seeds. Carbon credit payments generated by these activities could reduce financial barriers to adoption. Currently, adoption rates of regenerative practices in many regions remain low; for example, <2% of growers used cover crops and <12% practiced no-till in 2017 [United States Department of Agriculture National Agricultural Statistics Service (NASS), 2017]. Agricultural carbon credits have an opportunity to increase regenerative practice adoption, by incentivizing regenerative management strategies that minimize GHG emissions while maximizing carbon sequestration and co-beneficial outcomes to soil and crops.

Carbon markets have developed since the 1990s through voluntary efforts, such as independent project registries, and regulatory mechanisms, such as the Kyoto Protocol and the California cap-and-trade program [International Carbon Reduction and Offset Alliance (ICROA), 2020]. There is broad consensus around a suite of quality criteria that should underpin any credible offset program [Offset Quality Initiative (OQI), 2008]. Individual programs, such as the Climate Action Reserve (CAR), maintain their own programmatic standards built around these quality criteria, and then adopt individual protocols and methodologies for specific project activities, such as forestry or agricultural land management (Climate Action Reserve Offset Program Manual, 2021). Several protocols have been adopted to address implementation and monitoring of GHG mitigation projects on agricultural lands, including the CAR Nitrogen Management Protocol (Climate Action Reserve Nitrogen Management Protocol Version 1.0, 2012) and California Compliance Offset Protocol for Rice Cultivation Projects (COP RCP) (Compliance Offset Protocol Rice Cultivation Projects, 2015). Except for livestock manure digestion projects, these past efforts have not resulted in large-scale projects or significant credit volume. This lack of scale is at least partly a result of a reliance on the combined precedent of industrial emission reduction methodologies and forestry-focused land use methodologies, which proved ineffective in creating scalable agricultural projects. Additionally, those protocols faced significant challenges with farmer engagement and data collection, partly because either the programs or protocols were highly prescriptive and left little room for innovation by project aggregators or for growers to be responsive to changes in market demand for certain crops. For example, the 2015 COP RCP generated zero credits despite stable demand and above average prices in the California compliance offset market (Air Resources Board Offset Credit Issuance, 2020; Compliance Offset Protocol Rice Cultivation Projects, 2015). This protocol generated zero credits because of high data burdens, grower resistance to monitoring and data collection requirements, and limited opportunity to practically aggregate multiple fields into a single project. The protocol was also limited in geographic scope to rice growing regions in California, the Mississippi River delta, and Louisiana.

The CAR Soil Enrichment Protocol v1.0 (SEP) aims to generate high-quality carbon credits at scale by providing opportunities for projects to continually benefit from scientific advancements in agricultural sampling methods and soil biogeochemical modeling, while supporting credit generation at a grower-beneficial cadence (Climate Action Reserve Soil Enrichment Protocol Version 1.0, 2020). Indigo participated in the stakeholder working group for the CAR-led development of the SEP. The registry engaged with expert working groups that represented multiple perspectives, including growers, scientists, environmental NGOs, and industry representatives, and included public comment periods. This process resulted in an independently validated, publicly available, and scalable methodology with four critical advances from previous protocols: (1) a flexible approach in soil biogeochemical model use within a single project, (2) a new approach to generate field-level, modeled baselines, (3) a combined measurement and modeling approach to credit generation, and (4) a novel uncertainty quantification approach. These advances enable the SEP to yield high-quality carbon credits from the quantification and verification of GHG emission reductions associated with soil enrichment projects on agricultural lands.

Protocols like the SEP do not exist in a vacuum; national policies can play a key role in accelerating their impact. In the US, the Growing Climate Solutions Act aims to provide clarity around acceptable standards for agricultural carbon and GHG measurement and verification. If implemented as proposed, this act will reduce confusion on the quality and value of various carbon programs that farmers can choose from Growing Climate Solutions Act (2020). If quality standards are set too low, however, the problem would not be solved for growers because the USDA standard would not align with the minimum quality demanded by the wider carbon market. Another proposal, the establishment of a carbon bank, could encourage both farmers and project developers to invest in project implementation. There are many ways that this idea could be implemented (e.g., a buyer of last resort, transition payments, no interest loans for capital costs, etc.), but the basic concept of providing stable financing to encourage climate smart agricultural practices is helpful if the structure and timing of financing benefits growers and drives practice change. Lastly, policies that discourage regenerative practice adoption could be changed, such as Federal crop insurance rules, which, in some cases, penalize the use of cover crops.

In this perspective article, we share how the SEP supports a more robust carbon market in agriculture, as well as our learnings to date from operating as a CAR SEP project developer for a project on hundreds of thousands of acres. We also discuss how innovations in commercial soil analyses, advances in

TABLE 1 | Requirements for high-quality carbon offset credits.

Criteria	Description	How the SEP methodology ensures credit quality
Additional	Land management practices must not be "business as usual," be required by regulatory agencies, and must be implemented before the reporting and verification period.	Project fields must meet both performance standard and legal requirement tests, which establishes acceptable additional practices.
Address leakage	Changes in land management practices can potentially cause indirect emissions if the productive yield of the project area declines over time.	Changes in crop yield, for example, reduced yield in the first year of verified practice change, are monitored for each project field and aggregated at the project level. Significant leakage reduces the number of credits for the project.
Permanent	Changes to carbon stocks should represent a permanent change.	Offsets are only considered permanent if the organic carbon associated with the GHG reduction is stored for ≥100 years following credit issuance, as dictated by SEP monitoring against reversals and a buffer pool to provide insurance against reversals due to unavoidable causes.
Independently Verified	Project results should undergo 3rd-party auditing of data, methods, and reports prior to every issuance	Results undergo an intensive verification after every reporting period.
Real	Credits are a result of complete and accurate accounting based on proven, conservative methods.	Rigorous guidance for quantification and monitoring to ensure project benefits are not overstated.
Unambiguously owned	Offsets are assets that are owned by one entity at a time from creation through to retirement	Project developers must demonstrate ownership of GHG rights. Credits are serialized and tracked in the public registry to prevent double claiming.
Uncertainty	Project results account for sample, measurement, and model prediction errors affecting project emissions reduction and carbon estimates.	Projects take a hybrid direct measurement and modeling approach to account for uncertainty in credit estimation
Use realistic baselines	High-quality carbon offset projects should be structured around what the GHG impacts would have been had the project not occurred.	The GHG impacts of project fields are compared to a scenario in which historical management practices had continued without change.

agroecosystem and soil biogeochemical modeling, and targeted research can further reduce uncertainties, increase inclusivity, and strengthen the quality of agricultural soil carbon credits at a global scale.

QUANTIFYING AGRICULTURAL CARBON SEQUESTRATION AND GHG EMISSIONS AT SCALE REQUIRES LEVERAGING THE LATEST SCIENCE

Climate and environmental issues require pressing action and the science behind regenerative agriculture has reached a level of maturity where we can implement net beneficial solutions today (Pittelkow et al., 2015; Griscom et al., 2017; National Academies of Sciences, 2019; Oldfield et al., 2019; Paustian et al., 2020). Although many regenerative agriculture areas remain in need of additional research, the SEP provides a framework whereby these needs are not a bottleneck. Instead, the protocol balances the current state of scientific knowledge supporting each credit issuance iteration with standards that allow continual advancements in agricultural research, soil measurement methods, and biogeochemical modeling. These standards focus on the use of soil biogeochemical model simulations, realistic and adaptive baselines, the combined use of soil measurement with modeling to generate credits, and the quantification of credit uncertainty. The SEP also employs standards to ensure that carbon credited meets a 100-year permanence period (see **Supplementary Materials** for details).

New CAR SEP Model Guidance Standards Increase Soil Biogeochemical Modeling Flexibility and Ensure Verifiable Use for a Given SEP Project

Model requirements described in the stand-alone CAR SEP Model Guidance define new standards for the use of peer-reviewed published experimental data to validate the capacity of a model to simulate the practice changes, crop types and biophysical settings in a SEP project (Climate Action Reserve Requirements and Guidance for Model Calibration, Validation, Uncertainty, and Verification for Soil Enrichment Products Version 1.0, 2020). In previous crediting protocols such as the CARB Compliance forest offset protocol, models were not permitted to change model parameterizations or undergo updates during a project [California Air Resources Board (CARB) U.S. Forest Projects Compliance Offset Program, 2015]. Instead, models were typically approved for use individually based on expert input and the general robustness of evidence for model performance in peer-reviewed publications. Furthermore, crediting methods did not require quantification of model prediction error, and thus provided no mechanism to account for model performance in credit estimations.

In contrast, the SEP Model Guidance allows any model to be used in a SEP project if the specific model validation requirements are demonstrated, documented, and reviewed in a separate report prior to credit issuance (Climate Action Reserve Soil Enrichment Protocol Version 1.0, 2020). The SEP model validation report ensures each model version and associated parameter sets demonstrate appropriate calibration, validation, and model uncertainty quantification for the specific SEP project in which the model will be used, as defined by the project crop types, practice changes, soil properties, and geographies. These standards allow model recalibration and version improvements to be used over the project duration. Critically, independent expert-review, CAR approval, and public availability are required of every validation report to demonstrate that these standards are met. This requirement helps ensure that all model performance for SEP projects is transparent, and that associated data are available to the scientific community for side-by-side comparisons. In the development of the Model Guidance document, one of the critical challenges was how to best support verification entities who may not have the expertise needed to ensure that a soil biogeochemical model was used appropriately. SEP Model Guidance standards aim to balance rigor with practicality in implementation, requiring the engagement of expert review to verify model performance, but not requiring this expertise from verifiers. Verifiers are instead allowed to reference an approved model validation report to confirm model application in each project, checking that model versions, required information, and parameter sets match their application to quantify credits within a project.

The SEP Enables a Baseline Approach That Is Better Suited to the Dynamics of Agricultural Lands

Carbon credits are quantified as the difference in emissions that occurred in the project scenario and the baseline scenario—i.e., emissions that would have occurred in the counterfactual world in which the project did not incentivize a change. Methodologies for managed lands previously relied on two approaches to establish a project baseline: a static approach – wherein samples or historical data are used to create a single baseline that is used for several (often 5 or 10) years or an entire project, or a forward-modeling approach – wherein referential historical data is used to create a model projection (e.g., linear) of baseline emissions that is referenced to evaluate credits earned each year of the project. With re-baselining occurring at increments of 5 years or longer, neither approach accounts for variables, such as changes in weather or market demands, that may change grower choices practices, such as crop rotations. This limits the ability of such protocols to quantify offsets accurately and dynamically at scale. Recent work highlighted the potential to over-estimate emissions reductions from deforestation and forest degradation projects (REDD+) in the Brazilian Amazon (West et al., 2020). Significant changes in market forces reduced the expected level of deforestation during the project early implementation phase, but the model baselines were quantified with historical data and did not account for these changes. As a project developer, Indigo is now undertaking the first implementation of the new baseline approach in the SEP that generates what we term a Just-in-Time Adaptive Baseline (JITAB)—inspired by the Just-In-Time Adaptive Intervention approach in behavioral science (Nahum-Shani et al., 2018; Hardeman et al., 2019). This approach creates a baseline using static historic data and incorporates dynamic modeling to re-calculate the baseline every year in response to ongoing real-world changes in project crop rotation and weather (see **Supplementary Materials** for further discussion).

A Hybrid Sampling and Modeling Approach Enables Annual Quantification of Large Projects

Before the CAR SEP, agricultural GHG emission mitigation methodologies relied either on narrow use of models, solely on direct soil measurement, or on use of narrowly applicable default emission factors (Climate Action Reserve Nitrogen Management Protocol Version 1.0, 2012; Compliance Offset Protocol Rice Cultivation Projects, 2015). Direct measurement-only approaches have significant barriers to scale: they are expensive, struggle to handle short-term fluxes in soil organic carbon (SOC) content and trace gases, and can take a long time to deliver results (e.g., often a minimum of 5–10 years). Moreover, setting baselines for measurement-only projects requires either paired control plots which are infeasible at scale, or regional benchmarks for which there are not yet sufficient data. Using soil biogeochemical models exclusively might be less expensive but would only produce low-quality credits as the models would not be anchored to the reality of the individual site(s), even if provided accurate and spatially resolved soils, climate, and management data. Default emissions factor approaches do see common use in crediting protocols as they are the most straightforward and least expensive quantification option. However, they also have narrow scope of application, low field-level accuracy, and are unable to adapt to changing conditions and management. The SEP requirements provide a framework to overcome these limitations using a hybrid approach that balances in-field soil sampling and analysis with biogeochemical models that can be continually improved and validated (Climate Action Reserve Requirements and Guidance for Model Calibration, Validation, Uncertainty, and Verification for Soil Enrichment Products Version 1.0, 2020), as well as default equations for non-CO_2 GHG sources (N_2O and CH_4) that provide an alternative option when models cannot be validated for these trace gas fluxes. This approach enables scalability; for example, in Indigo's first project under the SEP, we are implementing a process that would use soil core measurements a quarter of all project fields. Combining soil measurements with modeling requires high-quality data yet enables wide-scale GHG estimation on project fields that accounts for and incentivizes the reduction of model uncertainty via improved model performance.

SEP Uncertainty Quantification Requirements Allow Innovative Post-stratification of Sampling Points and New Approaches for Handling Missing Data

The SEP requires uncertainty quantification to include multiple sources of uncertainty, including project sampling design uncertainty and uncertainty arising from model used in credit quantification. The benefits of this approach are twofold: one, model prediction error is explicitly represented in quantification of emission reductions and removals, allowing models to be used with measurable confidence to generate credits for the first time in an offset project protocol; and two, combining both sources of uncertainty enable post-stratification statistical methods able to meet the unique challenges of monitoring emission reductions in agricultural soils.

Agricultural soils can be highly heterogeneous both within fields and regions, and soil properties vary significantly across space and time (Wuest, 2014). Carbon credit projects that estimate climate benefits using a random, representative sampling points have highly uncertain climate benefit measures within a project unless many soil samples are pulled due to this inherent heterogeneity (Franzleubbers, 2010). One way to reduce the number of soil samples without increasing uncertainty is to divide the project lands into non-overlapping groups, called "strata," to draw a random sample in each stratum independently of the other strata, and to allocate more samples to strata that are expected to be more heterogeneous in the outcome variable (Cochran, 1977; Holt and Smith, 1979). The SEP, like many methodologies, encourages stratification.

For the estimation tasks in the SEP, stratification is challenging for two reasons. First, there are multiple outcome variables (i.e., emissions reductions in various gases) and the ideal stratification may vary significantly for one outcome variable to another. Second, practice changes made by growers are important stratification variables, as they differ substantially in their average reduction in emissions. Many growers, however, do not know what practice change they will make upon joining the program, or those they will make in the subsequent years, making it difficult to assign land to strata at enrollment. Indigo is forming strata after creating a random sample of the project because of these challenges, a technique is called *post-stratification* (Holt and Smith, 1979). Like pre-stratification, post-stratification can reduce variance, if strata are homogeneous in their outcome variable. Post-stratification can also reduce bias introduced by "missing soil samples" that were planned but not taken due to unforeseen challenges including temporary floods, tall crops, frozen soil, grazing cattle, and samples lost or damaged in shipment. Bias from these missing samples is mitigated if strata are formed such that the observed samples are representative of their stratum. This is useful in large sampling campaigns like those in SEP projects because the planned samples appear in thousands of fields that are accessible for sampling for just a few months per year.

NEW TECHNOLOGIES AND RESEARCH COUPLED WITH CARBON CREDITS CAN ACCELERATE THE IMPLEMENTATION OF REGENERATIVE AGRICULTURE AT THE GLOBAL SCALE

While the SEP provides a path forward for large-scale projects to quantify agricultural credits, it is also designed to advance with the state of the science. Several areas of research and innovation can improve projects, implementation, and the quality of agricultural carbon credits so that agricultural soils can realize their full potential as a negative emissions technology to mitigate climate change on a global scale (summarized in **Table 2**). Smith et al. provide a comprehensive assessment of soil measurement, reporting, and verification in the context of greenhouse gas removal projects (Smith et al., 2020). In this section, we discuss innovations that can reduce the cost of estimating baseline emissions, collecting data, and verifying offsets, could make agricultural carbon credits more accessible to all producers and enable greater adoption of environmentally beneficial practices. We highlight three of these areas: (1) improving soil analyses, (2) continuing research and updating models to better account for all soil gains and losses (including erosion and inorganic carbon), and (3) improving the accessibility and management of agricultural data.

Innovations in Soil Analyses Can Improve Scale and Throughput

Conventional soil carbon quantification methods require soil core sample collection, transportation, and multi-step lab analyses to deliver accurate and precise results. In practice, separate analyses are required to characterize soil carbon by dry combustion, bulk density by soil weight over volume, texture by hydrometer or pipet method, and pH by pH-meter. While these methods are trusted and widely adopted, they can be time consuming, labor intensive, and expensive. Novel rapid and accurate soil measurement technologies would revolutionize soil carbon sampling and measurement systems. Remote sensing of soil properties would be the most impactful advance, but current methods have not demonstrated strong performance for soil organic carbon ($R^2 > 0.85$) or are limited to fields with bare soil—a requirement that is hard to meet in no-till systems with residue and cover crops (Bhunia et al., 2017; Yu et al., 2017). In-field soil property measurements through probes or scanners still require in-person visit fields but would reduce sample shipping and tracking logistical needs (Viscarra Rossel and Bouma, 2016). Finally, improvements in lab analyses could decrease costs and already show promise in the near-term based on published data on spectroscopic techniques and existing spectral databases (Baldock et al., 2014; Yu et al., 2020) (further detail in **Supplementary Material**).

Research and Methodology Updates Could Improve Accounting for All Potential Soil Carbon Gains and Losses

Further research is critical to elucidate how key practices and crop systems impact GHG emissions and soil carbon sequestration. Recognizing this, Indigo has undertaken a long-term research effort, the Soil Carbon Experiment, described in the **Supplementary Material**. External research has also illustrated how methodologies and biogeochemical models could be improved to better account for carbon enrichment or loss in diverse soils. The methods described in this article and in the SEP primarily focus on organic carbon flux. The SEP

TABLE 2 | Landscape of research and technologies that could accelerate the impact of agriculture as a tool to reduce net GHG emissions.

Area of research	Challenge addressed	References	How data would improve credits
Soil research			
In-field soil property measurement	Improve model estimates and decrease logistics required for soil sampling	Viscarra Rossel and Bouma, 2016	Improves baselining and reduces model uncertainty to generate high-value credits
Remote sensing of soil properties	Improve model estimates and decrease need for soil sampling	Ge et al., 2011; Hively et al., 2011; Mulla, 2013; Bhunia et al., 2017; Yu et al., 2017; Lausch et al., 2019	Improves baselining and reduces model uncertainty to generate high-value credits
Improved lab analytical methods	Reduce the costs of analyses and enable higher throughput	Baldock et al., 2014; Wijewardane et al., 2018, 2020; Dangal et al., 2019; Yu et al., 2020	Improves baselining and reduces model uncertainty to generate high-value credits
New metrics for soil health	Earlier identification of practices that have an impact on soil carbon sequestration	Conant et al., 2011; Cotrufo et al., 2015; Vos et al., 2018; Lavallee et al., 2020	Enable faster validation of new practices to generate credits
Soil and emissions data on erosion and biogeochemical cycling	Reduce model uncertainty by integrating the role of soil erosion and sedimentation in CO_2 emissions and carbon sequestration	Asefaw Berhe et al., 2018	Reduced model uncertainty
Soil and emissions data on novel amendments to build soil carbon and/or stimulate soil health	Assess practices that capture carbon in stable forms or build soil organic carbon by stimulating microbial-mediated carbon mineralization	Ling et al., 2016; Haque et al., 2019, 2020; Beerling et al., 2020; Gryta et al., 2020; Kelland et al., 2020	Enable or increase credit generation for carbon-positive practices
Management practice research			
Remote sensing algorithms to verify management practices	Decrease data collection burden for grower	Huang et al., 2018; Sulla-Menashe et al., 2019; Hagen et al., 2020; Indigo Ag, 2020	Enable or increase credit generation for carbon-positive practices
Soil and emissions data on grazing practices	Decrease uncertainty and improve estimates of practice effect	Stanley et al., 2018; Godde et al., 2020	Enable or increase credit generation for carbon-positive practices
Data and reporting research			
Database of soil emissions and soil organic carbon measurements	Supports model calibration and validation requirements	Atwood and Wood, 2020	Reduces model uncertainty to generate high-value credits
Farm data interoperability	Decrease data collection burden for grower	Yeumo et al., 2017	Reduced timeline for credit generation

allows for use of amendments such as biochar, which includes a component of inorganic carbon, to enhance carbon sequestration provided that the carbon remains in the project area. Properly quantifying and verifying the inorganic carbon stocks, however, is challenging as it is not currently estimated by biogeochemical models. Similarly, soil erosion is an important factor to accurately estimate the benefit of practices such as no-till and cover cropping (Asefaw Berhe et al., 2018). Although some models like EPIC and RZWQM2 account for erosion, many do not. Updating models and methods to better account for these sources and losses of carbon could further incentivize adoption of regenerative practices. Recent research has also highlighted ways that soils could be used to capture carbon through enhanced rock weathering, in which the soil-captured carbon eventually travels through waterways and deposits on the ocean floor (Beerling et al., 2020). This type of sequestration has benefits in terms of greater certainty of permanence but would require a new methodology or significant revision to the SEP as the ultimate location of the carbon goes outside the bounds of the fields within a project.

Improved Data Collection Methods Can Reduce Barriers to Entry for Growers

The volume of data required to create high-quality credits cannot be understated. Precise, verifiable, and traceable soil and agronomic data must be collected from grower fields and grower records to keep uncertainty low. These documentation requirements represent significant investment from the grower and the project developer, both in interview time and in the effort to properly clean and assess the data for quality. Multiple ag-tech companies, including Indigo, have created software tools to support soil and grower data collection. Even so, the burden of data collection remains a challenge for growers as many farm records remain undigitized. Remote sensing technology can be leveraged as a gap-filling measure to help reduce the burden of historical data collection across project fields (Ge et al., 2011; Huang et al., 2018; Sulla-Menashe et al., 2019). Although growers must still corroborate the data and the project developer must still verify eligible practice changes have occurred, remote sensing could provide initial crop type and practice data across project fields for current and previous seasons. Research investments that improve and validate remote sensing tools for field-level practice determination can play a significant role in realizing its potential to decrease the data collection burden.

CONCLUSION

In this perspective article, we explored the theoretical underpinnings and key advancements of carbon crediting under the CAR SEP– a flexible modeling approach, a new approach to baselining, a hybrid measurement and modeling approach to credit generation, and a new approach to uncertainty quantification. Thanks to growing voluntary carbon market incentives and rigorous protocols like the SEP, there are financial mechanisms to reward producers who implement land management practices that sequester additional carbon in soil and mitigate GHG emissions. Agricultural carbon credits can be further enhanced by improving grower data collection through remote sensing, funding research on high-throughput and accurate soil quantification technologies, and leveraging research insights in comprehensive calibration-validation databases. It is important to acknowledge that agricultural offsets, while impactful, must be complemented by critical emissions reductions and natural climate solutions across all sectors to mitigate climate change (Griscom et al., 2017). However, wide-scale adoption of regenerative agriculture can serve as a viable, low-cost, and co-beneficial component of a global climate change impact reduction effort. By continuing to leverage scientific advancements and cutting-edge research, we can improve upon model uncertainties, issue high-quality credits, and implement this negative emissions technology at scale.

DATA AVAILABILITY STATEMENT

The original contributions generated for the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

AJ and AK contributed to manuscript ideation, primary writing, and editing. MM, MD, and EC contributed to writing, editing, and review. CB and GP contributed to writing and review. DH contributed to review. All authors contributed to the article and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2021.686440/full#supplementary-material

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Conflict of Interest: All authors are employed by Indigo Agriculture.

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CORRECTION
published: 06 September 2021
doi: 10.3389/fclim.2021.750344

Corrigendum: Implementing the Soil Enrichment Protocol at Scale: Opportunities for an Agricultural Carbon Market

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Keywords: negative emissions technology, agriculture, soil, carbon offset, carbon credit, regenerative agriculture

OPEN ACCESS

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Specialty section:
This article was submitted to Negative Emission Technologies, a section of the journal Frontiers in Climate

Received: *30 July 2021*
Accepted: *16 August 2021*
Published: *06 September 2021*

Citation:
Jackson Hammond AA, Motew M, Brummitt CD, DuBuisson ML, Pinjuv G, Harburg DV, Campbell EE and Kumar AA (2021) Corrigendum: Implementing the Soil Enrichment Protocol at Scale: Opportunities for an Agricultural Carbon Market. Front. Clim. 3:750344. doi: 10.3389/fclim.2021.750344

A Corrigendum on

Implementing the Soil Enrichment Protocol at Scale: Opportunities for an Agricultural Carbon Market
by Jackson Hammond, A. A., Motew, M., Brummitt, C. D., DuBuisson, M. L., Pinjuv, G., Harburg, D. V., Campbell, E. E., Kumar A. A. (2021). Front. Clim. 3:686440. doi: 10.3389/fclim.2021.686440

In the original article, there was an error. The original text read "The SEP allows for inorganic carbon amendments such as biochar to enhance carbon sequestration, provided that the carbon remains in the project area." The SEP does allow for biochar as an organic amendment since it impacts organic carbon. However, because biochar contains both organic and inorganic carbon, this sentence may cause undue confusion.

A correction has been made to the section "*New Technologies and Research Coupled With Carbon Credits Can Accelerate The Implementation of Regenerative Agriculture At The Global Scale,* subsection *Research and Methodology Updates Could Improve Accounting for All Potential Soil Carbon Gains and Losses,* paragraph 1.

Corrected Paragraph: Further research is critical to elucidate how key practices and crop systems impact GHG emissions and soil carbon sequestration. Recognizing this, Indigo has undertaken a long-term research effort, the Soil Carbon Experiment, described in the Supplementary Material. External research has also illustrated how methodologies and biogeochemical models could be improved to better account for carbon enrichment or loss in diverse soils. The methods described in this article and in the SEP primarily focus on organic carbon flux. The SEP allows for use of amendments such as biochar, which includes a component of inorganic carbon, to enhance carbon sequestration provided that the carbon remains in the project area. Properly quantifying and verifying the inorganic carbon stocks, however, is challenging as it is not currently estimated by biogeochemical models. Similarly, soil erosion is an important factor to accurately estimate the benefit of practices such as no-till and cover cropping (Asefaw Berhe et al., 2018). Although some models like EPIC and RZWQM2 account for erosion, many do not. Updating models and methods to better account for these sources and losses of carbon could further incentivize adoption of regenerative practices. Recent research has also highlighted ways that soils could be used to capture carbon through enhanced rock weathering, in which the soil-captured carbon eventually travels through waterways and deposits on the ocean floor (Beerling et al., 2020). This type of sequestration has benefits in terms of greater certainty of permanence but would require a new methodology or significant revision to the SEP as the ultimate location of the carbon goes outside the bounds of the fields within a project.

The authors apologize for this error and state that this does not change the scientific conclusions of the article in any way. The original article has been updated.

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frontiers in Climate

POLICY BRIEF
published: 27 September 2021
doi: 10.3389/fclim.2021.686787

Deploying Low Carbon Public Procurement to Accelerate Carbon Removal

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Carbon dioxide removal (CDR) will be required to keep global temperature rise below 2°C based on IPCC models. Greater adoption of carbon capture utilization and storage (CCUS) technologies will drive demand for CDR. Public procurement of low carbon materials is a powerful and under-utilized tool for accelerating the development and of CCUS through a targeted and well-regulated approach. The policy environment is nascent and presents significant barriers for scaling and guiding emerging technology solutions. The concrete sector has unique attributes that make it ideally suited for large-scale low-carbon public procurement strategies. This sector offers immediate opportunities to study the efficacy of a supportive policy and regulatory environment in driving the growth of CCUS solutions.

