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Climate policy for a net-zero future: ten recommendations for Direct Air Capture

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Abstract

Direct Air Capture with Carbon Storage (DACCS) technologies represent one of the most significant potential tools for tackling climate change by making net-zero and net-negative emissions achievable, as deemed necessary in reports from the Intergovernmental Panel on Climate Change and the European Green Deal. We draw from a novel and original dataset of expert interviews ($N = 125$) to distil ten recommendations for future DACCS policy. After providing a literature review on DACCS and explaining our methods of data collection, we present these recommendations as follows: (a) follow governance principles that ensure 'negative' emissions; (b) prioritize long-term carbon storage; (c) appreciate and incentivize scale; (d) co-develop with capture, transport, and storage; (e) phase in a carbon price; (f) couple with renewables; (g) harness hub deployment; (h) maintain separate targets; (i) embrace certification and compliance; and (j) recognize social acceptance. All ten recommendations are important, and all speak to the urgency and necessity of better managing and shaping the potentially impending DACCS transition.

1. Introduction

Direct Air Capture with Carbon Storage (DACCS) seeks to reverse the fundamental causes of climate change and repair the climatic damage humanity has undertaken over the previous centuries. DACCS facilities can capture carbon dioxide by collecting it directly from the ambient air, then storing it in reservoirs or putting that carbon to use in other industrial processes (EASAC 2018). While still in their infancy, DACCS facilities are expected to play an increasingly large and possibly highly significant role in our energy systems and climate change mitigation efforts of the future. National Academies of Sciences, Engineering, and Medicine (2019, p 8) identified DACCS as one of the few realistic technical options that 'could be scaled up to remove very large amounts of carbon.' McCormick (2022, p 1) adds that DACCS 'is a key climate technology with the potential to make major contributions to stabilizing atmospheric CO_2 levels.' Fasihi *et al* (2019) project that if DACCS systems are commercialized in the 2020s, they could see 'massive implementation' by the 2040s and 2050s, when they could be of a magnitude equal to existing sources of climate change mitigation such as wind energy or solar energy. McQueen *et al* (2021) anticipate major improvements in innovation and learning that could see the projected levelized costs of deploying DACCS drop by almost a factor of five as cumulative capacity grows. Such learning could foreseeably include the development of new approaches and materials, such as those being developed by a Massachusetts Institute of Technology spinoff, which could lower energy costs of DACCS by 70% by employing a novel plastic material (Rathi 2022). There are, however, important costs to this technology. Hanna *et al* (2021) speculate that, by the end of the century, global DACCS systems could, at the upper range, be responsible for

14% of global electricity use and up to 83% of global gas use.

In this article, we draw from a novel and original dataset of expert interviews ($N = 125$) to distil ten recommendations for future DACCS policy. After providing a technical literature review on DACCS and explaining our methods of data collection, we present these recommendations as follows: (a) follow governance principles that ensure 'negative' emissions; (b) prioritize long-term carbon storage; (c) appreciate and incentivize scale; (d) co-develop with capture, transport, and storage; (e) phase in a carbon price; (f) couple with renewables; (g) harness hub deployment; (h) maintain separate targets; (i) embrace certification and compliance; and (j) recognize social acceptance. All ten recommendations are important, and all speak to the urgency and necessity of better managing and shaping the potentially impending DACCS transition.

2. Brief background and literature review

The more time that passes without major reductions in carbon emissions, the more climate models and projected scenarios suggest that at some point in the 21st century, it will be necessary to actively remove carbon dioxide from the atmosphere to avoid dangerous warming (e.g. Minx *et al* 2018, Fuss *et al* 2016, Fuhrman *et al* 2019, 2021, Rickels *et al* 2019). Some analyses of the Nationally Determined Contributions underpinning the Paris Agreement (which is itself insufficient for keeping global average temperature rise within safe levels) argue that negative emissions technologies may be needed to close a gap between pledges and actual emissions cuts (Anderson and Peters 2016, Larkin *et al* 2018, Stler *et al* 2021). The most recent Intergovernmental Panel on Climate Change (IPCC) (Babiker *et al* 2022) report concludes that 'carbon dioxide removal (CDR) is a necessary element to achieve net zero CO_2 and greenhouse gas emissions both globally and nationally, counterbalancing residual emissions from hard-to-transition sectors' and that 'it is a key element in scenarios likely to limit warming to 2 °C or lower by 2100.' Figure 1 presents IPCC data underscoring these findings.

While there are some negative emissions schemes in operation today, ranging from tree-planting and coastal ecosystem restoration to first-generation direct air capture plants (Matter *et al* 2016, Kelleway *et al* 2017, Bertram *et al* 2021, Budinis 2021, Burke *et al* 2021, UNESCO 2021), none are currently deployed at the scale needed to reliably remove multiple gigatons that will likely be required to mitigate climate change (Fuss *et al* 2018, Budinis 2021). And many of the options currently on the table face significant constraints, or conflict with other environmental, social, or economic goals. Some technologies, such as large-scale afforestation, or bioenergy with carbon capture and storage (BECCS), conflict with land use for agriculture and therefore the food supply (Fuss *et al* 2018). Others, such as biochar, depend critically on uncertain side-benefits for their economic and social viability (Maroušek *et al* 2017). Still others, such as enhanced weathering, would require mining, processing, and distributing enormous amounts of material (Stler *et al* 2018).

2.1. The technical basis for direct air capture

With these limitations in mind, direct air capture has an obvious appeal (Lackner *et al* 1999). Such a system could, in principle, be installed almost anywhere, would require relatively little land (less