Keywords: carbon utilization, carbon removal, CCUS, low carbon public procurement, climate policy

OPEN ACCESS

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Specialty section:
This article was submitted to Negative Emission Technologies, a section of the journal Frontiers in Climate

Received: *27 March 2021*
Accepted: *01 September 2021*
Published: *27 September 2021*

Citation:
Dunford E, Niven R and Neidl C (2021) Deploying Low Carbon Public Procurement to Accelerate Carbon Removal. Front. Clim. 3:686787. doi: 10.3389/fclim.2021.686787

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) has identified that all pathways limiting global warming to 1.5°C include removal of carbon dioxide from the atmosphere in addition to aggressive mitigation of greenhouse gas emissions (Rogelj et al., 2018). Ten gigatonnes of CO_2 must be removed from the atmosphere each year by 2050 to keep temperature rise below 2°C (Mulligan et al., 2020). Carbon dioxide removal from the atmosphere, or CDR, is defined as:

"Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage but excludes natural CO_2 uptake not directly caused by human activities" (Masson-Delmotte et al., 2018).

Complete CDR solutions therefore must consist of two components: CO_2 capture from the atmosphere, and an endpoint where CO_2 is stored in geological or biological sinks or utilized within the production of economically valuable products. Multiple pathways have been identified for carbon removal, including the enhancement of natural systems (e.g., reforestation and agricultural soil management), and engineered approaches (e.g., direct air capture and enhanced mineralization).

Private sector entities have long utilized their purchasing power to influence their respective supply chains, a strategy increasingly deployed to achieve sustainability goals. This has been a consequential development as indirect emissions arising from the supply chain (referred to as Scope 3 emissions) account for as much as 75% of an organization's carbon footprint (Huang et al., 2009). Meta-analyses of sustainable supply chain studies indicate that deployment of capital to promote sustainable practices has a positive impact on operational and financial performance, especially for manufacturing industries (Govindan et al., 2020).

Private firms are now turning their attention toward the CDR challenge. This effort has been led by the information technology sector, with multiple firms (including Microsoft, Shopify, and Stripe) investing in research and development and the direct purchasing of carbon credits from CDR technology providers. Early private subsidization of innovation is enabling the continued development of nascent technologies and fueling investment interest. Private investment alone however will be insufficient to drive the advancement of CDR at the scale and rate necessary to avoid overshooting the 2°C target.

Federal, state, and local public agencies are the largest overall spenders in the market and have unmatched capacity to use their procurement to advance key policy objectives. Public procurement accounts for ∼13% of the gross domestic product of OECD countries (Baron, 2016). The scope and scale of public procurement makes it one of the most effective policy mechanisms available to governments to drive emissions reductions (Correia et al., 2013; Grandia and Meehan, 2017). Government agencies are expected to deliver the best value to civil society as stewards of public funds. Increasingly, this has come to mean the delivery of outcomes that offer a broader public benefit than purchasing the right material at the right quantity and best price. Recent studies have shown that citizens support the concept of public agencies using their buying power to deliver environmental benefits (Keulemans and Van de Walle, 2017).

Data on public views of CDR is more limited. A recent survey indicates that despite low awareness of CDR and skepticism that it will address root causes of climate change, there is public support for CDR provided it is pursued as part of a larger decarbonization agenda and not as a substitute for mitigation (Cox et al., 2020).

Low Carbon Procurement Policy Overview

Despite its potential impact and signs of support, there are few examples of public policy that target carbon reduction through procurement. As CDR is an emerging policy interest, governments have preferred to fund grants that support technology research and development and to provide tax subsidies for private entities investing in innovation. Low carbon procurement policies directly promote deployment by linking policy goals for decarbonization to the purchasing of materials. This requires government agencies to choose a tender design that awards a contract based on criteria other than price (Grandia and Meehan, 2017).

Government procurement focusing on lower carbon products would stimulate demand for carbon capture and utilization (CCUS) technologies that reduce the carbon content of materials vs. conventionally manufactured products. This would not necessarily lead to increased demand for CDR as the utilized CO_2 could come from industrial point sources. Growth of market segments that utilize carbon dioxide however would increase demand for CO_2 overall, potentially spurring greater investment in CDR.

The most prominent low carbon procurement policy model in North America is the Buy Clean California Act. Buy Clean directs state agencies to consider the carbon impact of materials purchased for infrastructure projects (Buy Clean California Act, 2017). Notably, Buy Clean does not yet cover all classes of materials, including emissions-intensive materials such as aluminum, wood, concrete, and cement. Similar legislation was recently adopted in Colorado, suggesting that it will be broadly applicable in the United States.

Cement and Concrete

Consumption of concrete materials is deeply interconnected with public spending, with public sector infrastructure one of the two largest drivers of concrete production. As much as 39% of all concrete in North America is purchased by public agencies (Hasanbeigi and Khutal, 2021). Research by the City of Portland, Oregon suggests that concrete is the single largest source of carbon in the supply chain for local governments (Trucost, 2016). This is largely due to the impact of Ordinary Portland Cement, the key binding ingredient in conventional concrete products. Cement is an inherently emissions-intensive industrial material that is difficult to decarbonize. Cement production generates ∼7% of annual global emissions (**Figure 1**) (Czigler et al., 2020).

The absence of cement and concrete from Buy Clean is notable and to date, there is no low carbon procurement policy enacted at a state or federal level that connects decarbonization policy objectives with the carbon impact of these materials. Beyond its importance as a significant source of Scope 3 emissions, concrete has the ability to mineralize CO_2. CO_2 can be utilized as a substitute, input, or enhancement for the various constituent materials of conventional concrete, including water, cement, aggregates, and supplementary cementitious materials (Cao et al., 2021).

Multiple early-stage companies are already active in this space that is expected to achieve 1-5Gt of carbon removal per year (refer to **Figure 2**). The market for CO_2 utilization in concrete products is expected to grow to \$150–\$400B by 2030 with 50% of all CO_2 reductions in the sector expected to come from carbon capture and utilization (CO_2 Sciences The Global CO_2 Initiative, 2016). This early innovation, combined with the fact that concrete is the most widely used human-made material in the world,

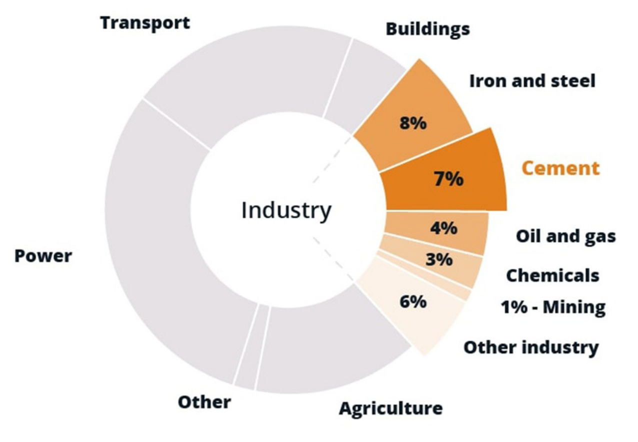

FIGURE 1 | Cement production's share of global CO_2 emissions (adapted from Czigler et al., 2020).

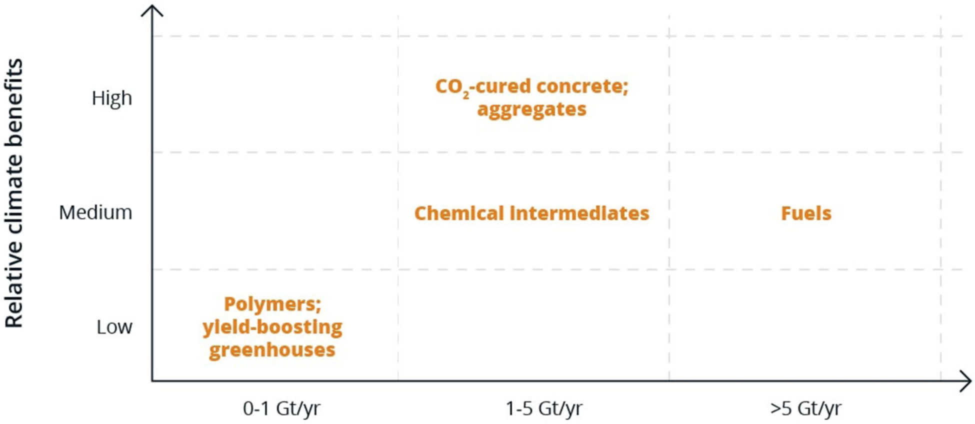

FIGURE 2 | Projected carbon removal potential and climate benefits of CO_2-derived products and services adapted from International Energy Agency (2019).

makes it the most immediate and scalable engineered technology pathway for mineralizing industrial CO_2, whether captured from industrial point sources or from CDR sources such as bioenergy with carbon capture and storage. Still, many emerging concrete CO_2 mineralization technologies are immature and not yet commercially deployed (Ravikumar et al., 2021). This sector therefore presents a crossroads of opportunities: the ability to achieve public decarbonization commitments and support scaling of technologies through the procurement of materials that are already needed for planned infrastructure expansion and renewal.

Portland cement is the definitive, difficult-to-abate global industry. For it to attain carbon neutrality within a timeframe that is meaningful from a climate perspective, breakthrough technologies must quickly emerge and penetrate the market at scale. Therefore, public procurement approaches should be designed to meet the core objective of reducing gross emissions while also explicitly increasing demand for high-impact innovations that the private sector would otherwise be too slow to adopt.

Here we review the potential that low carbon procurement could have to accelerate CCUS deployment by considering a recent policy model. The Low Embodied Carbon Concrete Leadership Act (LECCLA) is a sector-specific CCUS policy targeting the decarbonization of concrete materials purchased by public agencies. LECCLA was introduced separately in the New York (A2591/S542) and New Jersey (A5223) legislatures in 2019 and 2021, respectively (219th Legislature, 2020; Senate Bill S542A, 2021). At the time of this writing the New York legislature has passed legislation requiring consideration of the LECCLA policy mechanism as part of a broader directive to establish a low carbon concrete procurement standard.

POLICY OPTIONS AND IMPLICATIONS

Before low carbon procurement can occur, existing regulatory standards must be updated. Any requirement or specification that prescribes a certain approach or solution can be a significant obstacle to innovation in procurement (Uyarra et al., 2014). Existing standards may intentionally or inadvertently limit the ability of vendors to compete based on carbon impacts, so these standards must be reviewed and revised for procurement that considers climate impact to be successful.

All low carbon procurement policies must start from the same foundation, which is understanding the carbon content of materials available. If carbon is to be considered a criterion for contract award, it is necessary to be able to transparently contrast and compare bids received. The calculation of the carbon content of materials (referred to as embodied or embedded carbon) is conducted using life-cycle assessment (LCA) methodologies. As defined within the ISO 14040 standard, LCA methodologies study the environmental aspects and potential impacts throughout a product's life—from raw materials acquisition through production, use, and disposal (International Organization for Standardization, 2006). LCAs therefore serve as inputs to decision-making for selecting products based on their environmental impacts.

Under LECCLA, this foundational step is accomplished through a requirement for all concrete vendors to complete LCA analyses and report on carbon content. The standardized LCA methodology referred to as a Type III environmental declaration, or Environmental Product Declaration, is the specified reporting tool. The cost to complete these analyses is subsidized through a one-time state tax credit. This incurs a direct cost to the state, though as the number of concrete producers is limited and the credit is capped, the cost is nominal.

With the ability to assess the carbon content of materials well-established, the secondary question is how and to what extent carbon should contribute to competitive scoring criteria. Carbon disclosure and reporting may be voluntary or required. Scoring of carbon content may be binary (pass/fail) or incentives-based. Two approaches that have been proposed include:

- Benchmark Threshold (binary model)–To compete for public work, bidders must demonstrate that the carbon content of their products meets or exceeds the carbon reduction threshold established by the purchasing agency. Once this requirement is met, there is no additional incentive or consideration offered. Benchmark values are negotiated based on some balance between market readiness and policy ambition. Once established, baselines may be reviewed and adjusted at regular intervals to ensure continual progress. The low carbon fuel standard utilized by the State of California to advance vehicle fuel efficiency is an example of this approach (California Air Resources Board, 2020). This legislation requires fuel suppliers to ensure that the fuel that they sell is at or below a fixed carbon intensity target set by the state. Suppliers that cannot meet this baseline are instead compelled to purchase credits from other suppliers that generate fuels with carbon intensities below the fixed target.

- Competitive Bidding (incentives model)–Bidders are measured against each other's carbon performance during the competitive bidding process. Incentives are offered to the bidder that can provide the lowest impact material, subsidizing investment by the private sector into low carbon technologies. This approach is the basis for LECCLA and mimics the traditional price-based competitive bidding process commonly utilized by public procurement officials. The Dutch *CO_2 Performance Ladder* program is a comparable example that incorporates a discount mechanism directly linking LCA-assessed performance to bid competitiveness. First implemented in 2009 for national infrastructure tendering, the program is now also widely used by local governments across a multitude of sectors, including waste management, information technology, and healthcare (Vastbinder, 2021). Discount incentive mechanisms for procurement also have precedent in domains unrelated to environmental performance. For example, the State of California's Department of General Services applies a 5% price discount to certified small businesses (California Department of General Services, 2017).

With these elements in place, the only remaining question is to which materials the low carbon procurement policy should apply. Low carbon procurement policy concepts enacted to date such as Buy Clean have been broad-ranging, whereas LECCLA is restricted to one sector.

Challenges

There is inherent uncertainty in calculating the cost impact of low carbon procurement policies. As the carbon impact of materials is the combined result of many separate activities, selective procurement indirectly targets decarbonization in CO_2 sources. LCA calculation methodologies for Scope 3 emissions continue to improve, but any uncertainty in these calculations can make direct comparison of materials challenging and undermine confidence. This concern is reduced when the comparison is made within an individual materials category.

Adding carbon requirements to public tenders necessarily increases the complexity of the tendering process, which may reduce the number of qualified bids received (Cheng et al., 2018). This is compounded by the fact that there is limited awareness of climate policy or "carbon literacy" among procurement professionals. In practice, public procurers operate in an environment where accountability to complex administrative requirements is valued over any individual strategic goal such as decarbonization (Correia et al., 2013). Faced with competing aims, it can be expected that other agendas could be prioritized over decarbonization goals.

The use of voluntary frameworks or poorly defined criteria requirements may undermine the efficacy of any low carbon procurement policy. To effect change, vendors must experience a shift in equilibrium and experience new competitive pressure. Policies with insufficiently ambitious goals and/or weak incentives are unlikely to create this shift. Voluntary frameworks may however be desirable for sectors that are difficult to regulate or when measurement criteria are not fully established.

Understanding the appropriate incentive structure that will lead to change may also be challenging to predict. Experience in the Netherlands under the CO_2 Ladder suggests that an incentive as small as 5% is sufficient to drive change in the low-margin construction sector. Since the introduction of this low carbon procurement policy, total CO_2 emissions in the Netherlands have decreased beyond expected rates (Reitbergen et al., 2017). The same incentive for a separate market or jurisdiction however may not achieve equivalent results. Incentives that are too small will fail to generate a change in the market, while incentives that are too large are an inefficient use of public funds.

Policies that utilize a carbon benchmark are subject to gamesmanship and do not generate incentives to go beyond the new benchmark "floor." Benchmarks are necessarily established based on industry data and perspectives on what is possible to achieve, thus an opening is created for industry to lobby for a weaker benchmark than that preferred by the administering agency (Kadefors et al., 2021). Practical experience with policies requiring a benchmark suggests that there is also a significant administrative effort to establish, maintain, and update such benchmarks. Conversely, under the competitive bidding model it may be more difficult to measure and communicate progress due to the lack of a defined benchmark to compare progress against.

ACTIONABLE RECOMMENDATIONS

When developing effective low carbon procurement policy, evidence from relevant programs and policies suggest several principles for designing a public procurement strategy that can accelerate carbon removal:

Focus on High Potential Sectors

Initiate low carbon procurement policies in sectors that offer significant opportunities for emissions reduction and where the innovation gap is small. LECCLA focuses on concrete, as this sector is a large source of carbon in the public sector supply chain and is the most technologically mature. This is efficient from a public spending perspective, as these materials are already purchased by the state in large quantities. Leveraging the power of public procurement within a specific sector that is primed for it will provide learning opportunities that can be studied and used to inform future procurement approaches in less developed sectors.

Strategically Deploy Incentives

Contractor decision-making is not strongly driven by internal commitments to environmental performance (Kadefors et al., 2021). As shown by approaches such as the Dutch CO_2 Performance Ladder, industry players are responsive to appropriate incentives that tie carbon performance to commercial success (Reitbergen et al., 2017). Selectively using public funds to provide limited incentives in high-impact sectors sends powerful market, social, and political signals. In the context of a low margin commodity sector, even modest discounts applied to bid prices can result in considerable competitive advantages for high performers. LECCLA's maximum 8% discount for top performers is expected to be sufficient to drive a market response while having a limited fiscal impact.

Utilize a Simple Design

Low carbon procurement is complex and represents a change in how public procurement agencies operate. Elected officials and procurement professionals are not and cannot be expected to be CDR experts. Successful policies will foster an environment that supports innovation without being overly prescriptive or administratively burdensome. Striking the right balance between a policy that is clearly and rigorously structured while still being approachable so that the market can incrementally learn and adapt is key.

CONCLUSIONS

To reach ambitious carbon removal targets of 10GT per year, market signals will be needed beyond the level of investment observed within the private sector to date. As the largest consumers of construction materials like concrete, governments can play a critical role in mobilizing and shaping the development of nascent CCUS and CDR technologies. This can be accomplished directly through procurement and indirectly through policy goals and associated regulatory strategies. As the public sector procures 39% of all concrete used, procurement that prioritizes lower-carbon products will create demand that accelerates the transition to net zero or even net negative concrete. Without this economic impetus, these technology solutions may emerge too slowly to meaningfully contribute to the carbon removal target.

Although few policy examples exist today, case studies from the Netherlands, California, and New York lay the groundwork for further experimentation and evaluation of options for successful low carbon procurement policies.

AUTHOR CONTRIBUTIONS

ED was the primary author of this policy brief. CN conducted interviews and provided key insights to the legislative development process. All authors contributed to manuscript revision and read and approved the submitted version.

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Conflict of Interest: ED and RN are affiliated with the company Carbon Cure Technologies.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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PERSPECTIVE
published: 27 September 2021
doi: 10.3389/fclim.2021.682882

European Carbon Dioxide Removal Policy: Current Status and Future Opportunities

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Over the past two years, the European Union, Norway, Iceland, and the UK have increased climate ambition and aggressively pushed forward an agenda to pursue climate neutrality or net-zero emissions by mid-century. This increased ambition, partly the result of the Intergovernmental Panel on Climate Change's landmark findings on limiting global warming to 1.5°C, has also led to a renewed approach to and revitalized debate about the role of carbon capture and storage and carbon dioxide removal. With increasing climate ambition, including a mid-century climate neutrality goal for the whole European Union, the potential role of technological carbon dioxide removal (CDR) is emerging as one of the critical points of debate among NGOs, policymakers, and the private sector. Policymakers are starting to discuss how to incentivize a CDR scale-up. What encompasses the current debate, and how does it relate to CDR technologies' expected role in reaching climate neutrality? This perspective will highlight that policy must fill two gaps: the accounting and the commercialization gap for the near-term development of a comprehensive CDR policy framework. It will shine a light on the current status of negative emission technologies and the role of carbon capture and storage in delivering negative emissions in Europe's decarbonized future. It will also analyze the role of carbon markets, including voluntary markets, as potential incentives while exploring policy pathways for a near-term scale-up.

Keywords: European Union, carbon dioxide removal, policy, negative emissions, climate change, CDR, direct air capture, BECCS

OPEN ACCESS

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Specialty section:
This article was submitted to Negative Emission Technologies, a section of the journal Frontiers in Climate

Received: *19 March 2021*
Accepted: *01 September 2021*
Published: *27 September 2021*

Citation:
Tamme E and Beck LL (2021) European Carbon Dioxide Removal Policy: Current Status and Future Opportunities. Front. Clim. 3:682882. doi: 10.3389/fclim.2021.682882

INTRODUCTION

Three years ago, the Intergovernmental Panel on Climate Change released its Special Report on 1.5°C, outlining the potential role of CDR in meeting global climate targets in all four of its illustrative scenarios. With the world procrastinating substantial emissions reductions, overshooting global climate targets has become more likely, necessitating the scale-up of CDR technologies to balance out difficult or impossible-to-reduce emissions in sectors like aviation and agriculture on the pathway to net-zero, and eventually draw down historical emissions. Europe's vision for climate neutrality[1] was first presented in "A Clean Planet for All" communication in 2018 (European Commission, 2018a) and became the foundation of the European Green Deal a

[1] Climate neutrality is defined as achieving net-zero emissions of all greenhouse gases (European Commission, 2018a), as opposed to carbon neutrality target that would include only CO_2 emissions.

year later (European Commission, 2019). To pave the way toward climate neutrality by 2050, the EU raised its 2030 climate target in the recent Climate Law (European Commission, 2021b), with the Fit for 55 package laying the groundwork for its implementation.

Policy is needed to enable at scale deployment of technological CDR for three key reasons. First, little progress toward reducing emissions increases the likelihood of the need for CDR. Second, technology innovation experience has shown that it will take decades to make these technologies available at scale. Third, increased climate ambition in the near term means CDR will need to be scaled sooner. Drawing up CDR policy today would bolster the EU's position as a climate leader. Moreover, by enabling early investment in technological CDR solutions and thereby progressing commercialization and lowering the cost of these technologies, EU policy can support global access to CDR in the long term.

For successful deployment of CDR technologies, the policy must fill two gaps: the commercialization and the accounting gap, as currently, the EU policy only aims to enable a few demonstration projects. The commercialization gap is the gap between a few demonstration projects and at-scale deployment with technologies able to be deployed by climate policy, such as the EU Emissions Trading System (EU ETS) only. The commercialization gap needs to be filled by policy enabling (1) cost reductions (2) CO_2 transport and storage infrastructure (3) access to affordable financing and (4) compressing deployment timelines, to enable a large scale-deployment of CDR technologies (Nagabhushan et al., 2021). Addressing the accounting gap is critical to demonstrate that actual CDR is delivered and because incentive mechanisms can only be designed for quantifiable CDR approaches (Tamme, 2021).

The paper concludes that the EU provides a promising comprehensive climate policy framework where CDR is already included in some areas. These policies are likely to be able to drive CDR deployment once the technologies are commercialized *via* a technology-specific innovation policy. Thus, more must be done to ensure accurate accounting and that the technologies are commercialized in time to deliver on climate ambition.

DEFINING CARBON DIOXIDE REMOVAL

The IPCC defines CDR as anthropogenic activities removing CO_2 from the atmosphere and durably[2] storing it in geological, terrestrial, or ocean reservoirs, or in products[3] (IPCC, 2018). Tanzer and Ramírez have pointed out a high variance in how existing literature interprets CDR, and suggest a list of four criteria to determine whether a climate solution or technology can deliver greenhouse gas removal[4] (Tanzer and Ramírez, 2019).

CDR can be achieved through natural and technological approaches, ranging from biomass, soils, and oceans to storage in deep geological formations. Specific approaches like biochar and bioenergy with carbon capture and storage (BECCS) can be considered a mix of natural and technological approaches. Some approaches use biomass to draw CO_2 from the air; others like direct air capture with carbon storage (DACCS) and enhanced weathering remove CO_2 directly from the air. While some models, such as the illustrative P1 of the IPCC 1.5 degree report (IPCC, 2018), show that climate goals may be achieved without technological CDR options, the limited progress in making substantial emissions reductions and the challenges each solution faces suggests that a mix of CDR options will be needed.

Technological CDR approaches which rely on geologic CO_2 storage include three steps: (1) CO_2 is captured from the atmosphere, either directly or through biomass, (2) the CO_2 is compressed and transported to the location of geologic storage, and (3) CO_2 is injected to geologic formations for safe and permanent storage.

This perspective focuses mainly on the technological approaches of CDR—BECCS, and DACCS—in the context of the policy design under the European Green Deal.

THE EMERGING DEBATE ON THE ROLE OF CARBON DIOXIDE REMOVAL

The climate neutrality vision proposed in the European Green Deal and adopted in the Climate Law has substantially increased the interest in CDR. The indispensable role of CDR in achieving climate neutrality in Europe and potentially net negative emissions thereafter has led countries, corporations, cities, and regions to learn more about a range of CDR approaches, including BECCS and DACCS.

Stakeholders have voiced concerns that if emission reductions are not prioritized, CDR as a flexibility mechanism in getting to net-zero could delay climate action and water down the mitigation ambition (Carton et al., 2020). There is no common understanding of CDR's role and at least three different rationales are frequently put forward for considering CDR in public policy: (a) balancing out residual emissions from effectively-impossible-to-decarbonize sectors (like agriculture) for achieving a permanent steady state of net-zero emissions, (b) temporarily balancing out residual emissions from hard-to-decarbonize sectors (like construction, heavy industry, and heavy transport), while solutions for these sectors are being developed and just transformations with job-transitions are taking place, and/or (c) to return to historical CO_2 concentrations through a phase of global net-negative emissions

[2]"Durability" and "permanence" are used interchangeably in literature. In order to meet the long-term temperature goal of the Paris Agreement, CO_2 should be stored out of the atmosphere for at least hundreds of years. Shorter timescale (decades) would result in captured CO_2 to be released back to the atmosphere before the mitigation goals are met. The permanence of geologic CO_2 storage, if managed properly, is over a thousand years (Bergman and Rinberg, 2021).

[3]IPCC definition includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

[4]Greenhouse gas removal is a broader term compared to CDR. It covers removal of all greenhouse gases, including CO_2. CDR is the main type of greenhouse gas removal currently explored, due to the relative abundance of CO_2, its long atmospheric lifetime, and its chemical reactivity which make CO_2 an appealing candidate for removal (Bergman and Rinberg, 2021).

after achievement of complete decarbonization (Honegger et al., 2021b).

While it is widely accepted and evident from all mid-century net-zero pathways that emission reductions will need to be strongly prioritized over CDR, it is also clear that it takes time and effort to develop new policies and scale up removals as needed. Moreover, more research and consultations will be needed to understand the socio-environmental impacts of CDR technologies, particularly in a sustainable development context. Research has shown that even a portfolio approach of CDR options might still have potentially negative implications for SDGs. Early recognition of tradeoffs and lessons learned from other technology scale-ups need to be integrated into governance and policy frameworks, and future-oriented policy must aim to minimize negative interference of technology ambition with the achievement of the SDGs, and be designed to enhance them (Honegger et al., 2021a). To conclude, policy needs to reflect both the pressing need to deliver near-term reductions and carefully govern socio-environmental impacts, while also preparing the innovation landscape for delivering CDRs in the medium-to-long term.

Currently, the slowly emerging policy debate evidences no definitive agreement, neither on the role of CDR technologies nor the necessary scale of CDR. While discussions among policymakers are yet to delve deeper into this topic and have to find consensus, the research community has kickstarted their analysis, and suggested specific thresholds and considerations for setting separate emission reduction and CDR targets (McLaren et al., 2019; Geden and Schenuit, 2020).

THE ROLE OF CDR IN CLIMATE NEUTRALITY: STATUS AND POLICY

The European Commission has stated that "In the long run, DACCS has a real potential for technological development and could become the predominant technological option to remove CO_2 from the atmosphere in an energy system dominated by cheap renewable energy and batteries" (European Commission, 2018b). Indeed, CDR technologies such as DACCS are expected to deliver significant emissions reductions on the road to climate neutrality in the European Union and globally.

On the international level, the International Energy Agency's Net-Zero Scenario, a total of 2.4 Gt CO_2 is captured in 2050 from the atmosphere through bioenergy with CO_2 capture and DACCS, of which 1.9 GtCO_2 is permanently stored and 0.5 Gt CO_2 is used to provide synthetic fuels in particular for aviation (IEA, 2021). In the IPCC's illustrative scenarios, cumulative technological CDR until 2100 ranges from 151 GT in P2 to 1191 GT in P4 (IPCC, 2018).

For Europe, while there is a lack of comprehensive and technology-inclusive scenarios, the scenarios analyzed in the EU's communication include up to around 250 mtpa of CO_2 being removed *via* DACCS and BECCS in 2050 across various scenarios (European Commission, 2018b).

With regards to technological CDR, the agenda is often aligned with carbon capture and storage technologies. However, there is no single DACCS facility operating at scale[5] today, and just one in planning in the United States. There are about ten or so direct air capture pilot and demonstration plants across Europe, mostly demonstrating the Climeworks technology, with a total of 15 facilities operating globally (IEA, 2020). Other examples include the Carbfix project in Iceland, the only DACCS facility that stores the CO_2 underground. Climeworks also launched its 4000 tons/year Orca facility in September 2021 in Iceland (Carbfix, 2021).

Regarding BECCS, while there are several projects underway in Europe (Carbon180, 2021), including waste-to-energy plants, the Decatur Illinois BECCS facility in the United States is the only one currently operating at scale. In Europe, Drax's bio-energy CCS power station in the UK is currently in early development. The development of pilot facilities is promising, but now the technologies need to bridge the gap to at-scale deployment. This includes the pressing need to reduce costs.

While the scientific case for scaling CDR technologies is clear, there are three reasons why policy needs to support a near-term, at-scale deployment of CDR facilities, which lays out the case for filling the commercialization and accounting gaps.

First, there is a general misconception that there is sufficient time to test current, widely-adopted decarbonization technologies as main mitigation strategies before deploying more advanced decarbonization technologies like carbon capture, removal, and storage. This misconception invokes sufficient time to have a hierarchy of decarbonization technologies, i.e., that one can deploy the cheapest and politically most favored solutions first, see if they can eliminate emissions on their own, and then proceed to deploy other technologies. However, despite repeated warnings by scientists, the systems transformation at the level required to be on track to meet climate goals has not been delivered. This increases the likelihood of an emissions overshoot, requiring CDR. Coupled with the fact that the Intergovernmental Panel on Climate Change (IPCC, 2018) demonstrated that the sooner emissions are reduced, the better the chance at fending off the worst effects of climate change, it has become increasingly clear that all decarbonization options need to be deployed as soon as possible to achieve net-zero emissions by mid-century. A technology-inclusive approach that allows for multiple different technologies would increase the chances of reaching climate goals, as it would provide for a range of decarbonization technology options, mitigating the risk of any technology failing. Moreover, against the backdrop of climate change constituting a global problem, advanced economies like the European Union need to invest in decarbonization options to bring down their cost and make them available for other regions at more affordable prices. This includes CDR technologies.

Second, considering the history of innovation of primary energy production technologies, it has taken on average 20 years for technologies to reach a 1% market penetration level which is regarded mainly as an inflection point for a technology (Kramer and Haigh, 2009). This is a deft analogy because primary energy production technologies are similar in scale, complexity, additionality, and new infrastructure

[5] Capturing 500,000 tons of CO_2 or more.

requirement. Moreover, the investment risk profiles of new technologies are similar to other clean energy technologies at early stages. At a 1 % market penetration level, typically, hundreds of billions of dollars have been spent on technology development and early project deployment to reach the point of providing 1% of the world's primary energy production. Evidence suggests that it then takes about 30 additional years to get a threshold of 20–30% of primary energy demand, underlining the challenges of scaling technologies fast and within the required timeframe to achieve net-zero emissions. This provides evidence of the challenges of scaling these technologies in a short amount of time and supports the arguments of developing policies to scale them in the near term.

Third, as laid out in its new 2030 target to achieve at least a 55% emissions reduction below 2010, the EU's increased ambition necessitates CDR technologies to be scaled sooner. As the impact assessment states: "Increased ambition increases clarity on the pace of emissions reductions required (…) increasing the role of CDRs in our economy" (European Commission, 2020b). Moreover, CDR could also be considered a pathway to deliver climate change mitigation at different speed across the Member States to reach the 2030 goal and beyond, effectively contributing toward the collective goal.

To fill the commercialization gap and considering these implications of the innovation timeframe, an EU policy framework must speed up deployment timelines through enabling key success factors, including cost reductions, CO_2 networks, access to affordable investment, and compressing deployment timelines. Cost reductions are necessary to enable more effective deployment at a cheaper price and would eventually enable comprehensive climate policy such as carbon pricing to be the sole driver of technology deployment. Lower cost through deployment and learning-by-doing would also de-risk the technologies, and attract more investors, enabling more affordable capital to flow into CDR. Access to existing infrastructure such as CO_2 transport and storage would also make it much easier to build additional CDR facilities.

Fortunately, it is expected that DACCS and BECCS will benefit from the overall push to deploy point-source carbon capture and storage technologies. This includes the CO_2 infrastructure build-out currently underway in the Nordics and the Netherlands and is already evidenced by new partnerships built around these projects. For example, Climeworks announced a collaboration with the Northern Lights Project, a CO_2 transport and storage project off Norway's coast (Farmer, 2021). The Government of Norway committed some €2B to the project, covering initial capital investment and 10 years of operating expenses. By lowering the cost of transport and storage cost, which can be significant through achieving economies of scale, CO_2 transport and storage networks are essential enablers of CDR deployment. Moreover, Orsted, Aker Carbon Capture, and Microsoft also announced a Memorandum of Understanding to explore retrofitting one of Orsted's biomass facilities in Denmark (Ørsted, 2021).

PATH FORWARD, BUILDING ON THE CURRENT POLICY LANDSCAPE

As outlined above, the policy must serve to speed up commercialization timelines and enable the four success factors. This section will make the case that current EU policy is expected to enable some demonstration projects, but falls short of enabling at-scale deployment—evidencing the commercialization gap.

Over the following years, EU policy-making will be guided by aligning existing sectoral legislation—such as the EU ETS and the Effort Sharing Regulation—with the new 2030 and 2050 climate targets through the Fit for 55 package proposed by the European Commission in July 2021. This comprehensive climate policy reform is an opportunity to provide clear rules and policy pathways for CDR, as ultimately, the emerging policy framework described below is expected to drive the investments in CDR demonstrations in the near term.

The EU ETS currently covers around 40% of EU emissions and will be key to eventually driving investment in commercialized technologies on its own. Established as the world's largest cap and trade system, its carbon price is over 50€ in mid-2021.

One of the policies in the EU ETS toolbox is the EU Innovation Fund, a capital support mechanism for innovative technologies financed by auctions of EU allowances. Worth 22B€ at the current EU ETS allowance price, it is relatively small compared to the ambition. The Fit for 55 package proposes a doubling of its capacity and also including carbon contracts for difference (CCfDs). Innovation Fund's first round of applications was oversubscribed by a factor of 20. An analysis of the applications indicates that a handful of the submitted projects can deliver "net CDR," while around a fifth of total applications include carbon capture, utilization, and storage technologies (European Commission, 2020d). The Innovation Fund could indeed drive investment in CDR demonstration projects in Europe and form an essential risk-reduction tool to enable access to additional private capital for demonstration projects, and perhaps for further projects that could benefit from the grant and technology-specific incentive mechanisms alike. First-mover demonstration projects also make outsized contributions for cost reduction opportunities. However, due to its limited size and the funds being shared across a range of technologies, it is unlikely to be sufficient for at-scale commercialization.

The Trans-European Energy Networks Regulation, also known as TEN-E, is critical for transboundary CO_2 transportation networks and thus enabling CO_2 infrastructure success factors. TEN-E establishes criteria for projects (Projects of Common Interest) that have access to a list of benefits, including access to funding from the Connecting Europe Facility. In the ongoing revision, the European Commission proposed to continue including cross-border CO_2 pipelines in the scope of TEN-E while resisting stakeholder requests to include the entire value chain of carbon capture and storage, including alternative CO_2 transport options such as rail, barge, ship, and truck, along with geologic CO_2 storage (European Commission, 2020c). CDR advocates argue that a broader inclusion of CO_2 infrastructure would provide more certainty for project development. It would further incentivize long-term investment by demonstrating government commitment to the necessary infrastructure.

Establishing a well-designed cross-border CO_2 infrastructure in Europe is especially relevant in the context where the access CO_2 storage is not distributed evenly among countries. The hubs and cluster design of several CCS projects in development illustrates the need for CO_2 to cross several country borders to be transported to storage sites. It helps address the chicken and egg problem; capture carbon is needed to invest in the infrastructure to transport and store it, but firms are unlikely to support investment in capture without this infrastructure. Furthermore, geologic storage inclusion would alleviate the inequitable distribution of geologic storage resources among member states (Pozo et al., 2020). This argument becomes particularly relevant regarding technological CDR, as it is only permanent when coupled with geologic storage while providing transnational benefits of lowering the overall CO_2 concentration already in the atmosphere.

Overall, the currently existing European policy framework, with expected and necessary revisions forthcoming, is well-established to enable initial demonstration projects and anchor infrastructure to be built and offers promising opportunities for integrating incentive mechanisms for CDR.

FILLING THE ACCOUNTING AND COMMERCIALIZATION GAPS

To commercialize CDR technologies, two gaps must be filled by policy and regulation: the accounting gap and the commercialization gap.

Addressing the accounting gap is critical to demonstrate that actual CDR is delivered and because incentive mechanisms can only be designed for quantifiable CDR approaches (Tamme, 2021). This goes for CDR in general and more specifically in the context of the newer CDR approaches, including DACCS, that are not currently covered by sectoral climate policies. Below the authors provide an outline of opportunities for improvement in existing policies and pathways to improve the policy framework.

To address the accounting gap, the European Commission is preparing a regulatory framework carbon removal certification (CRC) to be proposed by 2023 (European Commission, 2020a). Commission communication on restoring sustainable carbon cycles, expected at the end of 2021, will "identify key elements to build a robust and credible framework allowing for authentic, transparent and verifiable carbon removals to be certified" (European Commission, 2021c). Preparation of this policy faces a two-fold challenge: (1) CRC should meaningfully incentivize the deployment of CDR approaches while (2) also supporting the notion of prioritizing emission reductions over removals, especially in the decades leading up to climate neutrality. Different levels of permanence among CDR approaches, coupled with challenging monitoring, reporting, and verification when it comes to nature-based approaches, will add to the complexity. Developing robust accounting rules that can be used to design policies for incentivizing CDR will also facilitate the commercialization of CDR technologies. The preparatory work on the CRC framework has already started, and it is expected to become operational in 2024–2025.

To address the commercialization gap, the policy must enable the four success factors to be met, while providing a long-term incentive for continued investment to build multiple facilities beyond just demonstration projects.

Policy options that could work on the Member State level include policies addressing upfront investment barriers and both CAPEX and OPEX economics of CDR projects. Many of the US projects under development received grants for feasibility and front-end-engineering design (FEED) studies (Beck, 2020) (Zapantis et al., 2019). While the initial public investment is relatively low—in the order of millions—such FEED study grants can help overcome initial barriers to investment by covering upfront cost even if the outcome is uncertain. To address financing gaps and draw in traditional financing, capital grants could increase certainty and demonstrate government commitment. These could be additional to capital grants to those offered through the EU Innovation Fund.

Moreover, CCfDs are gaining traction across Europe as incentive mechanisms for next-generation clean energy technologies, such as hydrogen. Their imperative is bridging the gap between the actual cost of decarbonization technologies and the price of a benchmark, i.e., the EU ETS if coupled with geologic storage of CO_2. The rationale for CCfDs is that the EU ETS carbon price is not high enough to incentivize technology uptake without complementary innovation policies. They have successfully supported the commercialization of renewable energy technologies in the form of feed-in tariffs, thus poised to integrate innovation objectives vis-à-vis existing climate policy. The new proposal for the revision of the EU ETS suggests CCfDs as part of the Innovation Fund (European Commission, 2021a). Moreover, specific instruments are discussed in several Member States. The Dutch SDE++ closed its first round of funding for decarbonization technologies. It offers a 15-year CCfD for the delta between an agreed price and the EU ETS carbon price. These mechanisms can generate sufficient funding to enable multiple projects.

While policymakers need to flesh out how to fill the commercialization gap, other mechanisms could help with project economics to accelerate the deployment of CDR technologies in Europe. First is the not well-known California Low Carbon Fuel Standard CCS Protocol. Second is carbon pricing, including compliance and voluntary carbon markets.

Counterintuitively, California's Low Carbon Fuel Standard (LCFS) incentivizes DACCS investment anywhere globally, including Europe. Trading at around \$200/t of CO_2, the LCFS aims to reduce the emissions intensity of fuels consumed in California by 20% by 2030. Recognizing that CO_2 emissions are a global problem, the LCFS incentivizes DACCS projects anywhere in the world, as long as they adhere to the LCFS CCS protocol's rules (Townsend and Havercroft, 2019). Working with private-sector stakeholders to deliver projects under the California LCFS might also open international collaboration opportunities on innovation and knowledge sharing (Beck and Livingston, 2019). However, policymakers should ensure accurate accounting, potentially aligning different policies.

DACCS and BECCS have also gained a lot of interest in the voluntary carbon markets since 2020 as over a thousand companies have already set net-zero targets. Currently, there are no methodologies for DACCS and BECCS projects under the major voluntary market standards[6] and the transactions take place outside the main standards. Some examples from Europe include Climeworks from Switzerland selling subscriptions for CDR from the air and the Puro.earth CDR marketplace in Finland offering a range of CDR products and preparing a methodology for BECCS and geologically stored carbon (Puro.earth, 2021).

Given that the current Nationally Determined Contributions under the Paris Agreement fall well short of the 2C target (let alone the 1.5C) (UNEP, 2020), the voluntary markets could play a role in bridging the mitigation gap to achieve the Paris Agreement temperature goal. However, the potential overlap in activities under compliance and voluntary markets, such as potential double claiming of emission reductions or removals, must be carefully tackled. As an example, more than 10 companies in Sweden are planning to implement BECCS between 2025 and 2030 (Schenuit et al., 2021). Some of these BECCS operators intend to supply removal credits to voluntary as well as compliance markets (Fridahl and Lundberg, 2021). Hence, both the governments and voluntary market actors will need to work together to ensure that double claiming risks are mitigated.

MOVING FORWARD: POLICY DESIGN FOR SCALING UP CDR UNDER THE EUROPEAN GREEN DEAL

This perspective aimed to give an overview of CDR technology and policy in the European Union. CDR technology commercialization is necessary in the near term because (1) the world will likely overshoot its climate goals—and is expected to do so as a global collective—highlighting the importance of investing in a diverse portfolio of decarbonization options as soon as possible. (2) History has shown that the commercialization of technologies takes several decades and can only be accelerated with adequate policy, which in itself has multi-year led times, and (3) higher EU climate ambition increases the importance of CDR technologies, both to address hard-to-abate sectors and deliver net-negative emissions, but there are two significant gaps: commercialization and accounting.

Yet, a policy must be designed to deliver on technology and climate ambition, including cost reduction, drawing in affordable finance, addressing CO_2 geologic storage and transport infrastructure needs, and accelerating deployment timelines. While the EU already has robust climate policy frameworks amenable to the inclusion of CDR incentives, there is an innovation policy gap that needs to be bridged to enable the large-scale commercialization of CDR technologies. There are several ways this gap could be filled, including through CCfDs and other CAPEX mechanisms and establishing robust greenhouse gas accounting for CDR approaches, incentivized by carbon removal certification framework.

The role of emission reductions and removals in the mitigation of climate change will change over time. Emission reductions will be prioritized on the path to net-zero. However, net-zero by mid-century is a point on the journey to addressing the climate crisis, not the final goal. Thus, CDR will become the main driver to deliver on climate ambition in the second half of the century.

[6]Clean Development Mechanism, Gold Standard, Verified Carbon Standard, American Carbon Registry, Climate Action Reserve, Plan Vivo.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

ACKNOWLEDGMENTS

The authors would like to thank Alex Zapantis from the Global CCS Institute for his review of the first draft of this piece.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Climate

PERSPECTIVE
published: 14 October 2021
doi: 10.3389/fclim.2021.686516

The Good Is Never Perfect: Why the Current Flaws of Voluntary Carbon Markets Are Services, Not Barriers to Successful Climate Change Action

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OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to
Negative Emission Technologies,
a section of the journal
Frontiers in Climate

Received: 27 March 2021
Accepted: 20 September 2021
Published: 14 October 2021

Citation:
Miltenberger O, Jospe C and
Pittman J (2021) The Good Is Never
Perfect: Why the Current Flaws of
Voluntary Carbon Markets Are
Services, Not Barriers to Successful
Climate Change Action.
Front. Clim. 3:686516.
doi: 10.3389/fclim.2021.686516

The world's current level of climate change action does not match its ambitions to tackle the issue, and its ambitions do not currently meet the levels of action science recommends. Voluntary carbon markets (VCMs) are one option proposed to lessen those disparities, and have been both criticized and championed by various groups. Critiques note them as being opaque, flawed, and ineffective. Yet they demonstrate tremendous potential for impact and unprecedented levels of finance. We contend that the critiques of these markets are not only resolvable, but are unavoidable challenges that must be addressed on the path to mobilizing climate change ambition and achieving targets. Furthermore, we believe that by 2050, the current discrete market-based solutions in climate action will become internalized aspects of our economies rather than separate remediations. This goal of internalizing the externalities that cause climate change will result in massive, sustained decarbonization, rapid reorganization of global economies, and an extraordinary push to invent, solve, and scale strategies that facilitate the transition. Pricing carbon is a key contemporary step for transitioning to that future. Voluntary carbon markets are one means to catalyze this action and while needing improvements, should be given appropriate leeway to improve and fulfill that role.

Keywords: emissions trading, carbon offsets, climate change, voluntary carbon markets, climate ambition, emissions reductions, market-based instruments

INTRODUCTION

Currently, countries and non-state actors are far from achieving the climate change ambitions set by the Paris Agreement (United Nations General Assembly, 2021). To meet these goals, the International Panel on Climate Change (IPCC) recommends a dramatic scale-up of greenhouse gas (GHG) reductions and increase global GHG sinks by 2050 (IPCC, 2018). Compliance carbon markets and carbon taxes, while increasingly common, are not scaling up fast enough to match this imperative (United Nations Framework Convention on Climate Change, 2017; United Nations Environment Programme and Green Financing Facility, 2021). Voluntary carbon markets (VCMs) are an alternative market-based instrument that reward GHG offsets. Voluntary carbon markets are projected to grow 15-fold by 2030 to accommodate increased demand for climate solutions in the private sector (Taskforce for Scaling the Voluntary Carbon Market and Final Report, 2021). Voluntary carbon markets provide financial incentives for increased climate action ambitions, developing mitigation projects, and if scaled, can facilitate significant climate action (Streck, 2021).

Voluntary carbon markets exist because there is an imperfect suite of carbon incentives to fully address GHG reductions. Due to lagging regulatory actions, and an interest to remain unregulated, corporate players are increasingly leading in climate action through pledges in VCMs that meet or exceed the analogous mandates of compliance markets. However, there are a number of issues and critiques concerning the design, function, and scale-up of VCMs (Blum, 2020). Critiques span from popular misunderstanding of carbon market economics, to fundamental flaws in their arrangements and implementation. We will discuss several of the most common critiques, clarify the issues of most concern, and offer insight around their solutions.

Beyond these insights, we posit two key perspectives in response to all such critiques. First, the urgency for large-scale climate action outweighs the risk of VCM flaws which can be corrected on an *ad hoc* basis. Secondly, we contend that, if global responses to climate change are effective, by 2050 these critiques will no longer be a concern—carbon markets will largely no longer exist. Instead, incentives related to GHG emissions reductions and removals will be fully internalized by economic activities with GHG accounting and integrated in all aspects of production and service, making carbon prices fully incorporated into all market prices.

Acknowledging obvious shortcomings, we contend that VCMs are a necessary sandbox for innovation as well as a mechanism to bridge the divide between current challenges and a GHG conscious economy of the future. We assert that current marketplaces should be reimagined as wellsprings of problem-solving and catalytic capital rather than instruments to be overly-disparaged, or abandoned. In this paper, we find the common problems of VCMs to be integral as problems of climate change action generally, and as such, represent the opportunity to solve those needs. Beyond addressing past and present issues, we call for governance frameworks that support integrated, interoperable, and inclusive economies and offer a clear understanding for what is mute, needs immediate attention, and what requires room to grow. Ultimately, we believe efforts in the VCM space will lead to economies free of external mechanisms that address climate-change and facilitate regenerative environments.

VOLUNTARY CARBON MARKET CRITIQUES

The following sections identify, clarify, and offer critical perspectives for several of the most relevant VCM critiques. We broadly group them into VCM issues of: *use, economics, implementation, and social impacts.*

Issues of Use

Greenwashing

Greenwashing happens when companies seek to appear as if they are making a greater contribution to environmentalism than the true impact of their actions (Laufer, 2003). To outsiders and some within the space, VCMs are critiqued as enabling this in climate action, resulting in actions indiscernible from business-as-usual or are simply a way of paying for a right-to-pollute (Monbiot, 2006). For instance, groups such as CDM-Watch, a UN watchdog group for the use of carbon credits and SEI, a climate policy think-tank, cite examples of false energy-efficiencies being claimed by coal-plants and alarming rates of ineffective credits being used to offset corporate emissions (Lazarus, 2016).

However, greenwashing can be mitigated through greater transparency from both VCM operators and credit purchasers. Public reporting of GHG accounting and receipts that link origin of the credit to the emissions being mitigated will uncut greenwashing significantly (Yang et al., 2020). Oversights bodies are beginning to address these issues (Taskforce for Scaling the Voluntary Carbon Market and Final Report, 2021) and the increasing demand for a social license to operate points toward progress. These concerns can be further assuaged through public pressure, shareholder initiatives, divestment, investment mandates, fines, and watchdog organizations.

Carbon Accounting

Net-zero claims are often accomplished through use of VCM offsets to balance unavoidable emissions. Recently publicized net-zero ambitions have created unmet and sometimes unrealistic demand for offsets, exposing them to misuse (Rogelj et al., 2021). For instance, the number of claims for offsetting emissions is simply unrealistic given ecosystem constraints—not every major emitter can plant a trillion trees (Kalesnik et al., 2020). Net-zero ambitions should therefore have disclosure requirements and be audited to legitimize or rate likelihood of their success.

Double counting is another example of misuse that occurs when two or more entities claim the same offset. This can happen intentionally, but is also emergent from the absence of consistent or complete accounting protocols and a lack of alignment between market jurisdictions or operators. This lack of coordinated standardization allows for claims to be made without clear means to judge their feasibility or quality (Schneider et al., 2019).

Further progress to resolve these concerns will require adoption of standardized nested accounting, and protocols for interoperability across accounting scales and systems such as between corporate net-zero accounting and reporting Nationally Determined Contributions under the Paris Agreement. This is an active area of innovation in policy and technology with momentum to establish a global framework accommodating diverse market arrangements (Waintstein, 2020).

Issues of Economics

Market Failures and Inefficiencies

Climate change impacts represent a market failure that yet lacks a financial incentive for change. A common industry critique of legislated carbon markets is the risk of excessively or unfairly burdening product and service markets with compliance costs. Historically, evidence is unsupportive for industries and businesses that voluntarily take action to mitigate an environmental impact without an incentive mechanism (Jaffe et al., 2005). Voluntary carbon markets may be one of the first clear examples, and resultantly instigate a quicker, wider participation in fixing the underlying market failure. However, given their voluntary nature it is unlikely VCMs would exist without the prior establishment of compliance markets initiating action to mitigate GHG emissions.

Another market economics critique is that all markets, no matter how well-designed, will always contain intrinsic flaws and externalities. It is true that real-world markets, regulated or voluntary, tend not to function in accordance with the theoretical conditions of economic science (Cullenward and Victor, 2020). Regardless, given the political palatability of carbon markets over taxes and sheer difficulty of negotiating alternative solutions at a moment requiring urgent and expedient action, we contend it is best to proceed with carbon markets despite inefficiencies, and refine over time to correct for key issues of concern.

Within market operations, critics note that voluntary offset markets in particular create excess supply and distorted prices that interfere with the effectiveness of compliance markets (World Bank Group, 2019). There is some potential validity to this concern in initial carbon market creation. However, as mentioned above, addressing interoperability will eventually placate this issue. More concerning is the significant risks of initial emissions baseline misreporting, as a means to create artificial emissions reductions and increase appearance of performance impact. Many of the dynamics giving rise to this concern are likely to be less significant over time as carbon markets mature and reporting normalizes over time.

Clearly due to the inherent limitations of human nature and economics carbon markets will fail to resolve all, or may even create new, patterns of market failure. However, with these significant areas of risk, the negative impacts of all the economic cases above are not likely to exceed the potential of net-benefit when comparing further delayed climate change intervention. Simply put, the existence of carbon markets is better from an environmental, social, and economic standpoint than the absence of any emissions reduction incentive mechanism.

Issues of Implementation

Monitoring, Reporting, and Verifying

Most VCM projects must evaluate, register, validate, monitor, report, and verify their outcomes in often dynamic and differing contexts (United Nation Framework Convention on Climate Change, 2021). It is a time and resource intensive process that represents a significant capacity and cost burden to project development. In some cases, the costs of these activities can constitute a majority of the market value of a carbon credit, reducing the incentive for implementation.

Requirements for monitoring and reporting are also complex and inconsistent across markets and project types. Data collection is tedious and idiomatic for verifying VCM project impacts. Managing these requirements, especially in regards to interoperability of markets, presents a high hurdle for validation, and verification of reporting (Knox-Hayes et al., 2020).

Technological breakthroughs in the availability and quality of remotely sensed data via satellite imagery, drones, laser-detecting devices (LiDAR) and proliferation of *in-situ* devices utilizing the internet of things (IoT) as well as machine learning and artificial intelligence analytics offer innovations that will decrease development costs while increasing the rigor and reach of verifiable impacts (Xiao et al., 2019). Over time, these advancements will enable smaller and more diverse projects to participate in market benefits and steer toward best practices. This will not only result in more trustworthy markets, but enable the scale-up climate mitigation activities. Infrastructure for high-resolution, temporal monitoring of the environment will also provide metrics that can serve decision-making in investment and finance, ecosystem management, and policy and regulation.

Additionality and Baselines

An outcome is *additional* if it would not have occurred without intervention. Activity-based additionality is the benchmark that desired changes in GHG stocks would not have occurred without purposeful intervention. This type of additionality is often the first test of eligibility for a VCM project. Financial-based additionality is slightly different. It presents further complexity and controversy by requiring that the emissions outcome would not have occurred without access to the financial return from the VCM project. The Paris Agreement and wider VCM stakeholders acknowledges these VCM criticisms are exemplified and needing redress (Michaelowa et al., 2019).

While there is a clear need for technical assessment of practice-based additionality relative to baselines, financial additionality is difficult to prove and does not have clear consensus for project implications (Michaelowa et al., 2019). Practice based additionality is the norm in VCMs, however, there should be added focus on funding projects through multiple streams as to avoid the confounding potential of financial additionality.

A baseline is the estimation of pre-intervention system measurements and business-as-usual projections. Baselines that estimate discrete GHG stocks for a project are known as static. Dynamic baselines alternatively account for natural environmental fluctuations and risks due to extreme weather or drought events (Greenhouse Gas Protocol, 2003). Assessment of baselines and additionality must also distinguish between projects that remove carbon from the atmosphere from those that avoid the release of carbon to the atmosphere. Carbon removal projects, such as natural climate solutions through expansion of biotic sinks, are broadly considered less contentious than avoidance markets (Gillenwater, 2012). Carbon removal projects utilize inherently subjective baselines and more assumptive estimations to determine impact.

This also calls to question risk of reversal such as through disturbance events, change of ownership or policy, or altered market dynamics. Buffer pools and thorough due diligence throughout project duration as well as establishment of organizing bodies and technological advances will help to mitigate these risks.

Permanence

Permanence in carbon markets refers to the assurance that carbon will remain in a stock for a long period of time, usually 30–100 years. Different VCM protocol and methodology administrators have built systems to balance technical requirements with the practical constraints of insuring against reversals (Offset Guide, 2021). Scientifically, anything short of guaranteed long-term immobilization of carbon is not possible without burdensome and complex legal and administrative maneuvers by market administrators and government agencies.

Since VCMs are a bridge incentive mechanism to internalizing an externality, the concept of permanence should be revisited. Voluntary carbon markets present an opportunity to protect and expand carbon sinks, incentivize low or negative carbon production, and increase the flow of carbon from the atmosphere to short term and durable stocks—even in cases with shorter term permanence.

A land-based system that transitions to a new management regime that is reasonable to continue for even as little as 10–15 years that results in retaining and removing carbon can provide significant value to the atmosphere and to a buyer in a VCM. It should not be required that VCM project developers seek administrative maneuverings or questionable or eccentric science to prove 100 years of permanence (Ruseva et al., 2020).

Issues of Social Impact

Stakeholder Inclusion and Inequity

Voluntary carbon markets, especially in nature-based projects, affect socio-economic, and environmental systems beyond the activities that directly produce carbon credits. If not stakeholders are not appropriately included in the design process, these projects can be at risk of disenfranchising local livelihoods and creating perverse economic incentives (McDermott et al., 2013). This stakeholder neglect is documented through diverse unintended consequences and lasting distrust for VCM projects (Morrow et al., 2020). For example, in some early project-based REDD+ projects, the financialized carbon benefits resulted in local communities restricted from access to their traditional land and livelihoods, echoing a neo-colonial model of land use that benefits developed nations' interests to the detriment of disadvantaged local communities (Beymer-Farris and Bassett, 2012).

In response, many standards now offer standalone certifications or additional eligibility requirements for stakeholder inclusions, such as Verra's Climate, Community, and Biodiversity program or in PlanVivo or GoldStandards' validation criteria. These added guardrails have shown higher willingness to pay indicating both VCMs are capable of self-correction and these inclusions are desirable to the marketplace (Forest Trends' Ecosystem Marketplace, 2021). Moreover, clear regulation on rights and ownership of credits needs to be developed at national and sub-national levels. This is a process currently taking place, but in need of further support (Streck, 2020). Continued adaptation of VCM standards and mechanisms to correct inequities is essential to durable VCM outcomes and requires wide community engagement in the design and management of a projects.

DISCUSSION

The issue VCMs attempt to solve is quintessentially a tragedy of the commons dilemma wherein atmospheric space for GHGs has been overexploited. To address the critiques of VCMs, we should look to governance frameworks for management of common pool resources (CPRs) (Ostrom, 1997). Community managed CPRs given enough buy-in will actually avoid over-exploitation and calibrate to desirable as well as sustainable management outcomes (Ostrom, 2003, 2014). The structure and operation of VCMs should reflect this framework to identify best practices based on local VCM circumstances and enforce restrictions based on large-scale CPR needs such as through capping emissions. Wider inclusion of stakeholders, adaptive management, and fairly allocating cost-benefits will ultimately serve both global economic outcomes and transform VCMs from market arrangements that abstracts GHG values to resource management that integrates their value.

Technological developments will play a crucial role. Though some technologies are deployed in advanced stages in service to VCMs, further innovation and integration is necessary to sacle impacts and improve trust. Given their explosive interest as tool for climate action and diverse arrangements, VCMs provide a unique sandbox for innovating and refining technological products that serve climate action. Continued development will widen bottlenecks and mediate criticisms in VCMs and improve the science of earth system management.

Rather than impairing or foregoing use of VCMs, we envision these critiques as pointed opportunities to reimagine and invigorate the way we steward our CPRs, and offer not a final solution, but a necessary stepping stone to the goals of climate action. While acknowledging them as only one tool in this endeavor as well as their shortcomings, VCMs nevertheless represent a pathway that encourages better characterization, standardization, and decision support for all climate actions, ultimately strengthening social systems that function alongside climate interventions.

The Future

We view the problems presented to be solutions in wait. The precision, thoughtfulness, and widespread understanding of VCM critiques is indicative of the need for these market-based solutions to climate change to be successful. The role of VCMs and the transition away from them we describe is back-casting perspective and posits that VCMs are not the right nor only tool, but a tool needed today for climate action success 30 years from now.

In that future, there will be little to no need for carbon markets, voluntary or regulated, and taxes and policy, as disincentive mechanisms, will have mostly corrected externalities of GHG emissions. Avoidance of GHG emissions and incentive to maintain GHG sinks will be integrated into the global exchange of goods and services at all scales and in all domains. No part of the economy will go unchanged, and no product or service prices will exclude the cost of that abatement. Voluntary carbon markets are a foray into the infrastructure and R&D of this transition that provides a platform to scope, prime, and initialize solutions to the issues of climate change with increased participation and investability in those actions.

As interests and investments continue to scale, many current VCM issues concerning transparency, manipulation, additionality, permanence, monitoring and reporting bottlenecks, friction, and transaction costs, will be made insignificant if not irrelevant due to the deluge of innovation and market participation we see in the space today. From this optimistic and back-casted perspective, the flaws of VCMs today are simply the growing pains of a maturing set of means to address the climate crisis. What seems unsolvable and unacceptable now will undoubtedly and, indeed, imperatively produce a net benefit for our climate, environment, and society. However, we simultaneously highlight the absolute need to approach VCM development with unshakably high-standards, a directive to adapt and improve wide stakeholder participation, and a clear-eyed vision permissive of current worries.

With this in mind, it is important to resolve key flaws in siloed VCM operations, avoid the creation of additional market failures, and mandate progress in social justice, equity, and the preservation of robust ecosystem services across all climate action developments. Opportunities to realize and empower these successes lay in the fertile space of VCMs.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

OM developed the organizational structure, led proofing, and prepared the manuscript for submission. CJ served as architect for subject matter inclusion and convened the group, including those mentioned in acknowledgments. JP led task management and provided technical and economic fact-checking. All authors shared responsibilities in idea origination, refinement, writing, editing, and narrative development.

ACKNOWLEDGMENTS

We would like to acknowledge Dr. Lauren Gifford, Steve Zwick, and Ryan Andersen for their contributions to idea formulation and input on the direction and subject matter of the paper. They each contributed unique and important perspectives to our finished work. We would also like to thank Eli Mitchel-Larson and Laurie Muzzy for their review and suggestions in final drafts.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers in Climate

PERSPECTIVE
published: 04 February 2022
doi: 10.3389/fclim.2021.787500

Inside-Out: Driving Down Direct Air Capture Costs With High-Efficiency Adsorbents

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As carbon emissions continue to grow, removing carbon dioxide (CO_2) from the atmosphere will be necessary to curb the impact of climate change, with the need to remove over a billion tons of CO_2 in the next decade. Direct air capture (DAC) is a promising technology for removing atmospheric carbon dioxide, with a handful of systems deployed around the globe. As currently deployed, however, tens of millions of these systems are needed to address current and historic emissions, which means creating an industry the size of the auto industry—along with consuming the associated resources—within the next decade. Improving DAC processes via scale is not enough; focusing on breakthroughs in sorbent performance is needed to reduce the number of systems and sheer volume of resources needed to rapidly bring DAC to the scales required to prevent further climate change. There are roles for government, corporations, and the carbon removal industry to play in enabling infrastructure, increasing demand, and creating clarity to accelerate deployment of DAC and, more broadly, carbon dioxide removal technologies.

Keywords: separations, adsorbent, CO_2, infrastructure, carbon capture, climate change

OPEN ACCESS

Edited by:
Phil Renforth, Heriot-Watt University, United Kingdom

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Specialty section:
This article was submitted to Negative Emission Technologies, a section of the journal Frontiers in Climate

Received: *30 September 2021*
Accepted: *17 December 2021*
Published: *04 February 2022*

Citation:
Husk JC and Wenz GB (2022) Inside-Out: Driving Down Direct Air Capture Costs With High-Efficiency Adsorbents. Front. Clim. 3:787500. doi: 10.3389/fclim.2021.787500

INTRODUCTION

There is little doubt that carbon dioxide emissions into the atmosphere are contributing to climate change. The latest IPCC report outlines the need to not just curb emissions, but to also actively remove carbon dioxide (CO_2) from the atmosphere using a number of carbon dioxide removal (CDR) solutions (IPCC, 2021). The amount of CO_2 to remove from the atmosphere is immense–the IPCC estimates that to limit global warming to under 2°C, globally we will need to pull one billion tons of CO_2 from the atmosphere by 2025, 10 billion tons by 2050, and 100 billion tons by the turn of the century (IPCC, 2021). With many countries currently falling short of their Paris Agreement targets, the ability to meet IPCC emissions targets in time to address climate change is dwindling (UNFCCC, 2021). Even if the global community was able to immediately arrest all CO_2 emissions, the current concentration of atmospheric CO_2, peaking at 420 ppm, is still about 140 ppm above pre-Industrial Revolution levels (NOAA, 2021). That means with no further emissions, there are still ∼300 billion tons of CO_2 to remove from the atmosphere (LBNL, 2021). And given there is no way today to completely stop CO_2 emissions, with CO_2 removal needed at scales this immense, a number of CDR solutions will need to be deployed to curb the growing CO_2 threat.

One promising CDR solution which has the potential to be deployed globally is direct air capture (DAC) (Beuttler et al., 2019). DAC is achieved by processing ambient air through a contactor where CO_2 interacts with a solid or liquid sorbent which separates the CO_2 from the air and allows purified air to exit back into the atmosphere. The CO_2 is then desorbed for sequestration or for subsequent utilization by the expanding Carbon-to-Value (C2V) industry, which is focused on replacing petrochemical sources of carbon by transforming CO_2 into useful chemicals, fuels, and other end products. But the growing number of C2V companies are dependent on finding an efficient and low-cost source of CO_2 to feed their processes (IEA, 2019). Sequestration is equally dependent on these efficient, low-cost sources of CO_2, as lower cost DAC systems will accelerate global adoption and deployment of this critical CDR solution.

BUILDING THE NEXT MEGA-INDUSTRY

One DAC-focused company who has garnered attention recently is Climeworks, who has recently commissioned their Orca DAC system in Iceland capable of capturing 4,000 tons of CO_2 each year (Climeworks, 2021). This is an excellent start to addressing this issue, however it brings the global DAC removal capacity to ~11,300 tons of CO_2 per year (Carbon180, 2021). Looking at the Orca system specifically, however, in light of the IPCC removal goals, the world will need to deploy 250,000 of these systems to hit 2025's one billion ton removal goal. To remove the 40 billion tons per year the globe currently emits, 10 million systems need to be deployed. To remove CO_2 back to pre-industrial levels, a stunning 75 million systems will be necessary. For perspective, the entire US auto industry produces 10 million cars each year (US Department of Transportation, 2021). While not all CO_2 will be removed via DAC, the supply chain and financial challenges associated with growing from today's scale to the scale required for even a million systems are enormous. While not an intractable problem, DAC will need to become an industry the size of automobile manufacturers or of oil and gas companies, which took over a century to reach their current scales (Peters, 2021).

The world does not have the luxury to wait a century to allow the DAC industry to reach these scales—we have a decade or two to get there. Most companies in the DAC space are small companies and start-ups—they have neither the reach nor the leverage to build a global supply chain at the scales required. Even with the support of government financing and strategic partnerships, such as the 1PointFive collaboration between Oxy Low Carbon Ventures and Carbon Engineering, constructing entirely new global supply chains to feed DAC at the scales needed will be a long, time consuming, and expensive process (Carbon Engineering, 2020). In addition, there are real concerns around the carbon emissions associated with manufacturing at this scale, concerns around land use for this size and number of systems, and concerns about the amount of energy required to operate this many systems (Leibling et al., 2021). While the learning-by-doing approach inherent in Wright's Law will inevitably reduce cost and improve efficiency, without a step-change in technology, we are limited in improvements by the curve set using today's systems (Wright, 1936).

To this end, leading solid-sorbent DAC technology developers Global Thermostat and Climeworks are adopting a "modular" approach where smaller sized (e.g., 50–4,000 tons per year) sized devices are the repeat unit in a large-scale DAC deployment to leverage gains in manufacturing scale (Carbon180, 2021). However, unless alternative solutions can be found to improve DAC performance and eliminate the need to build and operate tens of millions of systems, we may very well be stuck waiting for the technology to reach scale organically. Fortunately, there is an emerging technology solution which can have a massive impact on reducing the scale of DAC systems—*high capacity, high efficiency sorbents that improve DAC system performance and drive down DAC costs.*

STEP-CHANGE IN SEPARATIONS PERFORMANCE

Separations are ubiquitous in industrial processes, consuming more than 10% of the world's energy (Sholl and Lively, 2016). For example, most of the cost and complexity of a hydrocracking facility is a result of the downstream separations needed to overcome the inefficiencies in catalyst selectivity and conversion. Similarly, today's carbon capture systems are primarily designed to overcome inefficiencies in the CO_2 separation technology at the heart of the process. While both liquid and solid-sorbent based technologies are being developed for DAC, the relatively low mass transfer rates between gas-liquid interfaces in liquid-based systems necessitate the use of contactors with large surface areas. Furthermore, liquid-based DAC systems consume significant quantities of water making deployment in arid or resource-limited areas challenging (Keith et al., 2018; NASEM, 2019). The intrinsic porosity of solid adsorbents can overcome these limitations and should allow solid sorbent systems to outperform liquid-based systems due to inherently superior gas-solid mass transfer characteristics. Therefore, the following discussion will focus on solid sorbent-based technologies for improving DAC performance.

Leading companies in the CDR arena, and specifically within DAC, have taken the important first step of designing first generation processes and integrating sorbent materials into these processes. However, the solid adsorbents used in current DAC systems lack the ability to capture large quantities of CO_2 from ambient air because of their capacity limitations. A recent report by the National Academies of Science, Engineering, and Medicine estimated that the sorbent will account for 80% of all DAC costs (NASEM, 2019). Similarly, the Energy Futures Initiative notes that "[DAC] capital costs are dominated by the sorbent material…Other components are correspondingly less important to address unless and until sorbent material costs can be substantially reduced" (Energy Futures Initiative, 2019). Clearly a significant improvement in sorbent performance is needed to drive down the cost of DAC.

Mosaic Materials is focused on developing metal-organic framework (MOF) solid-sorbents for gas separations. Specifically, Mosaic has been developing amine-appended MOFs which display high capacities under dilute CO_2 conditions like ambient air (McDonald et al., 2012, 2015). Furthermore, owing to the cooperative chemisorption mechanism unique to this sorbent class they demonstrate high selectivity for CO_2 over other components, resulting in low co-adsorption of other components (McDonald et al., 2012). Pushing sorbent performance has been Mosaic Materials' focus, addressing the cost and scale issues of DAC from the heart of the system, i.e., the sorbent material.

The cost of DAC is driven largely by CO_2 throughput, given the relatively low concentration of CO_2 in the atmosphere. To maximize CO_2 throughput, there are two alternatives—move more air (process improvements) or capture more CO_2 (sorbent improvements). Given the low capacities of current sorbents, going after process improvements first has been the better path, and one which leading companies have pursued to date. Once a process is designed, however, the system will have a stringent operating window. As such, future "drop-in" sorbents will be subject to those operating windows or require a significant process redesign to leverage technology advantages. Now that sorbents with much higher capacities are being commercialized, it is critical to consider material performance, and subsequent process conditions to optimize material performance, in tandem with process design. Optimizing the material-process interface is critical to utilizing both aspects of a separation system to their fullest to reduce the cost of DAC.

To significantly reduce the cost of DAC and break the \$200/ton CO_2 captured price point, below the current combined pricing of \$250 from California's LCFS and Federal 45Q tax credits, sorbent material efficiency must be increased. We believe there are three key approaches to doing so: (1) reduce the cost of manufacturing materials, (2) increase the cyclic stability (reduce degradation) of materials, and (3) increase the capacity of materials. Herein, we assume that at the scales necessary for global CO_2 level reduction that sorbent manufacturing costs will come down to the same relative level regardless of technology provided no exotic or rare-earth components are needed; therefore, it is demonstrative to focus on the amount of CO_2 a sorbent material is projected to capture *over its useful life*. Our preliminary estimates, in conjunction with open literature values suggest that current sorbent technologies capture around 130 kg CO_2 captured/kg sorbent over its useful life (Deutz and Bardow, 2021). The NASEM report estimates, in their moderate cases, anywhere between 220 and 580 kg CO_2 captured/kg sorbent material in its useable lifetime (NASEM, 2019).

Our internal analyses and models for DAC costs indicate that of the three approaches to reducing DAC costs, the most effective strategy for drastically reducing these costs is increasing adsorbent capacity. Doubling adsorbent capacity is equivalent to halving materials manufacturing costs or doubling material lifetime, and has the additional benefits of also lowering the capital expenditures (CapEx) and operating expenditures (OpEx) of a DAC system. Mosaic has demonstrated the performance of materials at and above the "best case" NASEM scenario of 1.5 mol/kg, combined with deeper capture fractions as shown in **Figure 1** where a dynamic gas test demonstrates a working capacity of 2.7 mol/kg (NASEM, 2019). These two metrics combine to enable significant cost savings of DAC. Mosaic's near-term goal is development of a high capacity, high efficiency sorbent material that can enable 300 kg CO_2 captured/kg sorbent over its life, with long-term goals of >1,000 kg CO_2 captured/kg sorbent. However, rather than focus on specific material performance, the following discussion highlights the cascading effects a high-capacity, high-performance sorbent can yield for DAC separations.

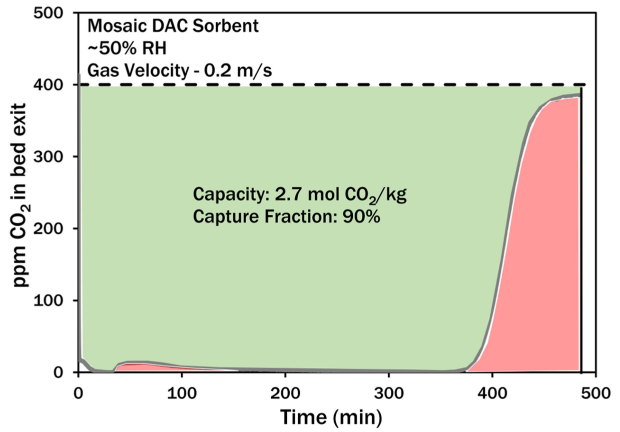

FIGURE 1 | Performance of Mosaic's DAC solid sorbent under ~400 ppm CO_2 in air, ~25°C and 40–50% RH. Shaded areas are included to guide the eye, with green corresponding to CO_2 that is retained by the material and red corresponding to CO_2 that "slips" through the bed uncaptured.

The impact of capture fraction, the percentage of CO_2 entering the system which is captured by the sorbent, has a fairly straightforward impact on CapEx and OpEx. As the system capture fraction rises, less air is required to be moved in order to capture a given amount of CO_2. Since the concentration of CO_2 in air is so low, small changes in capture fraction translate into large differences in air handling required to capture a ton of CO_2. As **Figure 2** shows, increasing the capture fraction from 60 to 80% reduces air handling requirements by ~500,000 m^3/ton CO_2. This means that fans can be sized smaller, lowering CapEx, and will require less energy (lower OpEx) to operate due to their smaller size. For simplicity, using the $6/10^{ths}$ power law engineering rule of thumb, this would lead to a CAPEX reduction of ~25%. Furthermore, reducing the air flow will result in a reduction in pressure drop across the contactor further lowering OpEx. Or for a given system design, a higher capture fraction results in a higher throughput of CO_2, again resulting in a lower capture cost per ton CO_2.

Higher capacity has more extensive effects on CapEx and OpEx than capture efficiency. If the sorbent can hold more CO_2 per kg of sorbent then less material is needed for a given amount of CO_2. Taking a 50% increase in sorbent capacity, again invoking the $6/10^{ths}$ rule for simplicity, results in a 35% reduction in CapEx. This has cascading benefits as fewer contactors are needed, reducing system size and thus capital required, as well as reducing regeneration energy requirements as less material will need to be heated/cooled during each adsorption/desorption cycle of the sorbent and less heat will be lost through the parasitic heat loads of sorbent and contactor sensible heating. Beyond

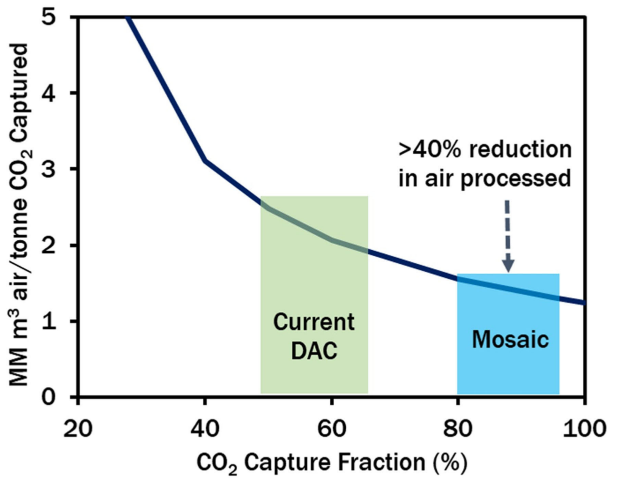

FIGURE 2 | Representation of the air required (in millions of m^3) to capture 1 tonne of CO_2 as a function of capture fraction in a DAC process. Current technologies operate under low capture fraction regimes, whereas Mosaic's efficient sorbent technology can reduce required air handling >40% depending upon ultimate performance under process conditions.

these CapEx and OpEx savings, higher capacities can also extend the useful life of the sorbent material because the sorbent will be cycled less often. Just as if you drive your car fewer miles per year, your tires last longer, if you cycle your sorbent less often, the sorbent will last longer, which lowers periodic sorbent bed replacement costs.

These cascading effects of higher capacity and capture fraction on driving down CapEx and OpEx have dramatic impacts on the global DAC deployment. Looking solely at the number of DAC systems, doubling sorbent capacity drops the number of systems required by 50%. Reexamining our earlier example, the number of systems needed to address current annual emissions drops from 10 million to 5 million. And Mosaic has demonstrated capacities in lab environments which can achieve three times the NASEM moderate case capacity, which would mean the number of systems can be halved again, down to 2.5M, or 75% below current projections. The savings in capital expenditures, energy requirements, and land resource requirements are substantial at these levels of system reductions. In addition to being much more feasible to achieve, the increased CO_2 captured per system also drops the cost of capture, enabling broader adoption of DAC as costs drop below the level of some existing government incentives, such as California's Low Carbon Fuel Standard, and global carbon credit markets, allowing businesses to do what is right for both their profitability and improve the ongoing health of the planet.

WHAT IS NEEDED?

There are three major areas which, with additional focus and support, can make the largest impact on the nascent CDR economy. These areas, broadly speaking, are enabling supply, increasing demand, and coordination across the CDR landscape.

Tackling the first area, enabling supply, is critical to ensuring companies can focus on developing and deploying the core technologies and solutions needed to enable CDR. The work on enabling supply must first be focused on infrastructure. In the case of DAC, if an industry the size of the auto industry is needed, where are the building materials for systems going to come from? Where will the chemicals needed for adsorbents come from? Do we have the labor and skills necessary to build, install, and operate these systems? Once captured, where is the infrastructure for transporting and storing CO_2? These questions point to a more centralized and broadly available infrastructure solution set, which is a role where government can best be leveraged, such as in the recently enacted Bipartisan Infrastructure Deal (Calma, 2021). While government can help financially with subsidies and investments in new technologies to ensure a meaningful number of technologies are developed, a more substantial impact can be achieved through establishing infrastructure so that each technology solution has a standardized set of downstream assumptions to work with, thus ensuring companies can focus on their core challenge of building, scaling, and deploying their CDR solution rather than spending resources on plugging into the broader infrastructure.

Although having governments subsidize CDR is initially a necessary and helpful activity, long-term businesses must be built to exist outside of government assistance. To increase demand for CDR solutions, companies and organizations stepping forward to continue purchasing carbon from verified projects will create the true market needed to allow CDR to grow. The continued support of corporate leaders in this space, such as exemplified in recent announcements by Swiss Re, Shopify, and Microsoft, is necessary in establishing this demand (Clancy, 2021). This idea can even be expanded for small- and mid-size companies through creating a type of group purchasing organization for these smaller, eco-conscious companies to buy into early-stage carbon removal projects. Broadening the accessibility and momentum of these early agreements will broaden and democratize CDR solutions. The corporate leaders buying small amounts of carbon now at high prices accelerates development and lowers future capture costs such that when the bulk of organizations are implementing internal carbon taxes and buying carbon offsets, then CDR solutions are available at prices which make investment in CDR solutions an easy decision for every organization.

Finally, given the enormity of addressing the billions of tons needed by CDR solutions, multiple approaches will be necessary. It is highly unlikely there will be one "silver bullet" approach that can be scaled quickly enough. As such, we should construct systems and awards to foster the success of multiple approaches. As multiple companies come forth with CDR solutions, an overarching cooperative approach and framework is needed to ensure companies are learning from each other and deploying successful solutions as quickly as possible. By leveraging the collective knowledge, identifying opportunities which can greatly benefit from one CDR solution over another, and collaborative supervision to ensure consistent metrics across CDR solutions, the CDR industry can expand faster than any one company could alone.

CONCLUSION

The growing climate challenge posed by carbon dioxide emissions will require several CDR solutions to reach massive scales to remove CO_2 from the atmosphere. One of these CDR solutions, direct air capture, will need tens of millions of systems to address the billions of tons of CO_2 already in the atmosphere—roughly equivalent with building an industry the size of the automotive industry in the next decade. While first generation systems are needed now to kickstart the process, focusing on sorbent material development, specifically on increasing sorbent capacity and capture efficiency, enables cascading process improvements that can cut the number of systems—and associated materials, land, and energy—needed by an order of magnitude. This will enable faster rollout and more efficient use of capital and resources in addressing carbon emissions. The major challenges around establishing supply chains at the scales needed and continuing to grow demand, especially in the early stages of CDR, will require massive levels of coordination. Collaboration within and between governments, corporations, and the industry itself will be required to ensure that new developments, like this and so many other new technologies, can be deployed in time to mitigate the growing climate challenge. Scientists have been highlighting the impacts and scale of carbon emissions and climate change for some time now, and there is finally widespread momentum within, and between, scientific, public and private sectors that we need to keep accelerating. This challenge is a seminal moment for our generation—the time to work together on it is now.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Both authors have contributed equally to the work and approved it for publication.

ACKNOWLEDGMENTS

The authors would like to thank the editors of this journal for the invitation to submit an article to the Negative Emission Technology section of Frontiers in Climate, and additionally thank Stripe for funding the open-access fees on this critical research topic. We would also like to thank the reviewers of this article.

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Author Disclaimer: Opinions and calculations presented within this article are the views and work of JCH and GBW.

Conflict of Interest: The authors are employees of Mosaic Materials, Inc.

frontiers in Climate

PERSPECTIVE
published: 10 February 2022
doi: 10.3389/fclim.2022.686762

The Role of Corporates in Governing Carbon Dioxide Removal: Outlining a Research Agenda

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With 1,500 companies now estimated to have set net zero targets, corporate engagement with carbon dioxide removal (CDR) has gained substantial momentum. Yet despite the corporate sector becoming a key domain of CDR decision-making, corporates have not received research attention as influential actors in the governance of CDR. This paper provides a perspective on how corporates influence and enact de facto governance of CDR. We collate a preliminary evidence base regarding possible modes of CDR governance by corporates. Focusing on voluntary corporate engagement with CDR, we examine how and why firm-level decision-making takes place, and interrogate the implications of such activity. We find that the current literature focuses on techno-economic attributes of CDR solutions as drivers of corporate engagement; however, the ability for corporates to formulate a (business) case for engaging with CDR is potentially shaped by a broader array of financial and non-financial factors that are currently overlooked. This gives corporates the influence to define what and how to govern, an inherently "political act." We finally highlight possible lenses for future research, noting lessons to be drawn from climate justice, anticipatory governance, responsible innovation, and futures literatures. These could provide a deepened understanding of the dynamics and implications of current de facto CDR governance, and allow this to be challenged where appropriate. Ultimately, without awareness and oversight of how CDR is being governed in the real world, policy and governance research may not be successful in driving us toward desired net zero futures.

Keywords: anticipatory governance, carbon dioxide removal, corporate climate practices, greenhouse gas removal, negative emission technologies, responsible research and innovation, climate governance

OPEN ACCESS

Edited by:
Phil Renforth,
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Reviewed by:
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Specialty section:
This article was submitted to Negative Emission Technologies, a section of the journal Frontiers in Climate

Received: *27 March 2021*
Accepted: *17 January 2022*
Published: *10 February 2022*

Citation:
Battersby F, Heap RJ, Gray AC, Workman M and Strivens F (2022) The Role of Corporates in Governing Carbon Dioxide Removal: Outlining a Research Agenda. Front. Clim. 4:686762. doi: 10.3389/fclim.2022.686762

INTRODUCTION

Recent years have seen the adoption of "net zero" targets across the private sector, and in turn, the emergence of carbon dioxide removal (CDR) as a key tenet of many climate action strategies, complementing conventional mitigation. With 1,500 companies estimated to have set targets (Black et al., 2021), net zero has given relevance and momentum to CDR in the corporate sector.

Removals will require care if they are to be deployed as a climate solution—both to manage associated risks and capture benefits (Dooley and Kartha, 2017; Fuss et al., 2018; McLaren et al., 2019; Honegger et al., 2021a). This has given rise to a substantial literature examining CDR "governance." Governance will be integral to whether, when, how, where, and what CDR gets deployed, which will have implications for the climate, natural environment, economy, and civil society.

As a key domain of CDR activity, the corporate sector requires examination as both a subject and object of governance. Yet at present, there is limited exploration in the CDR governance literature of how corporate involvement in CDR decision-making will shape outcomes. This governance research gap is made more concerning by gaps in real-world governance: despite playing an integral role in the delivery of 1.5°C, corporate climate action is currently not subject to systematic oversight (Honegger et al., 2021b), in the same way as nations under the Paris Agreement.

This paper will therefore explore the current and possible future role of corporates in governing CDR. Through a rapid review of peer-reviewed literature, summarized in **Table 1**, we collate a preliminary evidence base regarding possible modes of CDR governance by corporates. We set these in the context of the wider CDR governance literature to interrogate the issues and potential implications of such activity. We finally highlight emergent lenses for thinking about this into the future, and how these might be applied to the overlooked question of corporates.

CDR GOVERNANCE RESEARCH TO DATE

Framings of CDR Governance

CDR is described as requiring "responsible" governance (Bellamy, 2018), to ensure it is researched, developed, and deployed in a manner that maximizes beneficial and minimizes adverse outcomes. These encompass local-level impacts, for example on biodiversity and community wellbeing (Buck, 2016; Dooley and Kartha, 2017; Fuss et al., 2018), as well as system-level ones, like mitigation deterrence (McLaren, 2020), the transgression of planetary boundaries (Honegger et al., 2021a), and justice issues, for example international and intergenerational (Buck, 2018; Carton et al., 2021).

CDR governance has thus become the subject of much research, and takes on two broad frames in the literature. Firstly, governance is discussed as a means of structuring CDR activities to ensure they develop responsibly into the future. This body of literature spans from principle-based recommendations for CDR research (Rayner et al., 2013; Bellamy, 2018), to detailed examinations of policy options (Haszeldine et al., 2018; Honegger and Reiner, 2018). There is an extensive literature around this "preferred" governance, as we shall term it here (Lomax et al., 2015; Bellamy, 2016; McLaren et al., 2019).

Governance is also discussed as an "observed" system. Observed governance is examined in works like Geden et al. (2018), Cox and Edwards (2019), Boettcher (2020), Carton et al. (2020), and O'Beirne et al. (2020), in which historical and emergent interactions between incumbent governance architectures and CDR are considered. Going a step further, Gupta and Möller (2019) have described "de facto governance," as perhaps a subset of observed governance, whereby "sources of governance. . . are unacknowledged and unrecognized as seeking to govern, even as they exercise governance effects."

CDR is often seen as a "largely ungoverned space" (Gupta and Möller, 2019). Yet de facto governance may be critical to shaping outcomes, and thus demands research attention. It is worth observing how CDR governance is constructed through the activities of "real world" actors, and examining whether this deviates from "preferred" systems.

Corporates as Governance Actors in CDR

The current CDR discourse is highly techno-centric. However, there is a growing voice calling for narratives to be based around socio-technical constructs (Bellamy, 2016; Sovacool, 2021), acknowledging that technical elements of CDR cannot be considered independent of their social context—"the production, distribution and use of technology" (Geels, 2004). It is through this frame that the role of corporates becomes relevant. Corporate organizations are defined herein as large, for-profit companies, typically with a multinational presence, whose primary activity is not historically related to CDR.

The corporate sector faces pressure in the changing regulatory and market environment to reduce its contribution to climate change (FSB-TCFD, 2017). In this context, there is an increasingly clear argument for corporates to concern themselves with both the realization of CDR solutions and the mainstreaming of their use. Indeed, as the need for CDR is clarified at a societal level, corporate engagement may take on an anticipatory dimension—companies may "want to become active and front-run potentially emerging policies" (Honegger et al., 2021b). Corporates are thus inherent to CDR's "socio-technical system."

Recent years have seen corporates become investors in and buyers of removals (Muttitt, 2021), and embed themselves in decision-making about solution development and deployment. In doing so, they become central to the construction and dissemination of knowledge of CDR. Notably, a recent Comment piece published in Nature by the team behind Microsoft's CDR strategy outlines the governance developments needed to unlock further corporate action by corporates (Joppa et al., 2021). A CDR sector may already be emerging in this way from the "bottom up" (Bellamy and Geden, 2019).

Yet corporate interest in CDR is not purely a climate play. While climate and sustainability objectives have increasing weight in corporate decision-making, these sit within the broader

TABLE 1 | Search details for rapid literature review.

Databases searched	Carbon dioxide removal terms	AND corporates terms	Other search details
Web of Science—All Databases, article reference lists	"Carbon dioxide removal" OR "carbon removal" OR "greenhouse gas removal" OR "negative emission"	Corporate OR company OR companies OR private OR "private sector" OR business OR industry	2010–present

fiduciary duty of corporates directors to ensure a company's success. It is therefore worth examining how the distinct agendas of corporate governance and CDR governance interact.

OBSERVING HOW CORPORATES INFLUENCE AND ENACT CDR GOVERNANCE

The "observed" role of corporates in shaping CDR governance has been examined to a limited degree in research settings. This section offers a brief overview of this literature, to generate perspectives on the governing role of corporates in the current landscape.

Firm-Level Decision-Making

Platt et al. (2018) assert that "in many developed nations, the main drivers of decarbonisation are taking place in liberalized markets—comprising private firms making decisions about how to compete in open markets." If this is true, greater attention ought to be paid to how CDR decisions are informed at the firm level. Given that much CDR engagement by corporates today is voluntary (Honegger et al., 2021b), trends in firm preferences around, for example, solution options, financing approaches, and implementation strategies, exert a powerful structuring force on the CDR market. Research into firm-level decision-making can thus begin to anticipate these trends.

Platt et al. (2018) examine firm-level decision-making by assessing revenue-generating and cost-avoiding opportunities in CDR, evaluating the extent to which these might induce corporates to engage with CDR value chains. This techno-economic framing is echoed across the literature (Lomax et al., 2015; Nemet, 2018; Cox and Edwards, 2019; Izikowitz, 2021). Of course, in the absence of a regulatory requirement for corporate CDR, a clear business case is typically needed to stimulate engagement. However, other social drivers are relevant and contribute to such a "case"—such as a "sense of responsibility [for historical carbon]... and consumer and shareholder preferences" (Rodriguez et al., 2021), regulatory expectations, reputational interests, risk avoidance, and corporate purpose (South Pole, 2021). The "case" for CDR may not involve immediate, if any, financial return.

Limited work has been done to anticipate how firm-level decisions might translate to CDR outcomes. Buck (2018) considers how vested corporate interests in specific solutions—such as fossil fuel companies' interest in direct air capture for enhanced oil recovery—will influence the scale at which solutions are realized. This will have physical implications (for example for local communities, or regional resource use), but also political ones, allowing corporates to shape "commercialization strategies" and thus construct the paradigm under which CDR is used (in this case favoring carbon utilization over storage and removal).

Corporates may even define the very object to be governed. Corporate claims and strategies make a discursive contribution to governance, particularly by shaping what is and is not CDR. The inherently "political act" of categorization (Gupta and Möller, 2019) may reverberate through the modes, rationales, and influential "speakers," that all contribute to a resultant governance system (Boettcher, 2020; Boettcher and Kim, 2021).

Decision-Making in the Context of Policy

There is also merit in observing how corporates interact with policy, to produce new, or reinforce old, forms of governance. Honegger et al. (2021b) examine how corporate initiatives can complement policy mixes to address "CDR-specific policy design needs," considering some of today's major corporate initiatives by Microsoft, Shopify, Stripe, and Swiss Re. Key insights include the below.

1. Corporates could be instrumental in down-costing CDR. This (albeit small) sample of large corporates have demonstrated surprising willingness to pay high upfront costs for solutions, particularly those with higher levels of permanence.
2. Corporate CDR purchases are not systematically overseen, which could lead to issues like double counting. A comprehensive insurance framework for non-permanence is not yet in place, despite many traded credits involving biospheric storage.
3. Corporate purchases of CDR credits may not align with the Paris Agreement, if these risks are not managed.

Honegger et al. (2021b) also highlight diverging rationales for engagement, comparing corporates pursuing an early-mover approach by commercializing new technologies at significant cost, with those pursuing a "quick-fix corporate social responsibility" route by purchasing low-cost credits that may lack integrity. These differing rationales, and corresponding modes of engagement, highlight a potential need for policy intervention to address this divergence. Joppa et al. (2021) detail the need for (1) standardization of net zero, (2) robust measurement and accounting protocols, and (3) incentives that reward higher-integrity approaches, to address these "bugs" in the current voluntary system.

Schenuit et al. (2021) assess CDR policymaking in nine OECD countries, finding a correlation between the level of private sector engagement and the state of CDR development. Though the authors do not directly comment on the relationship between corporate activity and governance, they provide a useful framework to track governance development. Highlighting five key dimensions of CDR policy, each sitting on a continuum of possible manifestation, the authors use combinations of these possibilities to describe three possible policymaking "types," outlined in **Table 2**. These continua could be used to assess corporate policy preferences, and track how these are reflected in the emergent CDR governance paradigm.

Possible Analogs for Corporate Climate Engagement—Why CDR Is Distinct

Governance analogs can be found with CCS, forestry, bioenergy, and other renewables literatures (Carton et al., 2020). Yet while these works illuminate some key influences on corporate behavior, CDR solutions have distinct attributes that will shape corporate engagement. Primarily, the business case for removals is more complex: there are few markets in which the act of removal itself is rewarded (Cox and Edwards, 2019;

TABLE 2 | Empirically identified dimensions of CDR policymaking and continua of how these dimensions manifest, adapted from Schenuit et al. (2021).

Dimensions	Continua	I. Incremental modification	II. Early integration and fungibility	III. Proactive CDR entrepreneurship
CDR in mitigation targets	Fungible—Strictly separated	Strictly separated	Fungible	Fungible
View of CDR among actors of the incumbent regime	Proactive integration—Restrained integration	Restrained integration	Proactive integration	Proactive integration
CDR methods addressed	Only ecosystem-based—Wide range of methods	Ecosystem-based only	Focus on ecosystem-based	Proactive technology support
Relation of CDR policy instruments to broader climate policy mix	Incremental opening—Full integration	Incremental opening	Full integration	Specific instruments
Government support for developing CDR niches	Limited support—Nurturing and empowering	Limited support	Limited support	Nurturing and empowering

The three final columns describe different policymaking "types" that could arise from different manifestations.

Schenuit et al., 2021), and the per-ton cost varies significantly across solutions. Moreover, cost-minimization and commercial opportunity are likely not the only factors driving corporate action on CDR (Honegger et al., 2021b)—as per section Firm-Level Decision-Making.

Several parallels between traditional carbon markets, on which there is an extensive literature, and nascent removals markets are instructive here. Firstly, the "integrity" of traded credits has been hotly debated, encompassing questions about additionality (Michaelowa et al., 2019), measurement (Schwartzman et al., 2021), and social and environmental safeguarding of projects (Carton et al., 2020)—these issues will continue to be relevant for CDR (Carbon Direct Microsoft, 2021). Secondly, questions around the legitimate use of credits are increasingly raised by commentators—namely, how abatement challenges relate to offset need (Allen et al., 2020; Science Based Targets Initiative (SBTi), 2021). This experience has elevated corporate awareness of credit integrity issues, and the desire to avoid reputational damage stemming from "greenwashing" allegations may become more important in future decision-making. This potentially underpins corporate willingness to overpay for removals perceived as less risky (Honegger et al., 2021b).

Importantly, though, corporate CDR engagement is not bounded by the market—in fact, the market opportunity is currently limited, with CDR credits in poor supply (Zelikova, 2020). Corporates can alternatively engage through research (both technical and non-technical), knowledge sharing, even advocacy (Carbon Direct Microsoft, 2021; Joppa et al., 2021). De facto governance research should be alert to these possibilities. Understanding how corporates respond to financial and non-financial drivers, within and beyond the market, will be important for understanding how and why corporates govern CDR.

WHAT ROLE FOR CORPORATES IN FUTURE CDR GOVERNANCE?

Good Governance

Has any research been done to examine how corporates could and *should* behave with regard to, and indeed govern, CDR? Much of the "preferred governance" literature suggests that corporates should continue to play a role in future CDR decision-making, namely by investing in the development of, and guaranteeing demand for, solutions (Lomax et al., 2015; Haszeldine et al., 2018; Platt et al., 2018). Indeed, corporates are well-positioned to accelerate the urgently needed scale-up of CDR solutions, particularly where the right policy support is in place (Joppa et al., 2021). However, this techno-economic framing of governance overlooks the socio-political influence afforded to corporates in such systems, highlighted by Buck (2018) (see section Firm-Level Decision-Making). This challenges the notion that the role of corporates in CDR governance is simply to mobilize finance to solutions, with policy having overarching control. Being more deliberate about what, why, and how to incentivise corporates will be important for managing these socio-political influences toward a preferred outcome (Bellamy, 2018).

Some works have sought to define "good" corporate CDR behavior in the context of net zero. Smith (2020) and Rogelj et al. (2021) provide principle-based frameworks for emitters. These focus on transparency—recommending that corporates disclose the extent of removal relative to abatement, and the type of solutions and storage used. The recent SBTi Corporate Net-Zero Standard (Science Based Targets Initiative (SBTi), 2021) provides more formal criteria, for example regarding CDR quantity (requiring that companies remove and permanently store any emissions "that remain once companies have achieved their long-term science-based target"), and promotes "beyond value chain mitigation" activities like "investing in direct air capture (DAC) and geologic storage." Nonetheless, the techno-economic framing persists—the Standard governs corporate investment and purchasing decisions, without recognizing their wider normative influence. With net zero ill-defined (Joppa et al., 2021), the current governance of corporate CDR activity itself remains a "wild west."

Lenses for Examining Corporate CDR Governance in Future Research

How, then, might a research agenda around corporate CDR governance might be shaped? This section provides some suggestions for advancing the observed and preferred governance literature to better account for the role of corporates.

Framings of justice are increasingly adopted in climate and CDR dialogues, and could be helpful for thinking about the role of corporates in "preferred" CDR governance. Works like Fyson et al. (2020), Morrow et al. (2020), Pozo et al. (2020), Batres et al. (2021), and Carton et al. (2021) highlight where injustices might arise—considering for example geographical, temporal, and sectoral distributions of CDR activity—and provide principles for just CDR policymaking, such as the use of mitigation hierarchies, mixed solution portfolios, and criteria to evaluate the local and systemic impacts of projects. These insights could inform "best practice" approaches at the firm or standard-setting level, by expanding understandings of CDR's far-reaching justice implications and seeking to proactively manage them [this type of thinking is evident in Lenzi et al. (2021)].

Before we examine how corporates *should* govern CDR, we must better understand the nature and implications of their de facto role. This paper has provided a preliminary view of where issues might arise, but a more systemic approach to evaluating current governance dynamics and predicting future developments, using knowledge available today, is needed. This thinking is embodied in literatures around anticipatory governance and responsible innovation, which are increasingly being applied to climate solutions (Vervoort and Gupta, 2018; Low and Buck, 2020; Muiderman et al., 2020). These frameworks provide an opportunity to reflect on the development of new techno-scientific fields, and through the introduction of new narratives and framings, challenge and reshape trajectories of development in line with preferred futures (Low and Buck, 2020). Thinking about net zero not as a singular outcome, but in terms of different possible futures, which corporates will be instrumental in shaping through their actions on both abatement and CDR, might provide some clarity on the interventions required to make desired outcomes possible.

The de facto governing role of corporates ought to be better reflected in the literature. When observing governance, metrics are needed to assess the nature and implications of corporate CDR activity. Researchers and policymakers also need to engage directly with corporates to understand their motivations and internal decision-making structures, to better anticipate corporate preferences, and how these might shape the future CDR landscape. On preferred governance, commentators should seek to evaluate governance holistically, rather than atomistically—considering different possible governance paradigms, how different actors might take decisions within these, and whether these outcomes would be acceptable to society. Discourses around climate and CDR justice may provide helpful tenets for thinking about the implications of corporate CDR activity, strengthening preferred governance work by bolstering rationales of *why* to govern. Both bodies of literature could be advanced through the adoption of theoretical lenses such as anticipatory governance and responsible innovation. These would allow commentators to examine corporate CDR governance as it emerges, anticipate future outcomes, and potentially become part of governance itself by challenging dominant constructs and introducing new narratives better aligned with desired futures.

This paper has provided a brief perspective on potential de facto CDR governance by corporates, finding that corporates' potential to influence and enact governance has been viewed too narrowly to date, risking inadequate "political oversight" of how CDR is developing (Gupta and Möller, 2019) and necessitating greater research attention and new approaches. Being alert to the role of corporate decision-making is critical to ensuring the extensive body of research into how CDR should be governed is not made redundant by powerful de facto influences.

CONCLUSION

Though technical and economic decisions are the focal point of the corporate CDR discussion, corporates have an unrecognized socio-political influence: both in terms of how and why they make seemingly techo-economic decisions (the CDR strategies they adopt will shape both the physical and political landscape), but also in how they engage with CDR outside these boundaries, for example in how they construct and disseminate CDR knowledge. Corporates are already governing CDR in this way from the bottom up.

AUTHOR CONTRIBUTIONS

FB, RH, AG, and MW contributed to the conception and design of the study. FB and FS led the drafting of the paper. All authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

Funding for this research was provided to Foresight Transitions by the European Climate Foundation, Grant Number DG-2005-60546.

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Conflict of Interest: FB, RH, AG, MW, and FS were under contract to the company Foresight Transitions Ltd., at the time this research was undertaken. The European Climate Foundation helped to guide the research questions and objectives, but had no influence over the outcomes.

frontiers | Frontiers in Climate

ORIGINAL RESEARCH
published: 02 May 2022
doi: 10.3389/fclim.2022.758628

Framework for Assessing the Feasibility of Carbon Dioxide Removal Options Within the National Context of Germany

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OPEN ACCESS

Edited by:
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Specialty section:
*This article was submitted to
Negative Emission Technologies,
a section of the journal
Frontiers in Climate*

Received: *14 August 2021*
Accepted: *07 February 2022*
Published: *02 May 2022*

Citation:
*Förster J, Beck S, Borchers M,
Gawel E, Korte K, Markus T,
Mengis N, Oschlies A, Schaller R,
Stevenson A, Thoni T and Thrän D
(2022) Framework for Assessing the
Feasibility of Carbon Dioxide Removal
Options Within the National Context of
Germany. Front. Clim. 4:758628.
doi: 10.3389/fclim.2022.758628*

Removal of carbon dioxide from the atmosphere will be required over the next decades to achieve the Paris Agreement goal of limiting global warming to well below 2°C aiming at not exceeding 1.5°C. Technological and ecosystem-based options are considered for generating negative emissions through carbon dioxide removal (CDR) and several nations have already included these in their Long-Term Low Greenhouse Gas Emission Development Strategies. However, strategies for development, implementation, and upscaling of CDR options often remain vague. Considering the scale at which CDR deployment is envisioned in emission pathways for limiting global warming to 1.5°C, significant environmental, social, and institutional implications are to be expected and need to be included in national feasibility assessments of CDR options. Following a multi-disciplinary and comprehensive approach, we created a framework that considers the environmental, technological, economic, social, institutional, and systemic implications of upscaling CDR options. We propose the framework as a tool to help guide decision-relevant feasibility assessments of CDR options, as well as identify challenges and opportunities within the national context. As such, the framework can serve as a means to inform and support decision makers and stakeholders in the iterative science-policy process of determining the role of CDR options in national strategies of achieving net-zero carbon emissions.

Keywords: carbon dioxide removal (CDR), net-zero, climate change mitigation action, feasibility assessment, integrated assessment (IA) frameworks, national climate strategies

INTRODUCTION

All pathways for achieving the Paris Agreement (UNFCCC, 2015) goal of limiting the increase in global temperature to "well below 2°C" with aspirations to not exceed global warming by 1.5°C require carbon dioxide removal (CDR) from the atmosphere (IPCC, 2018). Accordingly, the Long-Term Low Greenhouse Gas Emission Development Strategies (LT-LEDS) proposed by national governments include CDR options (Thoni et al., 2020; Buylova et al., 2021). Hence, determining the feasibility of deployment of the envisioned CDR options within their respective national context is critical. Most LT-LEDS focus on strengthening natural carbon sinks including established strategies for tackling climate change such as afforestation/reforestation, wetland restoration and conservation, and options for the enhancement of soil carbon (Thoni et al., 2020). Few countries and the EU also propose the deployment of bioenergy with carbon capture and storage (BECCS) and direct air capture with carbon capture and storage (DACCS) (Schenuit et al., 2021).

CDR options differ considerably in terms of their technological maturity, carbon removal potentials, costs, co-benefits, risks, and trade-offs (IPCC, 2018; Minx et al., 2018; Schenuit et al., 2021). For example, afforestation/reforestation is not new, and thus it has a high readiness level. However, on the ground experience is mainly related to generating and accounting for mitigation benefits but not for negative emissions specifically and not at scale (Carton et al., 2020; Waller et al., 2020). The same goes for international and national climate policy, where enhancement of natural sinks has been discussed since the inception of the UNFCCC and widely included in national strategies, but the idea of generating net-negative emissions has only recently begun to appear in national strategies (Carton et al., 2020; Thoni et al., 2020). Other CDR options include technical approaches for capturing carbon dioxide (CO_2) directly from the atmosphere, which are in different development stages and in some cases tested in pilot phase (e.g., Dittmeyer et al., 2019). Each of the considered CDR options require resources, for example, ecosystem-based CDR options require land and water (Heck et al., 2016, 2018; Brack and King, 2021) and technical options require the supply of renewable energy (Dittmeyer et al., 2019; Beerling et al., 2020).

CDR assessments have addressed critical technological, economic and environmental aspects related to CDR implementation (e.g., Fuss et al., 2018; Dooley et al., 2020). Also approaches for assessing the effectiveness, efficiency, scale, risk, and synergies of CDR options have been proposed and require to be tailored to the specific context (Fridahl et al., 2020). Hence it is pivotal to get a better understanding of the implications and feasibility of a large-scale deployment of diverse CDR options within the national context and as part of long-term strategies for achieving net-zero carbon emissions (Thoni et al., 2020; Schenuit et al., 2021). Significant challenges for the feasibility of CDR options are to be expected in particular if CDR were to be deployed at a scale required for achieving international climate targets (IPCC, 2018). Among others, the deployment and upscaling of CDR options can create a competition for resources such as land, water, and renewable energy, posing trade-offs with a variety of societal goals related to sustainable development (e.g., food security, biodiversity conservation, and renewable energy supply) (e.g., Dooley et al., 2018; Dittmeyer et al., 2019; Brack and King, 2021). While the scientific literature addresses selected questions about environmental, technological and economic feasibility of CDR options (e.g., Nemet et al., 2018; Fajardy et al., 2019; Dooley et al., 2020), aspects related to societal and institutional feasibility of the deployment and upscaling of CDR options are underrepresented (Thoni et al., 2020; Schenuit et al., 2021). For example, understanding societal aspects such as public acceptance are critical for the feasibility of deployment of CDR options, their design, and the upscaling of CDR options and related policies (Braun et al., 2018; Cox et al., 2020, 2021). This has also been shown, for example, by the public debates on the controversies related to the deployment of windmills, nuclear energy, energy crop production, and carbon capture and storage (CCS) pilot scale deployments (Lock et al., 2014; Dauber and Miyake, 2016; Jami and Walsh, 2017; Janhunen et al., 2018; Gough and Mander, 2019).

CDR deployment has to happen at multiple levels of governance and eventually has to take place at local scale within the institutional setting of federal states and municipalities involving public and private actors, land and infrastructure (Schenuit et al., 2021). There is the need for comprehensive feasibility assessments that consider the social and institutional realities in the specific context in which CDR options potentially have to operate (Thoni et al., 2020; Schenuit et al., 2021). Honegger et al. (2021b) provides an assessment of possible synergies and trade-offs of CDR deployment with the sustainable development goals (SDGs). There is also the need to translate such assessments to the national and sub-national context (e.g., by focusing on indicators of national relevance). This is in particular important for supporting participatory processes, including public and private stakeholder engagement, in identifying, developing and deploying CDR options, which are required to ensure that stakeholder perspectives are adequately taken into account (cf. Winickoff and Mondou, 2017; Bellamy et al., 2021).

Participatory processes are also considered to be key to ensure public acceptance (Dütschke, 2011; Honegger et al., 2021a), and strategies of co-producing the design and deployment of CDR options important for adequate consideration of sustainable development broadly (Dooley et al., 2018). At an international scale, more comprehensive assessment frameworks for a scientific assessment of CDR options have been proposed (e.g., Dooley et al., 2020; Forster et al., 2020, etc.). However, policies and strategies for CDR remain very broad with significant knowledge gaps when it comes to implementation (Thoni et al., 2020; Schenuit et al., 2021). There is the need to bridge this gap between science and policy and provide tools that can inform participatory science-policy processes.

For example, Germany's national long-term climate strategy lays out possible CDR options, but vaguely discusses the feasibility of these options, and the challenges and opportunities they pose to the nation. The plan also acknowledges that there are industrial and agricultural emissions that are unavoidable (e.g., emissions related to cement and steel production or agricultural activities), which will require the implementation of technological CDR options to compensate for these emissions (BMUB, 2016). There is a heavy emphasis in the plan on ecosystem-based CDR options with a focus on enhancing carbon sinks through sustainable forest management, the use of wood as construction material, as well as the conservation of grassland and peatlands (BMUB, 2016). However, it acknowledges that ecosystems not only serve as carbon sinks but also offer other societal benefits and possible trade-offs are mentioned (e.g., land competition, impacts on biodiversity and ecosystem services). However, it remains unclear how these trade-offs should be addressed.

There is the need for approaches that can help to elicit and synthesize knowledge on CDR options in a transparent, comprehensive, and inclusive manner in order to support participatory and deliberative processes for defining the governance of CDR within the national context (Borth and Nicholson, 2021). Lessons learned from the assessment of bioenergy options in Germany suggest that using indicators tailored to specific decision-making processes can enable co-design in collaboration with key stakeholder groups (e.g., Thrän et al., 2020). Herein we propose a comprehensive framework as a tool to assess the feasibility of deploying CDR options in order to support and inform science-policy processes on CDR deployment within the national and local contexts of Germany. We consider a CDR option to be feasible if key indicators related to implementation are deemed to pose no or few hurdles (see Sections Environmental dimension, Technological dimension, Economic dimension, Social dimension, Institutional dimension, and System utility on key assessment dimensions and Section Traffic light system on the traffic light system for assessing if an indicator is likely to pose a hurdle to implementation). The framework is not intended for the purpose of assessing whether or not different CDR options are desirable mitigation options or for enhancing their acceptance. That being said, desirability and feasibility often overlap. For instance, for a CDR option to be seen as politically and socially acceptable it needs to be deemed desirable and not encounter too much opposition. Hence we use a conditional understanding of feasibility: if hurdles to implementation of key indicators are considered to be low then the CDR option is likely to be more feasible. In our assessment framework, indicators important for feasibility are defined based on recent literature and expert elicitation involving an iterative peer review (see also Singh et al., 2020).

Objectives of the proposed assessment framework for CDR options:

- Provide a comprehensive framework to assess the feasibility of CDR options including challenges and opportunities along six dimensions: environmental, technological, economic, social, institutional, and systemic dimensions;
- Identify co-benefits and trade-offs involved in the implementation of CDR options, as well as interlinkages across the assessment dimensions;
- Provide a flexible tool that will support inclusive, participatory, adaptive and iterative science-policy processes on the design, implementation and upscaling of CDR options in Germany;

MATERIALS AND METHODS

The comprehensive framework presented herein to assess the feasibility of CDR options in Germany is based on recent literature and expert elicitation (Singh et al., 2020) involving experts of the Helmholtz Climate Initiative (https://www.helmholtz-klima.de/en/about-us). The initiative brought together expertise on CDR options including biomass production for bioenergy (BE), BE combined with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), and anthropogenic actions for enhancing natural carbon sinks (nature-based solutions) (**Figure 1**). There is ongoing research on these CDR options and nature-based solutions are already being considered within Germany's long-term climate strategy (BMUB, 2016; Thoni et al., 2020). Besides involving experts on the technical aspects of each CDR option, experts from the social sciences with expertise in laws and regulations, stakeholder participation and science-policy processes were part of this multidisciplinary effort to ensure that the framework would include the most relevant aspects for assessing the feasibility of available CDR options (see **Supplementary Material 1** for more information on the experts involved).

For determining the thematic dimensions relevant for the feasibility assessment of CDR options, the feasibility assessment of mitigation options designed by the IPCC Special Report on Global Warming of 1.5°C (Table 4.10 in de Coninck et al., 2018a) served as a starting point. This was complemented by dimensions identified for assessing the feasibility of bioenergy strategies in Germany (Thrän et al., 2020). Because no CDR option has yet been deployed at a large scale, the construction of the assessment framework was also informed by literature from other fields, such as new technologies and large infrastructure projects (e.g., wind energy, fossil CCS, and nuclear energy) (Lock et al., 2014; L'Orange Seigo et al., 2014; Jami and Walsh, 2017; Winickoff and Mondou, 2017; Janhunen et al., 2018), as well as by expert consultations.

As our assessment framework focuses on Germany, we aimed to include indicators that are relevant at the national level, which might not be applicable and too fine grained for a global assessment. We were therefore drawing on insights from assessments of national Long-Term Low Greenhouse Gas Emission Development Strategies (Thoni et al., 2020), previous CDR assessment studies (Fuss et al., 2018), assessments of economic barriers to the deployment of new technologies (Agora Verkehrswende, 2020a,b) and assessments related to the bioenergy system in Germany (Thrän et al., 2020). Where possible, indicators with relevance to the German national level were selected, for example, German-based environmental impact assessments (UBA, 2020a).

The dimensions of the assessment framework were thus adjusted to include criteria and indicators that address information needs for national-scale decision-making. Criteria and indicators already used within established planning and assessment processes (e.g., regulatory impact assessments) were preferred in order to ensure useful information transfer to decision makers in Germany (Fridahl et al., 2020; Thrän et al., 2020; see also Table 4.10 in de Coninck et al., 2018a).

Following the approach used by Thrän et al. (2020), a traffic light system was introduced for each indicator in order to evaluate whether or not it would likely pose a hurdle to a CDR option. We chose a traffic light system mainly for communication purposes. In general, red refers to an indicator that is likely to pose a large hurdle to implementation, while green poses no hurdle (see also similar approaches used by e.g. Boehm et al.,

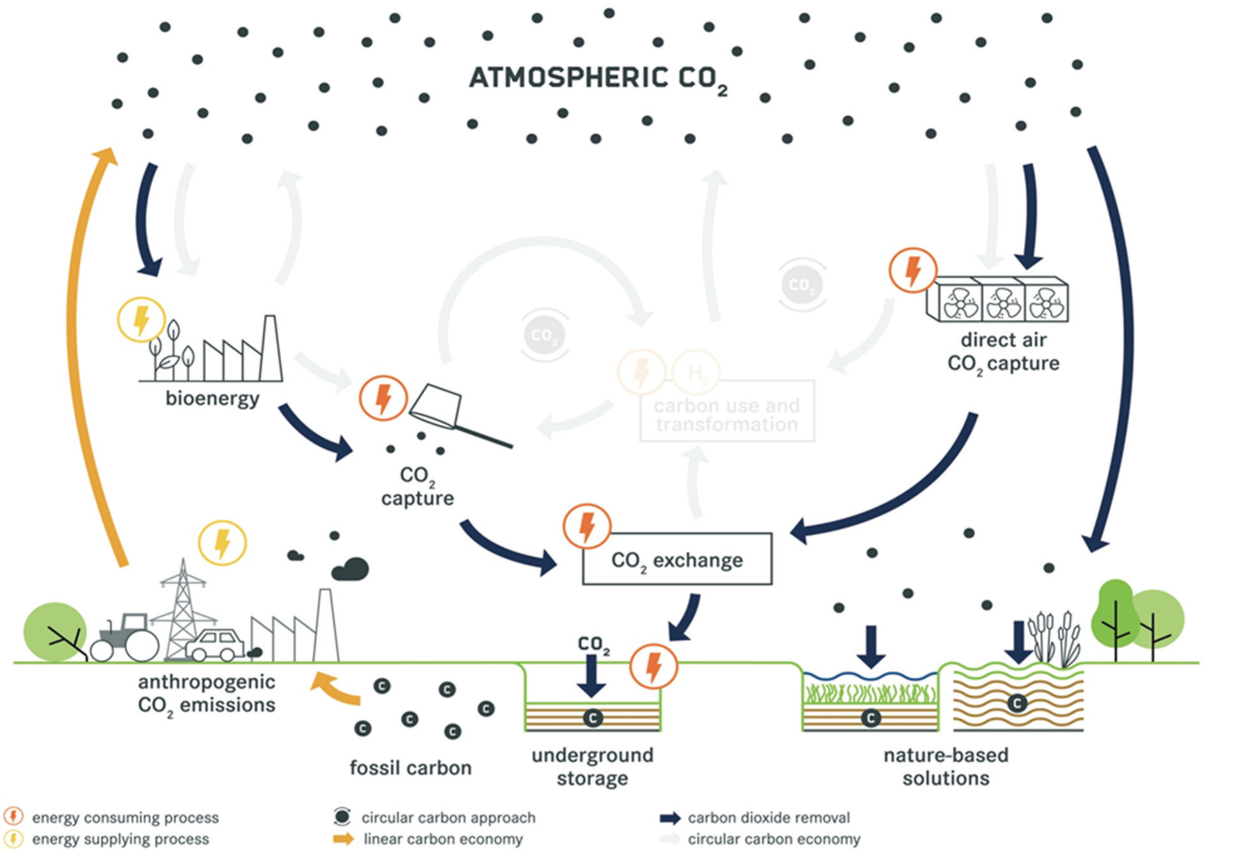

FIGURE 1 | Illustration of the historical burning of fossil carbon (orange arrows), and novel approaches allowing for a more circular carbon economy (light blue arrows, blurred) and carbon dioxide removal (dark blue arrows). Carbon dioxide removal includes point capture at the source of carbon dioxide from bioenergy production, direct air capture and nature-based solutions. Circular carbon approaches have been faded as the framework presented herein focuses on assessing options for carbon dioxide removal (CDR) (source: Helmholtz Climate Initiative // Tanja Hildebrandt, Creative Commons CC-BY NC 4.0 license).

2021 and Climate Action Tracker, 2021). In addition, the color code of the traffic light system of each indicator is complemented with a description of the ranking and thus the system is not only dependent on this red/green color coding.

To ensure the plausibility of the selected dimensions, criteria, indicators and the definition of the traffic light system, we organized an internal review process involving 32 interdisciplinary experts of the Helmholtz Climate Initiative (further information on the review process is provided in the **Supplementary Material 1**). During a workshop the assessment framework, the selection of criteria, indicators and the respective traffic light system were reviewed by groups of experts. These involved experts with knowledge on the technological and biophysical processes involved in the aforementioned CDR options (see **Figure 1**), experts with knowledge on and experiences with stakeholder participation and science-policy processes, and experts on the laws and regulations related to climate policies in Germany. Overall, the review process included experts from a broad range of disciplines including environmental science (including agricultural science, climate modeling, climate physics, ecology, geology, meteorology and physics), social science (including economics, political science, and law), engineering as well as business and management, geography, resource management, infrastructure planning, and sustainability studies.

RESULTS

The developed framework (**Table 1**) includes key dimensions for assessing the feasibility of climate change mitigation options proposed by the IPCC (de Coninck et al., 2018b) (**Figure 2**), complemented with criteria and indicators as described in the section above. The complete framework for assessing the feasibility of CDR options with references for the selected criteria and indicators is included in **Supplementary Material 2**.

The framework aims to support actors and decision makers working at the science-policy interface (e.g., actors from scientific organizations and government agencies) by providing (a) guidance on relevant criteria and indicators to be considered and included when addressing the feasibility of CDR options and (b) a traffic light ranking system for assessing whether or not the topics

TABLE 1 | Overview of criteria and indicators included in the assessment framework, including the traffic light system.

Criteria	Indicator	Likely large hurdle to implementation	Uncertain, likely large hurdle to implementation	Likely medium hurdle	Uncertain, likely no hurdle to implementation	Likely no hurdle to implementation
Environmental dimension		(– – –)	(– –)	(–/+)	(++)	(+ + +)
A1 Impact on air/atmosphere	A1.1 Outdoor air quality (with an impact on human health)	Likely worsens	Uncertain, likely worsens	Likely no impact	Uncertain, likely improves	Likely improves
	A1.2 GHG emissions related to land/sea use change	Likely increases	Uncertain, likely increases	Likely no emissions	Uncertain, likely reduces	Likely reduces
	A1.3 Net biophysical effect on local climate (different scales)	Likely negative	Uncertain, likely negative	Likely no impact	Uncertain, likely positive	Likely positive
	A1.4 Net effects of audible noise on humans and ecosystems					
A2 Impact on land and sea area (from land-use/sea-use changes)	A2.1 Area demand and competition with other area use (land and/or sea)	Likely area demand + land under competition	Likely area demand + not under competition	Likely no area demand	Uncertain, likely reduces demand + reduces competition	Likely reduces demand + reduces competition
	A2.2 Biodiversity (ecosystems, species, genes)	Likely negative	Uncertain, likely negative	Likely no impact	Uncertain, likely positive	Likely positive
	A2.3 Soils (chemical and physical quality)					
A3 Impact on water	A3.1 Ground water quality	Likely negative	Uncertain, likely negative	Likely no impact	Uncertain, likely positive	Likely positive
	A3.2 Water demand / local water availability	Likely high water demand + decreases water availability	Uncertain, likely water demand + no impact on water availability	Likely no water demand	Uncertain, likely reduces water demand + increases availability	Likely reduces water demand + increases availability
	A3.3 Surface water quality	Likely deteriorates	Uncertain, likely deteriorates	Likely no impact	Uncertain, likely improves	Likely improves
	A3.4 Marine water quality					
Technological dimension		(– – –)	(– –)	(–/+)	(++)	(+ + +)
B1 Technology efficiency/Conversion efficiency	B1.1 Net energy demand vs. provision	Likely net energy demand		Likely no energy demand or provision		Likely net energy provision
	B1.2 CO_2 removed per unit of energy produced/required	<0; Technology requires energy per unit CO_2 removed		0; The process of CO_2 removal is energy neutral		>0; Technology produces energy per unit CO_2 removed
B2 Technology availability	B2.1 Technology Readiness Level (TRL)	Concept is theoretically defined, but is not scientifically proven yet (stage of development: theoretical concept/on paper)	Concept is defined, but only some components are scientifically proven (stage of development: tests on laboratory scale)	Most components are scientifically proven, but not yet combined (stage of development: demonstration in deployment environment)	All components are scientifically proven, but not yet combined (stage of development: pilot implemented)	All components are commercially available, value chain technically proven (stage of development: successful deployment, market roll-out)

(Continued)

TABLE 1 | Continued

Criteria	Indicator	Likely large hurdle to implementation	Uncertain, likely large hurdle to implementation	Likely medium hurdle	Uncertain, likely no hurdle to implementation	Likely no hurdle to implementation
B3 Infrastructure	B3.1 Compatibility of infrastructure	Complete infrastructure is not available and would require substantial efforts to be set up	Some components of the infrastructure are not available; they need to be created	Some components of the infrastructure are missing, but existing infrastructure can be expanded; does not require much effort	All components of the infrastructure are available, but integration is not proven yet	All components of the infrastructure are available and integration is proven
B4 Compatibility with the future energy system	B4.1 Effort for CO_2 collection	Constant energy demand for CO_2 capture	Flexible energy demand (covered with fluctuating renewables)	Major share of energy used for CO_2 capture	Minor share of energy produced used for CO_2 capture	No energy demand for CO_2 capture
	B4.2 Access to low carbon energy sources	No access to low carbon energy sources		Limited access to low carbon energy sources		Access to low carbon energy sources (and/or to process energy)
Economic dimension		(−−−)	(−−)	(−/+)	(++)	(+ + +)
C1 Market costs	C1.1 Marginal removal cost (€ per unit of CO_2 removed)	Higher marginal removal cost		Moderate marginal removal cost		Lower marginal removal cost
	C1.2 Opportunity cost	High opportunity cost		Moderate opportunity cost		Low opportunity cost
C2 Dynamic cost efficiency	C2.1 Potential for cost reductions by technological progress	Low potential for cost reductions by technological progress		Moderate potential for cost reductions by technological progress		High potential for cost reductions by technological progress
	C2.2 Potential for economies of scale	Low potential for economies of scale		Moderate potential for economies of scale		High potential for economies of scale
	C2.3 Contribution margin of jointly produced goods (€ per ton of CO_2 removal)	No jointly produced goods		Jointly produced goods with low contribution margin		Jointly produced goods with high contribution margin
C3 Transaction cost efficiency	C3.1 Public transaction costs	High public transaction costs		Moderate public transaction costs		Low public transaction costs
	C3.2 Private transaction costs	High private transaction costs		Moderate private transaction costs		Low private transaction costs
C4 External effects	C4.1 External costs per unit of CO_2 abated/removed	High external costs		Moderate external costs		Low external costs
	C4.2 External benefits	Low external benefits		Moderate external benefits		High external benefits
C5 Effects on domestic/regional economy	C5.1 Potential for domestic/regional value added	Low potential for domestic/regional value added		Moderate potential for domestic/regional value added		High potential for domestic/regional value added
	C5.2 Potential for domestic/regional employment	Low potential for domestic/regional employment		Moderate potential for domestic/regional employment		High potential for domestic/regional employment
C6 Investment barriers	C6.1 Capital intensity (i.e., share of capital cost in total cost of CDR measure)	High capital intensity (high share of capital costs in total cost)		Moderate capital intensity (medium share of capital costs in total cost)		Low capital intensity (low share of capital costs in total cost)

(Continued)

TABLE 1 | Continued

Criteria	Indicator	Likely large hurdle to implementation	Uncertain, likely large hurdle to implementation	Likely medium hurdle	Uncertain, likely no hurdle to implementation	Likely no hurdle to implementation
	C6.2 Specificity of investment	High specificity of investment		Moderate specificity of investment		Low specificity of investment
	C6.3 Revenue risk	High revenue risk		Moderate revenue risk		Low revenue risk
Social dimension		(−−−)	(−−)	(−/+)	(++)	(+ + +)
D1 Public perception of CDR approaches (risks/benefits) and/or process	D1.1 Perceived risk of CDR measure	Deemed high risk	Deemed medium risk	Ambivalent risk perception	Deemed low risk	Deemed risk free
	D1.2 Trust in institutions	Distrust	Low level of trust	Ambivalent/neither high nor low level of trust	High level of trust	Very high level of trust
D2 Social co-benefits	D2.1 Health	Trade-offs/losses	Uncertain leading to trade-offs/losses	No co-benefits/trade-offs	Uncertain leading to co-benefits	Co-benefits
	D2.2 Employment	Lost employment opportunities	Lost employment opportunities expected	No co-benefits/trade-offs	New employment opportunities expected	New employment opportunities
D3 Inclusiveness/ participation	D3.1 Participation during different steps of the process	Not existing	Low	Neither low nor high	High	Very high
	D3.2 National dialogue/regional planning	No		Planned		Yes
	D3.3 Transparency of process	Low degree of communication and low degree of access	Either low degree of communication or low degree of access	Medium degree of communication and access	Medium to high degree of communication and access	High degree of communication, high degree of access
D4 Ethical considerations	D4.1 Discursive legitimation	Low	Uncertain, leaning to low	Ambivalent	Uncertain, leaning to high	High
	D4.2 Intergenerational equity					
	D4.3 Ethical reservations (of resource use)	High degree	Slight degree	Ambivalent	Low degree	None
D5 Social context (case-by-case basis)	D5.1 Previous experience of large-scale development/infrastructure projects	Very negative	Negative	Neutral/no previous experience	Positive	Very positive
	D5.2 Local narrative					
Institutional dimension		(−−−)	(−−)	(−/+)	(++)	(+ + +)
E1 Political maturity (as indication for political acceptability)	E1.1 Placement within policy cycle	Not at all in any policy development	Agenda setting	Policy formulation and policy adoption	Policy implementation	Policy evaluation

(Continued)

TABLE 1 | Continued

Criteria	Indicator	Likely large hurdle to implementation	Uncertain, likely large hurdle to implementation	Likely medium hurdle	Uncertain, likely no hurdle to implementation	Likely no hurdle to implementation
E2 Political acceptability: support for CDR within the current policy landscape	E2.1 Level of acceptance in policy debate	Low		Minor		High
	E2.2 Government supported research on CDRs	No		Under development		Yes
	E2.3 Inclusion of CDR in existing national and/or regional climate strategies	No		Proposal available		Yes
E3 Legal and regulatory feasibility	E3.1 Possible scale of legal conflicts	Global conflict	Regional and transboundary conflict	Local conflict		No conflict
	E3.2 Conformity with human rights	Low		Minor		High
	E3.3 Conformity with environmental laws and conservation requirements					
	E3.4 Conformity with climate laws					
	E3.5 Regulatory effort	No overlap with existing regulations (high effort)		Some overlap requiring additional regulations (minor effort)		Synergies / overlap with existing laws and regulations (low effort)
E4 Transparency and institutional capacity	E4.1 Monitoring, Reporting and Verification (MRV) system	Difficult to develop		Easy to develop		Already existing
	E4.2 Integration of negative emissions from CDR in national emission reporting	Difficult to include		Easy to include		Already included
	E4.3 Integration of CDR (or elements of CDR) in carbon market					
	E4.4 Adaptive and responsive management					
	E4.5 Administrative demand	High		Medium		Low

(Continued)

TABLE 1 | Continued

Criteria	Indicator	Likely large hurdle to implementation	Uncertain, likely large hurdle to implementation	Likely medium hurdle	Uncertain, likely no hurdle to implementation	Likely no hurdle to implementation
Systemic dimension		(−−−)	(−−)	(−/+)	(++)	(+ + +)
F1 CDR potential	F1.1 Max. feasible net CO_2 emissions removal deployed by 2050	10%<	10–30%	30–50%	50–100%	100%>
	F1.2 Max. feasible 'near-term' net CO_2 emissions removal					
	F1.3 Max. total sequestration potential between 2020 and 2050					
F2 CO_2 emissions avoidance potential (CirC potential)	F2.1 Max. of CO_2 emissions avoided through deployment in 2050	10%<	10–30%	30–50%	50–100%	100%>
	F2.2 Max. CO_2 emissions avoided in the 'near-term' through deployment					
F3 Permanence	F3.1 Natural persistence of storage	Decades	Decades to century	Centuries	Centuries to millennia	Millennia
	F3.2 Risk of carbon loss due to climate change and/or natural disturbances	High risk (i.e., high likelihood and large carbon loss)	Medium risk (i.e., low likelihood but high loss, or high likelihood but low loss)	Low risk (i.e., low likelihood and low loss)	Uncertain but probably no risk of carbon loss	No risk of carbon loss
	F3.3 Risk of carbon loss due to anthropogenic disturbances					
F4 Verifiability	F4.1 Ability to confirm the amount of CO_2 captured/avoided	Unfeasible and not foreseen to be feasible with new technology	Difficult to verify but potentially possible with new technology	Moderately difficult/existing systems would need to be adapted	Planned observation system feasible	Already possible to verify with existing system
	F4.2 Ability to confirm the amount of CO_2 stored / the amount of increase in carbon stock of sequestration reservoir					
	F4.3 Uncertainty of estimates for CO_2 removal/avoidance	>100%	100–60%	60–30%	30–10%	<10%

Red, Likely large hurdle to Implementation; Orange, Uncertain, likely large hurdle to implementation; Yellow, Likely medium hurdle; Green, Uncertain, likely no hurdle to implementation; Dark green, Likely no hurdle to implementation.

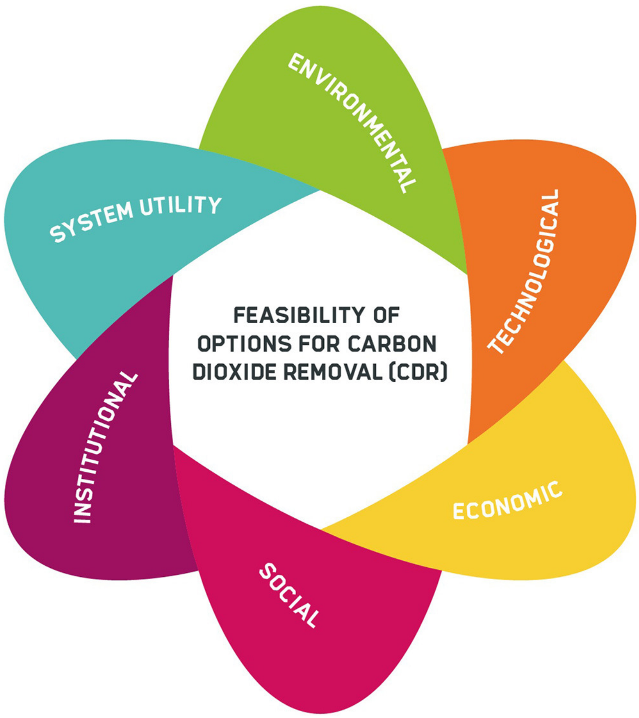

FIGURE 2 | Overview of thematic dimensions included in the feasibility assessment framework of carbon dioxide removal (CDR) options (source: UFZ/Conor Ó Beoláin, Helmholtz Climate Initiative // Julia Blenn, Creative Commons CC-BY NC 4.0 license).

addressed by the criteria and indicators could pose a hurdle to CDR implementation. The developed framework can be regarded as a tool for better understanding and navigating the feasibility of CDR options. Furthermore, the assessment framework can be adapted and complemented with indicators in accordance with user needs such as including more fine-grained indicators and data if needed. The assessment framework presented herein may serve as a starting point to then be adapted to meet the needs of particular stakeholders and national circumstances. For example, besides applying the framework to assess the feasibility of CDR options at a national scale, the criteria and indicators can be adapted to assess pilot-sized projects. Thereby, the focus of the assessment framework can also be adapted to the specific local context depending on the respective social-ecological, economic, legal and political situation and the information needed by stakeholders (Fridahl et al., 2020). A case specific adaptation of the assessment framework can address particular information needs of stakeholders and provide more relevant information for decision-making processes to make CDR assessments fit-for-purpose.

Environmental Dimension

The potential impacts of deploying a CDR option on air/atmosphere, land and sea, and freshwater bodies is explored in the environmental dimension. The selection of environmental criteria and related indicators is partly based on established environmental impact assessments used in Germany (UBA, 2020a).

Impact on the air/atmosphere (A1) includes an air quality indicator that considers air changes that affect human health, GHG emissions related to land/sea use changes, net biophysical effects on local climate, and net effects of audible noise on humans and ecosystems. For the air quality indicator, any impacts that have implications for human health should be considered, including changes in ground level ozone, particle pollution (also known as particulate matter), sulfur dioxide and nitrogen dioxide. GHG emissions related to changes in land/sea use indicates whether the CDR measure is likely to cause or avoid any non-CO_2 GHG emissions, including methane, nitrous oxide, or fluorinated GHGs. Changes in the use of land and sea can cause emissions of a range of GHGs, for comparability the indicator refers to CO_2 equivalents using global warming potential over 100 years (GWP100). Due to time lags in the impact of CDR measures on GHG emissions (e.g., forest, seagrass or peatland restoration can take decades before reaching their full potential in GHG uptake) this indicator considers GHG effects starting from implementation until 2050. Net biophysical effects indicate impacts of CDR implementation on local climate conditions due to changes in albedo, water and heat fluxes caused by e.g., land cover changes. The indicator on noise effects is referring to any impacts on humans and ecosystems from audible noise caused by the CDR option.

Impacts on land and sea (A2) include indicators for assessing area demand resulting from CDR implementation and related competition, impacts on biodiversity (ecosystems, species, genes), and impacts on soil quality. While the IPCC (de Coninck et al., 2018a) includes land use under the geophysical dimension, we follow Thrän et al. (2020) and include it under the environmental dimension as land/sea use has implications for multiple environmental impact categories. Area demand assesses whether the implementation of the CDR measure requires land/sea area and if the area is under competition for alternative uses (e.g., food production, conservation, reforestation). This includes indirect land use impacts, with area demand being shifted to other regions (teleconnections), which requires also to account for related indirect emissions (Fridahl et al., 2020). Most area demand caused by CDR options in Germany is likely to increase land competition. However, some CDR options can reduce competition by introducing multi-purpose use of the affected area (e.g., paludiculture on rewetted peatlands and restored seagrass meadows can allow alternative use of the same area). The biodiversity indicator refers to expected changes in ecosystems (genes to species) as a result of the implementation of a CDR option. Impacts on biodiversity can be assessed by e.g., changes in species richness of an ecosystem (alpha diversity), changes in species turnover (beta diversity) or mean species abundance. We suggest using a biotope valuation point system established for Germany that allows assessing habitat quality related to biodiversity and which is also applied for determining restoration costs (Schweppe-Kraft et al., 2020). Impacts on soil quality include changes in chemical and physical soil characteristics including nutrients (e.g., nitrate or phosphate), heavy metal concentrations, soil erosion and compaction/consolidation.

Assessing impacts on water (A3) includes indicators on the quality of groundwater, surface water, and sea water, as well as indicators on water demand and consequences for its availability. In general, the indicators follow the EU Water Framework Directive and the EU Groundwater Directive (EC, 2000, 2006). Indicators on quality of surface water and groundwater consider impacts on chemical composition, such as nutrient content (in particular nitrate and phosphate), pesticides and heavy metal concentrations (Geidel et al., 2021).

Technological Dimension

Technological performance is the key to deploying and upscaling CDR options, as well as determining CDR efficiency (e.g., see also Fridahl et al., 2020). This performance is evaluated under the technical dimension. It accounts for efficiency (i.e., energetic and CO_2 removal capability), market maturity, infrastructural requirements and integration into the future energy system. The criteria and indicators have been adapted based on the integrated assessment framework of bioenergy strategies by Thrän et al. (2020) and contribute to operationalizing indicators on efficiency and scale (e.g., proposed by Fridahl et al., 2020) within the national context of Germany.

Technology efficiency (B1) addresses two aspects: (1) the net energy balance of the CDR option, which can either be positive (net energy provision), neutral or negative (net energy demand); and (2) the CO_2 reduction and removal efficiency per energy unit used or produced, which describes how energy intensive a CO_2 removal process is and hence the leverage potential for negative emission generation. **Availability of the technology (B2)** is used to assess the extent to which a technology is commercially available on the market. It is described by the technology readiness level (TRL) in terms of its stage of implementation (laboratory, demonstration, pilot, market rollout) (DOE, 2011; as defined by EC in HORIZON 2020 Work Programme). Another relevant aspect for the feasibility of a CDR option is the compatibility of the already **existing infrastructure with that needed to implement the CDR option (B3),** such as availability of plants/installations (e.g., pipelines for natural gas, hydrogen, or CO_2 transportation) or the operation of ecosystem-based options (e.g., materials and machinery for habitat restoration, ease of access for harvesting biomass). This criterion specifically addresses whether a suitable infrastructure already exists, or if it has to be created before implementing the CDR option. Finally, the **compatibility with the future energy system (B4)** is assessed, which includes the operation effort of the CO_2 collection and also the possibility to access low carbon energy carriers on different stages of the option's life cycle (Fajardy et al., 2018).

Economic Dimension

The economic criteria focus on costs related to the deployment of CDR measures, effects of CDR deployment on the domestic economy, as well as on potential investment barriers that might hamper the deployment of CDR measures.

The criterion **market costs (C1)** analyzes the private cost for CO_2 removal from the atmosphere (Minx et al., 2018). A first indicator are today's marginal removal cost, i. e. the cost that needs to be spent in order to remove one additional metric ton of CO_2 from the atmosphere under this CDR option. All else being equal, a higher marginal removal cost means a higher cost for reaching a given CO_2 removal target and hence a lower cost-effectiveness from a static point of view as also stressed by Fridahl et al. (2020). Additionally, a second indicator analyzes the opportunity cost of applying a CDR measure, meaning that it looks at forgone and/or restricted other economic uses of the deployed production factors, e.g., land use (United Nations Environment Programme, 2020). As Fridahl et al. (2020) point out, CDR options, particularly land based ones, often compete with alternative uses, and thus can come along with considerable opportunity cost.

However, the cost of a CDR option might change over time and thus can alter the relative cost-effectiveness when compared with other CDR options. This is mirrored in the criterion **dynamic cost efficiency (C2)** which aims to assess the potential for future cost discrepancies (e.g., cost reductions) and depends on various influencing factors. This criterion provides an indication for future subsidy needs (Yao et al., 2020). A first indicator for this criterion is the potential for future cost reductions due to technological advancements of a CDR option. Another source for future cost reductions is a potential decrease of the average production cost per unit of CDR when the overall production of the respective CDR measure is increased (potential for economies of scale). However, average production cost can also increase, e.g., if increasing the scale means higher opportunity costs of land use. A third indicator is the contribution margin of marketable, jointly produced goods produced by a CDR option which allows for reducing the cost for the CDR service. The contribution margin describes the share that the revenue of a certain product contributes to the coverage of the fixed costs. By covering a part of the fixed costs, the contribution margin of jointly produced goods thus reduces the (fixed) costs that need to be refinanced by the CDR service.

Like all environmental policy instruments the deployment of CDR options do not only come along with production costs, but also generates **transaction costs (C3)**, i.e., costs that accrue for transactions that are related to the deployment of a CDR measure, such as for using the market, for insuring against risks, or for regulating the deployment of a CDR option (Krutilla, 2011). High transaction costs can decrease the relative economic efficiency of CDR measures, e.g., if a large number of actors is involved in transactions or permanent and long-lasting regulatory control of retention of removed CDR is necessary. Transaction costs accrue both on the side of regulators as well as on the side of private actors who apply CDR measures. On the side of public actors transaction costs encompass for instance the costs of legislative procedures or the enforcement of laws and regulations. On the private side transaction costs can accrue due to, for example, the compliance with laws and regulations or the usage of the market (e.g., finding transaction partners, settlement of trade disputes, etc.). Both higher public and private transaction costs increase the cost of deploying the respective CDR option.

External effects (C4) of CDR options describe negative effects or benefits to third party actors who did not choose to incur that damage or benefit and that accrue due to the deployment of the respective measure. Classic examples include environmental damages or health impacts. External effects constitute a major economic cost and play an important role for the economic assessment of a CDR option (Fuss et al., 2018).

Besides economic efficiency reasons, policy decisions for or against the deployment of a certain technology are often also based on economic policy, which is considered in the **effects on domestic/regional economy (C5)** criterion. In this regard, effects on domestic value added and employment are often analyzed in multicriteria assessments of technology options (cf. Thrän et al., 2020) as well as in the context of CDR options in particular (Honegger et al., 2021a).

In a sixth criterion, the economic dimension examines **investment barriers (C6)** as these might impede the implementation of (potentially cost-effective) CDR options. This criterion encompasses three indicators. The first indicator looks at the capital intensity of CDR options, i.e., the share of capital cost in the total cost of the CDR option which can differ significantly between different CDR options (Fridahl et al., 2020). If capital markets are imperfect, e.g., due to incomplete information, a high share of capital intensity can restrain investments in the respective measure (cf. Hu et al., 2018). A second indicator is the specificity of investment, asking for other potential uses of the investment than the envisaged one. If other applications for the investment are absent or significantly reduce its value then the investment is highly specific and means a high financial loss to the investor in case of failure, i.e., the CDR investment might end up as a stranded asset (Minx et al., 2018). Accordingly, a highly specific investment bears a high risk and hence might discourage investors from investing. A third indicator is the revenue risk of a CDR investment (cf. Hu et al., 2018). This indicator considers the risk that revenues fail to accrue once the investment is made. For instance, some CDR measures may rely greatly on regulated revenues or state subsidies, which are subject to the discretion of political actors, while others have to cover their costs by market revenues (Fridahl et al., 2020). A higher revenue risk indicates a larger investment barrier. However, it is important to consider interactions between these indicators because, for instance, a highly specific investment might be less of an investment barrier if the revenue risk is low.

Social Dimension

The social dimension focuses on understanding social acceptance in a specific setting, informed by the following criteria: public perception of CDR options, social co-benefits or costs, inclusiveness and participation, ethical considerations, and social context. In addition to consideration of previous (global) assessments, as discussed above, the selection of the criteria for the social dimension were informed by literature on social acceptance, while recognizing that complex social processes are not easily captured by fixed criteria and indicators. For instance, while the assessment framework has been developed for the national level, the criterion 'social context' points to the relevance of even more fine-grained analyses (cf. Bellamy et al., 2019). As much research on CDR options focuses on modeled or projected policy outcomes ('supply-side' of knowledge production), another consideration going into the social dimension was to include actors' expectations projected to these emerging technologies and governance. In practice, this means that we have included a broad range of criteria and indicators, such as consideration of perceived, absolute, and/or anticipated risks and benefits, based on input from various actors.

While **public perception (D1)** and social acceptance are sometimes used synonymously in the literature, for the purpose of this assessment framework, we treat social acceptance as an overarching theme, for which all criteria under the social dimension are relevant. This differentiation marks an important methodological distinction, reflecting the fact that asking people what they think about CDR today is not necessarily a good indicator for how they will feel about it in the future (cf. Dowd et al., 2015; Winickoff and Mondou, 2017; Bellamy et al., 2019). Social acceptance can instead be understood as something that is built over time, associated with creating trust in the process (e.g., Mabon et al., 2013; Braun et al., 2018; Gough and Mander, 2019; Waller et al., 2020). Moreover, emerging research on social acceptance in the context of CDR options shows that rather than that the public lacks information, resistance to technology deployment often stems from basic value conflicts, distrust in authorities and institutions and perceived injustice (Winickoff and Mondou, 2017; Markusson et al., 2020; Waller et al., 2020). This research highlights the need for qualitative-procedural based research on politics—the input into the policy process—as much focus has already been given to quantitative-distributional studies on outcomes of policies. The social dimension covers both these aspects—input into the policy process through considerations of inclusiveness and participation, and output of policies through considerations of co-benefits and risks. The proposed indicators are therefore a contribution to translating more general indicators of CDR acceptance (e.g., as proposed by Fridahl et al., 2020) to more specific indicators for application within the national context of Germany.

One criterion that has been linked to positive public perception is perceived benefits. The criterion **social co-benefits (D2)** is thus linked to public perception. However, perceived benefits and absolute or anticipated benefits are not the same (L'Orange Seigo et al., 2014). Given that CDR is not yet implemented at large scale, anticipated social co-benefits such as positive health effects or new jobs are relevant to give an idea regarding acceptance in the future. While such social benefits are critical for determining public acceptance, it should also be noted that the selected indicators represent common discussions in the literature, and that other social co-benefits exist (e.g., enhancing climate resilience through ecosystem-based CDR options). When the assessment framework is applied, it would therefore be beneficial to consider the most important co-benefits and risks for the specific context.

The degree of public trust has been linked to inclusiveness and participation, transparency, and perceived fairness of processes, but previous research also highlights that the picture is complex and context specific (Lock et al., 2014; Jami and Walsh, 2017; Janhunen et al., 2018). Consequently, trust is here assessed as both public perception of trust in the process, as well as indirectly through assessments of **inclusiveness and participation (D3)** in the knowledge and decision-making process. By way of comparison, public perception is a criterion where we consider—at a given moment in time—risk perception on the one hand, and trust in the process on the other. This is also in line with literature on CCS where perceived risks/benefits and trust in stakeholders are the most common indicators for public perception (L'Orange Seigo et al., 2014).

The criterion **ethical considerations (D4)** goes beyond the evaluation of direct and personal benefits to include more general notions of what is regarded as right or good. For instance, perceived interference with nature has been linked to negative attitudes toward CO_2-storage (Wallquist et al., 2012; Wolske et al., 2019). The criterion also includes the linkage between discursive legitimation and social acceptance (cf. Bäckstrand and Lövbrand, 2019). Research indicates that negative perceptions of fracking may conjure negative feelings toward CDR (Cox et al., 2021), and that associating CCS with bioenergy and negative emissions could positively affect attitudes toward CCS compared to when CCS is associated with the fossil fuel industry, for example (e.g., Wallquist et al., 2012; Haikola et al., 2019).

Overall, an important consideration for the choice of criteria and indicators selected for the social dimension has been to highlight that the socio-technical systems that CDR options are embedded in, and the social context in which citizens decide, matter for social acceptance. For instance, in a study about perceptions of BECCS, Bellamy et al. (2019) show that the support or resistance for BECCS cannot be well-understood merely by looking at technological characteristics. Instead, public perception is affected by the type of policy instrument (e.g., taxes, funding, standards) used to incentivize it. Social acceptance has also been linked to much more local/social context-specific factors than the more generic ones discussed above, such as previous experience with similar projects (e.g., Braun, 2017; Gough et al., 2018; Cox et al., 2021). It is also important to note that "the public" cannot be well-understood as one actor and that public reaction is context specific (Dowd et al., 2015; OECD, 2017).

Institutional Dimension

The institutional dimension evaluates the political and legal conditions for the development and deployment of CDR options. Four criteria have been selected for this purpose: political and institutional maturity, support for CDR within the current policy landscape, legal and regulatory feasibility, and transparency and institutional capacity. As highlighted by Fridahl et al. (2020), it is important to assess the juridical compatibility of CDR options within their respective political context and our proposed indicators allow for operationalizing this assessment within the German national context.

Political (and institutional) maturity (E1) can help to locate CDR approaches in the different phases of the policy cycle, ranging from agenda setting to policy evaluation. This criterion could also give an indication of political acceptance, since if a specific CDR option faces opposition, it will be less likely to advance in the policy cycle than CDR options that are widely accepted (Geden, 2016; Zelli et al., 2017; Pye et al., 2021).

The second criterion, **political acceptability (E2)**, is the institutional and public support for the different approaches that seek to generate negative emissions within the current political landscape. It allows for the level of acceptance to be assessed in the political debate as indicated, for example, by the inclusion of CDR options in national and/or regional climate strategies (Geden and Schenuit, 2020; Thoni et al., 2020). Political acceptability can be broadly understood as support for a policy or measure (including a lack of opposition). This criterion is also closely related to the policy cycle. For example, if a specific CDR approach is a taboo topic, it means that it may not even reach the agenda setting phase and therefore not be assessed with respect to the policy cycle. To date, it is still difficult to assess the political acceptability of specific CDR approaches, because of its early stage of development and the need to anticipate governance needs and challenges.

Legal and regulatory feasibility (E3) addresses the questions whether CDR approaches will generate legal conflicts, i.e., with a view to existing laws at different levels, i.e., at the global, regional or local level and/or presents any conflicts with legal requirements (Brent et al., 2018; Geden et al., 2019; Markus et al., 2021a). Any CDR approach to be deployed must conform with international human rights instruments (e.g., regarding the restriction of free use of property rights) and various environmental laws, including general principles (e.g., prevention and precautionary principles), as well as rules set out in specific legislation (e.g., at the European level: RED II, EU-Emissions trading system) (Creutzig et al., 2013; Burns and Nicholson, 2017; Brent et al., 2018; IPCC, 2018; Markus et al., 2020, 2021b). This criterion is used to assess whether the development or deployment of the CDR approach is adequately regulated or requires the creation of a new regulation, either at the European or national level or whether it can be integrated into existing legal instruments (Hester, 2019; Honegger et al., 2019; Markus et al., 2020, 2021a).

Finally, the criterion on **transparency and institutional capacity (E4)** examines whether a monitoring, reporting, and verification (MRV) system is in place to evaluate the CO_2 sequestered, and report on compliance with social and environmental safeguards related to CDR options (Lin, 2018; Royal Society and Royal Academy of Engineering, 2018; UBA, 2020b). To avoid introducing too much complexity, we have not included further indicators for the quality of the MRV-system. It is more of a first step, rather than a complete picture. That being said, the criterion verifiability (F4) in the system utility dimension looks at scientific and technological advancements and uncertainty ranges of measuring systems for CDR options, which in turn could inform MRV-assessments. This criterion of transparency and institutional capacity (E4) also addresses the integration of negative emissions from CDR approaches in national emission reports and the integration of CDR approaches in the carbon market (Geden and Schenuit, 2020). With regard to institutional capacity, this criterion seeks to determine whether there is adaptive and responsive management in place to evaluate and possibly adapt mechanisms and procedures in a transparent manner for the governance of the deployment of CDR technologies (Armeni and Redgewell, 2015; Forster et al., 2020. It may be concluded whether the existing capacity is sufficient or whether new institutions or new institutional arrangements are required. For example, potential administrative or institutional demands for specific CDR approaches may arise with a view to establishing and implementing permitting regimes, monitoring requirements, standards, control and enforcement schemes, as well as participation in planning measures (Lin, 2018; Hester, 2019; Markus et al., 2021a). The indicator on administrative demand addresses the effort related to building such institutional capacity and includes aspects such as costs, time, capacity building, etc.

System Utility

The system utility dimension describes the CDR option's potential for CO_2 removal, which relates to the effectiveness of CDR options (e.g., addressed by Fridahl et al., 2020). Removing CO_2 can have a two-fold system utility. First, removing CO_2 during periods of net positive emissions can compensate for remaining gross positive emissions and therefore close the gap to net-zero CO_2. And second, removing CO_2 can enable net-negative CO_2 emissions and therefore would enable the mitigation of a carbon budget overshoot. The **CDR potential (F1)** criterion describes the maximum negative emissions potential in the short and longer term (2025 and 2050), including both annual capacities and cumulative effects over time. In addition, we include the **CO_2 emissions avoidance potential (F2)** showing possible co-benefits of additionally avoiding current emissions to the system. For example, emissions from agricultural soils can be avoided by rewetting previously drained organic soils, and in addition to that, these ecosystems will sequester carbon. We here explicitly exclude future avoided emissions (e.g., future anthropogenic disturbances of existing carbon stocks), as this assessment would require additional scenario assumptions about a future counterfactual scenario. **Permanence of CO_2 storage (F3)** explores the risks and efforts associated with maintaining an intact carbon stock. This includes the natural persistence of the chosen storage reservoir over time scales of decades, centuries to millennia, as well as the level of risk associated with natural and anthropogenic disturbances of a carbon stock.

Finally, **verifiability (F4)** indicates if adequate measuring systems exist and are in place to confirm the amount of CO_2 sequestered or captured and stored. This can be assessed by the scientific community, for example, by verifying the amount of carbon added to the overall carbon stock or measuring CO_2 fluxes. Where possible, uncertainty estimates for CO_2 removal or avoidance can be added to this criterion. The focus here is on scientific and technological certainty, whereas the MRV-indicator (E4.1) assesses whether on an institutional level MRV-systems are in place as a means for creating transparency. For instance, the measuring systems for verifying carbon dioxide removal by a CDR option with adequate accuracy might exist (F4.3), but there is no MRV-system in place (E4.1) to ensure transparent accounting of the removed carbon dioxide as part of a national accounting scheme.

Interlinkages of Dimensions

Interlinkages arise between the dimensions due to the complexity of the reality in which CDR options operate and resulting overlaps in the dimensions (**Table 2**). Here, we identify and discuss some of these interlinkages that consequently might cause synergies or trade-offs between objectives when CDR options are implemented or scaled up. This can provide useful information for decision-makers on the expected added value or unintended side effects from CDR implementation and identify where effort is required to harness synergies and address trade-offs.

For example, area demand (A2.1) of a CDR option, assessed within the environmental dimension, has wide ranging environmental (A1 to A3) and social (D2 and D4) implications, with positive or negative externalities accounted for in the economic dimension (C4). These environmental impacts are also subject to laws and regulations (E3) being assessed under the institutional dimension. If the implementation and upscaling of CDR options requires compliance with multiple environmental laws and regulations, then CDR deployment would likely involve a high regulatory effort (E3.5) and a need for transparency with implications for the administrative demand (E4).

There are also overlaps between the environmental and economic dimensions with regards to externalities (C4) (i.e., negative and positive impacts related to CDR deployment). For selected environmental impacts, economic cost estimates have been established for Germany, for example, to inform regulatory impact assessments (UBA, 2020a). They can be used to determine negative and positive externalities related to environmental impacts resulting from the implementation of CDR options. Cost estimates are also available for carbon emissions resulting from land-use change (based on damage cost of carbon emissions), air pollution, noise pollution, the sealing of soils with impermeable surfaces, and the release of nutrients to surface water, groundwater and coastal waters (UBA, 2020a). Where CDR implementation is having positive environmental impacts (e.g., reduce carbon emissions, enhance carbon uptake, reduce nutrients, air and noise pollution, and reverse the sealing of surfaces), the same cost estimates can be used to determine the positive externalities.

Interlinkages can reveal potential correlations between indicators as well as highlight those that bear the risk of being considered twice in the assessment. While the former might apply, for example, to the interlinkage of environmental impacts and the resulting need for environmental regulation, the latter is inherent for instance in the economic evaluation of external effects, such as environmental damages or health impacts. This is an important limitation of the assessment framework when weighing different CDR options against one another. As double consideration should be avoided in multi-criteria assessments to prevent overweighting of particular aspects, the respective feature should only be evaluated in one of the dimensions concerned.

The presented framework can provide an important tool to systematically assess interlinkages in order to better understand effort, risks, and opportunities involved in the development and potential large-scale implementation of CDR options. This analysis also helps identify possible stakeholder groups impacted

TABLE 2 | Interlinkages between the dimensions of the feasibility assessment framework of carbon dioxide removal (CDR) options (interlinkages between dimensions are idicated by "‖".

	Environmental	Technological	Economic	Social	Institutional	System utility
Environmental						
Technological	A 2.1 Area demand and competition for other area uses ‖ B1 Technology efficiency/Conversion efficiency;					
Economic	C2.1 Other external costs per unit of CDR ‖ A1 Impact on air/atmosphere and A2 Impact on land and sea area and A3 Impact on water; C2.2 external benefits ‖ A1 Impact on air/atmosphere and A2 Impact on land and sea area and A3 Impact on water;	C2.1 Potential for cost reductions by technological progress ‖ B2.1 Technology Readiness Level;				
Social	D2.1 Health ‖ A1.1 Outdoor air quality and A1.3 Net biophysical effect/effects on local climate and A3.1 Groundwater quality; D4.3 Ethical reservations and D5.1 Previous experience of large-scale projects and D5.2 Local narrative ‖ A2.1 Area demand and competition for other area uses;	D4.3 Ethical reservations ‖ B1.1 Net energy demand vs. provision;	D2.1 Health ‖ C 4.1/4.2 External costs/benefits; D2.2 Employment ‖ C5.2 Potential for regional employment;			
Institutional	E3.1 Possible scale of legal conflicts and E3.3 Conformity with environmental laws and conservation requirements and E3.5 Regulatory effort and E4.1 Monitoring, Reporting and Verification (MRV) system ‖ A1 Impact on air/atmosphere and A2 Impact on land and sea area and A3 Impact on water;	E1 Political maturity (as indication for political acceptability) ‖ B2.1 Technology Readiness Level and B3.1 Compatibility of infrastructure and B4.1 Effort of CO_2 collection and B4.2 Access to low carbon energy sources;	E3.5 Regulatory effort and E4.1 Monitoring, Reporting and Verification (MRV) system and E4.5 Administrative demands ‖ C3.1 Public transaction costs and C3.2 Private transactions costs;	E2 Support for NET within the current policy landscape ‖ D3 Inclusiveness/participation; E2.1 Level of acceptance in policy debate ‖ D4.1 Discursive legitimation; E3.2 Conformity with human rights and E3.3 Conformity with environmental laws and conservation requirements ‖ D2.1 Health		

(Continued)

TABLE 2 | Continued

	Environmental	Technological	Economic	Social	Institutional	System utility
		E2 Support for NET within the current policy landscape ‖ B1.1 Net energy demand vs. provision and B1.2 CO_2 removed/reduced per unit of energy produced and B2.1 Technology Readiness Level and B3.1 Compatibility of infrastructure and B4.1 Effort of CO_2 collection and B4.2 Access to low carbon energy sources; E3 Legal and regulatory feasibility ‖ B1.1 Net energy demand vs. provision and B1.2 CO_2 removed/reduced per unit of energy produced and B2.1 Technology Readiness Level and B4.2 Access to low carbon energy sources; E4 Transparency and institutional capacity ‖ B2.1 Technology Readiness Level;		E4 Transparency and institutional capacity ‖ D3 Inclusiveness/participation; E4.1 Monitoring, Reporting and Verification (MRV) system and E4.4 Adaptive and responsive management ‖ D3.3 Transparency of process;		
System utility	F1 CDR potential and F2 CO_2 emissions avoidance potential ‖ A1.2 GHG emissions related to land/sea use change; F3.3 Risk of carbon loss due to anthropogenic disturbances ‖ A2.1 Area demand and competition for other area uses;	F1 CDR potential ‖ B1.2 CO_2 removed/reduced per unit of energy produced; F2 CO_2 emissions avoidance potential ‖ B1.2 CO_2 removed/reduced per unit of energy produced; F3.4 Storage maintenance ‖ B1.2 CO_2 removed/reduced per unit of energy produced;		F4 Verifiability ‖ D3.3 Transparency of process;	F3.3 Risk of carbon loss due to anthropogenic disturbances ‖ E3.3 Conformity with environmental laws and conservation requirements and E3.5 Regulatory effort and E4.5 Administrative demand;	

by CDR implementation and related consequences that require participatory processes.

Traffic Light System

To assess the implications of CDR options *via* the identified indicators, a traffic light system was developed. The general idea behind the traffic light system is to provide a systematic overview of and communicate challenges and opportunities for CDR options. It also indicates where efforts are needed to overcome hurdles for the implementation and deployment of CDR options, in line with previous efforts to develop similar systems (e.g., Thrän et al., 2020). Our traffic light system combined with the proposed indicators are adapted to the German national context and the framework is, to the best of our knowledge, the only one with this scope. There are other color coded assessments in the field of CDR (e.g., de Coninck et al., 2018b; Honegger et al., 2019), and other traffic light assessment systems in the field of climate governance, for instance the Boehm et al. (2021) and Climate Action Tracker (2021).

We regard the combination of a descriptive ranking system together with a traffic light color coding system to be an effective tool to support science-policy processes on CDR development and deployment as it helps structure and evaluate the available information on the feasibility of CDR options. The ranking can serve as an input to and be informed by participatory science-policy processes involving relevant stakeholders, but it cannot replace decision making processes. The assessment is also not meant to be policy prescriptive. For example, where an indicator for a CDR option has been ranked with a red traffic light color code (which means that the issue addressed by the indicator is likely to represent a high hurdle to implementation), the assessment does not imply that this CDR option should be increased or abandoned. Such conclusions will have to be drawn within participatory stakeholder processes and under consideration of multiple decision-relevant criteria, which can be supported but not replaced by such an assessment.

The color code of the traffic light system ranges from green colors (no or little hurdle/effort for implementation) to yellow color (medium hurdle/effort for implementation) to red colors (large hurdle/effort for implementation) with five different codes for most indicators and three (green-yellow-red) for some, depending on the characteristics of the indicator.

In general, green traffic lights represent a high feasibility with no or little effort/hurdles for implementation. In other words, implementation would be possible under current conditions. In contrast, red traffic lights indicate the need for high efforts, or existence of large hurdles, for the implementation of the CDR option and/or for the prevention of side effects. Yellow traffic lights consequently indicate medium effort needed. Due to the different nature of the dimensions, the specific logic behind the traffic light system varies between indicators. More specifically, the traffic light system covers three overarching logics:

Traffic light based on *advancement within a given process:* Several dimensions (e.g., for E1: Political maturity) have indicators coupled with a traffic light system representing steps in a process, where green represents that the development has come a long way through the process, red that it has not even or barely started. This type of logic is obvious for the technological dimension, where the rate of technological development is assessed, for instance based on the Technology Readiness Level (TRL). Other examples include the policy process, included as an indicator under the institutional dimension.

Traffic light based on *improvement or worsening of the current condition*: For most indicators, current conditions (unless specified otherwise) comprise the reference system or baseline of the assessment and all indicators are assessed relative to this. For example, the environmental dimension is assessed against current environmental conditions so yellow, green, red light classifications represent no change, improving and worsening conditions, respectively. In contrast, indicators of the systemic dimension assess how much CO_2 could be removed by certain CDR options along different time frames and the ranking follows order of magnitude of removal from zero/low (red) to high (green). Many indicators of the institutional dimension also use current conditions as the starting point, assessing for instance the applicability of existing regulatory frameworks and institutions. Similarly, indicators of the social dimension assess possibilities to participate in the decision-making process against current institutional settings, as well as trade-offs and synergies compared with today's world.

Traffic light based on *assessment against expectations/what is deemed low vs. high effort:* For some dimensions, the expected effort for deployment is not meaningfully assessed against current conditions. For instance, for the economic dimension, all interventions imply some cost. Hence, it would not be informative to apply the same logic to the economic dimension as that of the environmental one, since using current conditions as a baseline would imply that all approaches would get a red light due to associated costs. Instead, the traffic light system for the economic dimension represents a qualitative assessment based on what can be considered a high or low cost for different economic indicators. Similarly, most of the indicators of the systemic dimension have a traffic light system that corresponds to what would arguably be deemed low vs. high effort for deployment. For instance, high maintenance costs get a red light, low costs a green light, and moderate costs a yellow light. The social dimension also includes indicators that instead of current conditions need to be assessed against what is deemed acceptable or not, which in turn is subjective and depends on who is deciding what is acceptable or not. For instance, what is deemed high or low risk may differ between an expert-based impact assessment and an assessment by the people at risk of being adversely affected. Hence there is a need to contextualize the assessment and to specify the underlying assumptions including whose perspective the evaluation represents (e.g., the perspective of technical experts vs. science vs. policy vs. practice vs. civil society vs. etc.), and the degree of participation in and transparency of the assessment process.

Where applicable, quantitative values are used for defining the different colors of the traffic light system, for instance related to emissions removed or avoided in the systemic dimension. In most cases however, a qualitative approach to the traffic light system is used (cf. Thrän et al., 2020). An advantage of the traffic light system is to allow for flexibility in the use of qualitative and quantitative information as long as the underlying assumptions are transparent. What is a high cost or risk in one place can be medium cost or risk in another place, depending on circumstances. A region that wants to reach net-zero carbon emissions and has access to a range of natural carbon sinks may judge investments in DAC too costly, while regions that do not have any natural carbon sinks may find the costs of DAC reasonable. Moreover, for the application of the assessment framework, actors applying the framework to a specific case may choose to specify the traffic lights in more detail. For example, the indicator 'transparency of process' (D3.3) only specifies the degree of communication and stakeholder access to the process. Therefore, users applying the assessment framework to a specific case have to define what a high or low degree means for their context and purposes (e.g., a high/low degree of access means that a certain number of meetings per year are open to the public, etc.). Hence, when the assessment framework is applied to a different national or regional context, the traffic light system needs to be specified in more detail.

An alternative approach to assessing indicators against a baseline or reference is to assess CDR options against one another (comparative analysis of CDR options). For instance, for the economic dimension, a comparative analysis of CDR options would result in identifying options with lower or higher costs. However, comparing CDR options against one another only provides information about which ones require more or less effort relative to one another, not the effort needed in absolute terms. Another alternative would be to assess CDR options against a reference system (cf. Thrän et al., 2020), such as paying for CO_2 removal from verified CDR services, such as the Climeworks DACCS-project on Iceland[1].

However, if the reference system, as in the example given, requires only limited land, then all land-based CDR options would require more effort relative to the reference system, but we would not know the expected level of effort in absolute terms. Moreover, including a reference system outside the national context (e.g., establishing an international trading system for emission removal from CDR measures) would add another layer of uncertainty, not least given the uncertainties around international climate policies, transparency with regards to monitoring, reporting and verification (MRV) and disagreement around Article 6 of the Paris Agreement on internationally transferable mitigation outcomes. Moreover, CDR potential is limited worldwide, and not all countries that want to compensate for residual emissions will be able to do so abroad.

DISCUSSION

Although many Long-Term Low Greenhouse Gas Emission Development Strategies (LT-LEDS) of Parties under the UNFCCC already include options for carbon dioxide removal (CDR), there are still considerable uncertainties regarding the feasibility of deploying CDR options at a large scale (IPCC, 2018). Without an understanding of the feasibility of such CDR options the inclusion of CDR options in current national strategies for reaching net-zero carbon emissions can involve the risk of misleading current climate strategies. Previous research has raised concerns about the risk of mitigation deterrence, meaning that alone the anticipation of generating future carbon removal could slow down action on climate change today (e.g., Carton, 2019; Low and Schäfer, 2020; McLaren, 2020; Waller et al., 2020). In models, the greater the contribution from CDR options is, the slower the rate of decarbonization becomes (Holz et al., 2018; Butnar et al., 2020). This in turn can make it difficult to understand the magnitude of societal transformation needed, if CDR options do not deliver as assumed in emission pathways (Larkin et al., 2018).

There is a growing literature focusing on the feasibility of deploying CDR options under current conditions instead of focusing on the theoretical, technical, maximum potential in the future (Boysen et al., 2017; Geden et al., 2018; Vaughan et al., 2018; Asayama and Hulme, 2019; Fridahl et al., 2020; Wieding et al., 2020; Brack and King, 2021). Assessments also highlight the importance of policy design for CDR in order to address potential trade-offs with other policy objectives such as achieving the Sustainable Development Goals (e.g., Honegger et al., 2021b).

Our assessment framework contributes to this effort by providing a comprehensive set of criteria to explore the feasibility of CDR options within the national context of Germany. Where possible, criteria and indicators were selected with a specific focus on Germany in order to ensure their relevance for and compatibility with established assessment and decision-making processes. This includes, for example, indicators used in national environmental and regulatory impact assessments (UBA, 2020a) and in assessments of renewable energies (Thrän et al., 2020). This contextualization of the assessment framework to the national level is a first step of adapting CDR assessments to specific decision-making contexts. We include previously underexplored criteria in particular related to the social and institutional dimensions that are relevant for assessing opportunities for and barriers to the deployment of CDR options within the current political landscape. This complements previous CDR assessments with a more global perspective (e.g., Fridahl et al., 2020; Honegger et al., 2021b) and assessments with focus on technical or environmental implications (cf. Forster et al., 2020; Waller et al., 2020). Our national level framework, adapted to Germany, can also function as a starting point for discussion of what indicators and criteria are relevant for other countries or regions.

Assessing the numerous indicators of the proposed framework poses a challenge and requires the involvement of experts and stakeholders from multiple disciplines and backgrounds related to both the thematic dimensions and CDR options. This can make the assessment process a complex and demanding task, including the challenge of identifying adequate information and data for each indicator. In order to address these challenges, the rating combined with the traffic light system facilitates the assessment of indicators in both quantitative and qualitative terms (e.g., expert judgement in case no primary or secondary data exists). While this system can support the assessment of complex information from a diversity of sources (e.g., publications, gray literature, expert evaluation), the ranking of

[1]URL: https://climeworks.com/orca

indicators also involves the simplification of information with the risk of information loss (Barnett et al., 2008; Fridahl et al., 2020). Therefore, it is critical to ensure the transparency of underlying information and assumptions in order to gauge their validity and the uncertainties involved in the assessment outcome.

Users applying the framework need to have experience in synthesizing knowledge (e.g., working with multi-criteria analysis) and in facilitating multidisciplinary assessment processes. This can include users from academia, as well as public and private agencies working at the science-policy interface for informing the design of CDR options and policies. Given that the ranking of indicators using the traffic light system involves interpretation of the underlying information based on the judgement of experts or stakeholders from different disciplines and backgrounds, different actors may disagree in the interpretation and ranking of indicators. Therefore, to build credibility, relevance and legitimacy of assessment outcomes, it is also important to be transparent about the actors involved in the assessment process.

Experts, stakeholders, and decision makers might have different opinions on the ranking and relevance of criteria and indicators for determining the feasibility of a CDR option. For example, from a technical perspective CDR options involving CCS technology might be considered feasible by technical experts. However, from a social perspective a lack of public acceptance of CCS due to a different perception of the risks involved could potentially block the implementation of CDR options with CCS (Wallquist et al., 2012). It would arguably be easier for DAC to find public acceptance as part of industrial processes or integrated into air conditioning systems together with the recycling and use of carbon compared to implementation in large scale plants with CCS. However, high demand for renewable energy could undermine energy efficiency and thereby pose a trade-off for the feasibility of DAC technology (Dittmeyer et al., 2019). Hence the assessment framework can help to elicit such trade-offs and open up the policy debate on the feasibility CDR options.

Furthermore, some indicators can be conceptually challenging involving a simplification of the actual underlying processes. For example, determining the placement of the implementation of CDR policies within the policy cycle (E1.1) can be ambiguous as the evolution of decisions leading to policies is often complex with multiple policy processes taking place in parallel, at different policy levels, involving networks and coalitions with a diversity of interests, with policy development taking different paths over time (Wellstead et al., 2018). Hence the evolution of CDR policies is not a linear process as a placement within the policy cycle might suggest. When applying the assessment framework, it is critical to be aware of such ambiguities in order to avoid simplistic conclusions. The indicators allow structuring complex information, eliciting different perspectives and discussing ambiguities within the larger context of the multiple dimensions. Therefore, we understand the framework to be an approach for structuring complex information, bringing together different expertise, perspectives and knowledge types. This can help elicit and reduce ambiguities and thereby support an iterative science-policy process on the development and implementation of CDR.

Starting with a comprehensive assessment framework and using participatory and iterative processes can help to identify and narrow down the criteria and indicators requiring closer attention in decision making on CDR development and implementation (e.g., indicators associated with hurdles to implementation). Hence the process of conducting such multi-criteria assessment is in itself an important part of generating decision relevant information. For example, it could help to better understand which aspects are of particular relevance for stakeholder groups and how priorities differ. It would also help to elicit the underlying assumptions and information sources the different stakeholder groups use for justifying their evaluation of CDR options and assess their relevance, credibility and legitimacy. This benefit could potentially be lost when aggregating the ranking of indicators into a single index (Barnett et al., 2008; Fridahl et al., 2020).

While working with such a comprehensive assessment framework can be challenging, it can support the identification of expertise and stakeholder perspectives that need to be considered in the feasibility assessment. This helps to elicit the various perspectives of actors who are involved in or impacted by the development and implementation of CDR options, such as experts from academia, engineering and practice, as well as representatives of public and private stakeholder groups. Ensuring inclusiveness also helps build the credibility, relevance and legitimacy of the assessment process and its outcomes for informing decision making on CDR options (Sarkki et al., 2015). As the framework includes indicators on assessing the inclusiveness and transparency of processes (D3) related to CDR development and deployment, these indicators could change and potentially improve over time as a result of a participatory assessment process.

In order to avoid being overwhelmed by the complexity of information involved, the level of detail in the application of the assessment framework can be adapted to particular information needs and data availability, ranging from a coarse scoping of CDR options to more detailed assessments of selected indicators. When applying the framework to pilot projects or other national contexts, the choice of criteria and indicators can be adapted and specified further according to environmental and societal conditions and particular information needs. Depending on the information needed within a specific decision-making context, categories of the framework can be prioritized over others. For instance, some indicators could be set as a minimum requirement, and the full assessment will only be carried out if these indicators have been fulfilled (e.g., only if removal potential is deemed to be high enough). Thereby, the traffic light system can help identify trends in indicators, expected impacts and related trade-offs and synergies with particular relevance for informing decision making. However, further in-depth analysis might be required in order to enhance the accuracy and thereby the credibility of such findings for informing decision making.

Informing decision-making processes is a dynamic process, which requires different levels of detail of information at different points in time. Therefore, defining the information needed and the level of detail of the assessment should be part of an iterative science-policy process. While this can help to reduce complexity and resource needs for conducting the assessment, the framework allows for keeping track of outstanding knowledge gaps for achieving a comprehensive assessment of CDR options. Keeping track of criteria and indicators that might have been overlooked in more technical assessments can also facilitate the inclusion of more diverse stakeholder perspectives within CDR assessments, leading to a broader and more comprehensive debate on the feasibility of CDR options (e.g., stakeholder perspectives on social acceptance). As such, the framework is flexible in its application as a tool for guiding the design of comprehensive assessment processes of CDR options.

However, the assessment framework has its limitations in particular in understanding systemic implications, trade-offs and synergies between the assessed criteria, effects related to the upscaling of potential CDR options, and indirect impacts within and outside the national boundaries (e.g., so-called teleconnections). It is important to note that the assessment outcome does not prescribe conclusions for decision making on CDR policies or implementation. For example, if societal acceptance of a CDR option is low and rated as a hurdle to its implementation, the consequence of this information can include finding ways to increase its acceptance or abandoning its implementation altogether. Such conclusions need to be taken as part of an informed and inclusive decision making process, which the assessment framework can support but not replace. Ambiguities are inherent in feasibility assessments and we hope that the proposed framework can help in making the processes of navigating opportunities and challenges related to CDR options more transparent. Furthermore, the presented assessment framework is not a panacea, decision makers and actors involved in assessing the feasibility of CDR options might prefer different assessment approaches and processes. This has to be taken into account when designing CDR feasibility assessments with outcomes that ought to generate credible, relevant, and legitimate information for decision making (Sarkki et al., 2015).

CONCLUSIONS

Given the tremendous challenges involved in achieving net-zero carbon emissions at a national scale and the uncertainties prevailing in the feasibility of CDR options, it is critical to assess the challenges and opportunities of CDR options with decision-relevant indicators tailored for specific national contexts. We believe that the proposed assessment framework for CDR options can be an appropriate tool to help navigate this process. The process of adapting the assessment framework and discussing evaluations of the traffic light system in a transdisciplinary effort, together with scientific experts and stakeholders, becomes part of a participatory and iterative approach to better understand the effort involved in developing and implementing CDR options that will be required to reach the goal of the Paris Agreement.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SB, MB, JF, KK, TM, NM, RS, AS, TT, and DT conceived of and designed the study and reviewed the assessment framework based on an interdisciplinary expert workshop. SB, MB, JF, EG, KK, TM, NM, RS, AS, TT, and DT developed the dimensions of the assessment framework including criteria, indicators, and traffic light system. JF designed **Table 1** and led the drafting of the article, with contributions from all authors. NM designed **Table 2**. AS and AO edited and revised the text. All authors contributed to the article and approved the submitted version.

FUNDING

The Helmholtz Climate Initiative enabled the development of this publication, which was funded by the Helmholtz Associations Initiative and Networking Fund.

ACKNOWLEDGMENTS

We would like to thank all participants of the expert workshop for contributing to the review and improvement of the assessment framework and Conor Ó. Beoláin for contributing to the design of **Figure 2**. We would also like to thank the two reviewers for the constructive comments and suggestions.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2022.758628/full#supplementary-material

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frontiers | Frontiers in Climate

PERSPECTIVE
published: 18 July 2022
doi: 10.3389/fclim.2022.756013

Making Direct Air Capture Affordable; Technology, Market and Regulatory Approaches

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Direct Air Capture (DAC) is an important solution to curb global warming and enable a circular economy. As fossil fuels dwindle, carbon for commodities such as plastic, cement, steel and liquid fuel, will need to come from somewhere. With the low cost of industrial CO2 (roughly $80 a ton) as well as the low value of most carbon credits, making DAC-produced CO2 competitive at scale is almost impossible. But what if we could scale DAC processes in markets that make sense now, building on learnings as we go while making industries less carbon intensive? The first such application is air quality and energy efficiency in indoor spaces. DAC technology can stabilize CO2 and water levels inside indoor environments to enhance the recirculation rate of internal air, thereby saving significant energy for the HVAC. Another application is the use of small-scale DAC units—providing CO2 at the scale of kilos a day rather than tons, taking advantage of the high CO2 price at that scale as well as B2C markets that otherwise rely on bottled CO2. The approach is called Decentralised DAC or DDAC (analogous to decentralised solar). DAC processes need to be developed but to scale our learnings and drive down costs, we must fund R&D and introduce a significant carbon tax. Finally, interesting new developments such as electro-swing and humidity-swing carbon capture, have the potential to drastically decrease the energy footprint of DAC (its main cost driver), paving the way to making DAC affordable.

Keywords: Direct Air Capture (DAC), HVAC, industrial CO2 emission, climate mitigation, NETs, Decentralised Direct Air Capture (DDAC), Carbon Direct Removal (CDR), Cleantech

OPEN ACCESS

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Specialty section:
This article was submitted to Negative Emission Technologies, a section of the journal Frontiers in Climate

Received: *09 August 2021*
Accepted: *21 June 2022*
Published: *18 July 2022*

Citation:
Beaumont MLL (2022) Making Direct Air Capture Affordable; Technology, Market and Regulatory Approaches. Front. Clim. 4:756013. doi: 10.3389/fclim.2022.756013

INTRODUCTION: DIRECT AIR CAPTURE—THE CASE FOR IT

Almost all IPCC scenarios in which global warming is limited to 1.5°C, require NETs (Negative Emissions Technologies). NETs are needed as we will likely exceed our quota of CO2 emissions as a society no matter what we do. The legacy of our fossil fuel infrastructure means that we will not transition to renewables quickly enough. We will likely still require them in certain sectors such as aviation. Therefore, the only way to stop the build-up of CO2 in our atmosphere from exceeding IPCC limits, will be by directly removing it from the air.

There exist many promising techniques to achieve such a feat on a meaningful, global scale. First and foremost is reforestation. With the number of trees in the world reduced by almost half (to 3.04 trillion) since the advent of modern society, particularly *via* agriculture, there's a lot of scope for replanting them and the carbon sink they in turn could represent (Crowther et al., 2015). Best estimates indicate that 1–2 trillion trees could be replanted. A benefit of reforestation, apart from the sequestration of carbon, is the parallel effect it has on the re-wilding of natural landscapes which in turn provides habitable space for wildlife. Reforestation also battles erosion, desertification and can provide local communities with livelihoods in farming or forest management. Pachama (pachama.com) and Mossy Earth (mossy.earth) are two examples of how reforestation can be inspiring and commercially viable at the same time.

Another natural means to achieving negative emissions includes mineral weathering. An example is seeding agricultural soil with rock powders (such a ground olivine) that go on to naturally absorb CO2 over time. Such passive CO2 sequestration techniques are cost effective, require little to no energy and have minimal side-effects on the local ecosystem. Another example is farming fast growing kelp. The plant absorbs carbon from the ocean at a phenomenal rate. Once the organism reaches a certain size, it is either processed into useful material or sunk to the bottom of the ocean where the carbon remains locked up.

These techniques, while their effect in reducing the amount of CO2 in our atmosphere is real, do nothing for the provision of carbon dioxide as a molecule. As we move away from fossil fuel production and our CO2 supply dwindles, we will still require our carbon from somewhere, especially to produce liquid fuels, plastics and even cement. Other industrial processes such as crop fertilization and beverage carbonation also require it. Both these sectors consume millions of tons of industrial CO2 every year.

Controllable, and potentially quick to implement, unlike natural means, Direct Air Capture (DAC) can supply carbon from the air. The process works in similar way to trees. Carbon dioxide is removed from the air *via* a capture medium (rather than leaves, a solid or liquid "sorbent" is exposed to the air) and once the medium is full, the CO2 is released from it usually *via* the application of heat. In doing so, a clean stream of concentrated atmospheric CO2 is created which can then be sequestered or used (or both). There is an associated cost with the process; mainly the energy required for the heating of the sorbent. Its energy footprint makes it currently the most expensive way to remove CO2 from the air. However, the technology is nascent, and much as solar did, could benefit from technological breakthroughs and economics of scale in the near-term.

THE CHALLENGES TODAY

There are two main techniques used in DAC processes to capture atmospheric CO2: the use of solid sorbents functionalised with amines (a molecular compound widely used in liquid form for Carbon Capture & Storage applications) and the use of liquid chemicals which upon contact with CO2, turn to limestone (Carbon Engineering uses this technique).

Both techniques require an enormous amount of infrastructure to set-up on a meaningful scale. Unfortunately, DAC is a volume game. The more carbon we aim to capture, the more solid or liquid sorbent required to do so, and the more surrounding machinery required to manage the process. In addition, the energy consumed in the process is largely linear to the size of the plant desired. We have not even addressed the post-processing requirements, where if CO2 is to be sequestered, it will need to be injected into storage sites (e.g., old oil wells or saline aquifers) at considerable pressure or if used in industry, may need to be concentrated and cleaned to pass as food-grade.

The challenge is compounded by the fact that industrial CO2 today is extremely low-cost at between $20 and 80 per ton (The Business Research Company, 2021). The sources of industrial CO2 are mainly gas refineries, where CO2 is siphoned off in a nearly pure form from a natural gas stream, or in fertilizer plants, where again, it is emitted in a nearly pure form. So while the carbon from a DAC process could potentially be re-used (e.g., in the production of cement), and therefore possess added value beyond that of simply sequestering it, there exists steep competition.

There is also no well-regulated, standardized price for a carbon credit. After failing in the early 2000s cap & trade markets never fully recovered. There are at least local regulations in place now, namely the 45Q Tax Credit implemented in California, or the EU's cap and trade program, but there's no standard price of a carbon credit to be relied upon wherever you might find yourself in the world. Implementing consistent carbon pricing across regions and nations will be critical to promoting the widespread adoption of NETs. Governments need to do more here.

NEW MATERIALS AND SMART BUSINESS CASES

While there is scope for existing DAC methods, if scaled correctly and complemented with consistent and high enough carbon pricing, to be commercially and technically viable at a globally meaningful scale, it would make it far easier if higher-performing CO2-capture materials were to be developed. The main parameter to improve is the ratio of CO2 captured per unit weight of capture medium over time. Such an improvement would not only reduce the volume and weight of material required to capture the same amount of CO2, but also the energy penalty incurred in the process (the less underlying capture medium to heat up to release the carbon dioxide molecules, the less energy required for regeneration). However, if the energy cost for regeneration could also be reduced, for example by engineering the bonding between the CO2 and the capture medium to be weaker or using a means to release CO2 other than heat or vacuum (e.g., humidity-swing, currently being explored at ASU by Prof. Klaus Lackner, or electro-swing currently being developed at Verdox), then all the better.

The development of marketplaces in which individuals and companies can permanently offset their carbon footprint will itself benefit the DAC sector, and they need to be regulated and supported by governments. It should be expected that as the DAC process becomes less costly, more and more entities will be tempted to fund the sequestration of their carbon emissions.

Abbreviations: NETs, Negative Emissions Technologies; DAC, Direct Air Capture; DDAC, Decentralised Direct Air Capture; CCS, Carbon Capture and Storage; DoE, US Department of Energy; HVAC, Heating Ventilation & Air Conditioning.

ADVANCED FILTRATION IN BUILDINGS

Removing CO2 from a building environment or "advanced filtration" as it has been coined by the Department of Energy (DoE), was recently included in the top ten of over forty technologies assessed to have the highest potential in improving building energy efficiency (Goetzler et al., 2017). By stabilizing CO2 as well as humidity levels inside a building, a higher indoor air recirculation rate can be enabled, thereby limiting the in-take of fresh air and the load on the HVAC system. The energy gains of doing so can be huge, especially in climates where the outdoor temperature is quite hot or cold. Recent pilots by enVerid show 20–40% reductions in building energy consumption and recent studies corroborate their findings (Baus and Nehr, 2022). The technology is currently being applied to large commercial buildings such as offices and hotels, where operating costs are closely monitored. It is also easier to apply the technology to these buildings, as opposed to private homes, due to advanced HVAC infrastructure already in place.

The benefit of pursuing a business case here for DAC, is that it's an easier sell. The product is not the carbon itself (a rather inexpensive commodity), but instead energy efficiency and air quality. People understand those things, people do not, on the whole, understand carbon capture. With HVAC sales exploding in developing countries, the case for advanced filtration and energy efficiency solutions becomes ever more urgent. According to a recent UN report, improving the energy efficiency of HVACs and reducing the use of HFCs, could lead to a reduction of 0.4°C in global warming by 2100 compared to the status quo (Millen and Logan, 2020).

Linking DAC units in buildings to local demand for CO2 will close the loop fully. For example, captured CO2 could be converted into fuel on the roof of a building to be used as a back-up energy source for the renewable grid, or it could be used to promote crop growth at a local vertical farm.

A CARBON PRICE

Setting a price on carbon emissions, not only those created at source, but the carbon footprint generated in corporate supply chains or in running commercial property, will be crucial to stemming the amount of carbon going into the air. Just as we place a tax on cigarettes (which levy a huge cost on national healthcare systems), we need to start doing the same for carbon emissions, which take a huge toll on our environment, and ultimately lead to reduced GDP growth due to the economic damage cause by extreme weather events.

Standardizing such a carbon tax on a national level is hard enough, let alone internationally. However, once the cost of offsetting carbon becomes less than paying the tax, massive markets will be created. To make DAC viable at scale, a carbon tax of over >$200 per ton needs to be levied. Combined with the value of the captured CO2, the cost of the capture process then becomes less than the revenue earned, and the operation becomes profitable.

SKYTREE'S LESSONS LEARNED

One of the key drivers of the energy required in atmospheric carbon-capture processes (as well as traditional CCS processes), is the heating of the capture medium (McQueen et al., 2021b). In traditional approaches to DAC, a solid sorbent requires exposure to air to capture CO2, and subsequent heating combined potentially with exposure to vacuum, to release it again. Roughly 80% of the energy used in the process goes to thermal heat applied to the capture medium, while the remaining 20% to electricity to power the fans, vacuum pumps, compressors as well as other equipment (McQueen et al., 2021a). It follows that the more CO2 required from a DAC system, the more capture medium needs to be deployed and in turn, the more energy is required to heat it and subsequently concentrate the CO2 released from that process.

The holy grail will be to find a capture medium with the ability to adsorb much more CO2 relative to its weight, allowing for less material to be used for the same amount of carbon captured. Doing so will reduce the energy required to drive the heating and concentration process, as there will be less material to heat, and less volume around which to create a vacuum. Some materials have the potential to do this (eg. Metal Organic Frameworks otherwise known as MOFs) but are relatively expensive and not yet reliably produced at scale.

Another approach would be the ability to apply thermal energy directly to the capture sites, without having to heat up their structural support. The approach is being investigated by Verdox (www.verdox.com), which is using a electro-swing adsorption process to capture CO2 from the air. The energy provided in the process is delivered through a redox reaction and has the potential to reduce the energy footprint of the regeneration process by 80% (Voskian and Hatton, 2019).

One of the best ways to reduce the cost of a process is to simplify it. We've already discussed how a significant amount of energy is required to concentrate CO2. We also see huge energy demand in compressing it so that it can be stored for later use in industrial processes or pumped underground for long-term sequestration. The former almost always requires the creation of a vacuum (energy intensive), the latter the use of a high-power pump and pressure vessels (again, energy intensive and expensive).

At Skytree, we've seen that for certain small-scale applications, there is no need to compress CO2 or even supply it at high concentration. For example, in fertilizing crops in vertical farms, the concentration of CO2 in the air only needs to be increased by 2–3 fold. Such a "CO2 enrichment" process forgoes the need to concentrate and compress the CO2, allowing the hardware to be less costly and the process less energy intensive.

We've also seen that at smaller volumes, the relative price of industrial CO2 increases exponentially due to the higher infrastructure costs relative the value of the gas itself. These infrastructure costs include replacement gas cylinders or cryogenic storage systems. At a volume of a few kilos a day, DAC can be competitive to current commercial sources of CO2 without any need for subsidies or carbon credits. In fact, it will make for a more convenient supply of CO2 for customers located in areas without nearby sources of CO2 such as the

Middle-East or most of Africa. We've coined the approach as Decentralised-DAC (DDAC).

Applying DDAC to indoor air purification removes the needs of the second step of the process as well. Removing the need to concentrate or compress the CO2, by venting it instead, simplifies the hardware, reduces costs, and reduces the energy requirement of the system. On top of that, the performance of the system improves when applying DDAC to indoor air purification as the sorbent beds are exposed to much higher concentrations of CO2 (1,500–3,000 ppm) found indoors compared to those found outdoors (400 ppm), allowing the system again, to be smaller and more energy efficient.

To be meaningful on an industrial scale, most DAC plants will have to be huge (think an apartment block or larger). Such a requirement means high initial investments and extended lead times as well as return on investment. Applying DAC technology to small-scale CO2-supply or indoor air purification entails that the DDAC modules can be much smaller (think refrigerator-size), allowing them to be deployed at a fraction of the cost and to start paying for themselves right away. Such an approach will allow for a more rapid and organic rollout of DAC technology, potentially creating a far greater reduction in carbon footprint sooner than a more traditional approach would allow. Technical learnings in the process of doing so could then be applied to larger-scale DAC plants.

DISCUSSION

A number of initiatives have been kicked off to accelerate the development of DAC. Biden's infrastructure bill earmarks ten billion dollars for carbon removal technology, the European Green Deal supports it as does Elon Musk's $100M X-prize and finally VCs are pouring $100M's into DAC start-ups. All are important to accelerating R&D efforts around the technology. But just as we taxed cigarettes and alcohol due the immense burden they placed on our healthcare systems, carbon emissions should also be taxed. The emission of CO2 causes immense negative externalities in the form environmental destruction (much like CFCs did or air pollution and plastic production are doing today) which are not costed into the price of the carbon-emitting goods and services we consume.

Minimum government intervention is a useful free-market philosophy, but in the case of DAC and other tools we need to fight the climate emergency, we need to be more pro-active. The biggest and most effective driver of change will be a carbon tax. The massive effect it could have on reducing our emissions is reflected in the En-ROADS model developed at MIT (en/roads.climateinteractive.org/) and strongly supported by Bill Gates in his book "How to Avoid a Climate Disaster" published in 2021. Just as certain economic structures (i.e., the free market) can propel massive growth, a carbon tax will level-up our efforts to fight climate change. Large-scale DAC can be viable once a carbon tax of at least $200/ton is established.

Developing commercially viable routes to market is an approach that can be taken until then. For example, there may be quicker, more effective ways of deploying DAC technology in small-scale CO2-supply or indoor air purification applications otherwise known as DDAC. And a key breakthrough for the DAC sector will be the discovery of a capture medium with a much higher CO2-capture capacity with respect to weight ratio, and one with a minimal energy footprint. Promising methods such as humidity and electro-swing adsorption could completely decouple the volume of CO2 captured from the amount of energy and space required by a DAC plant. With significantly increased government funding, and the eventual introduction of a high carbon tax, DAC will become affordable and common place.

DAC is just one of many tools at our disposal to fight climate change—others include CCS, reforestation, sustainable agriculture, meat substitutes, wind & solar, electrification, circular materials, synthetic fuels and nuclear energy, to name a few. Many of these represent more bang for our buck compared to DAC and should be pursued in parallel. But DAC is unique in its ability to draw down CO2 and reuse it—both processes that will become ever more important as the climate emergency heightens and we move towards a circular economy.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

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

FUNDING

Stripe has agreed to fund the first 30 publications contributed to the topic Scaling-Up Negative Emissions: The Power of Leveraging Policy, Philanthropy, Purchasing and Investment, which applies to this perspective piece as well. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

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Conflict of Interest: MB is employed by Skytree.

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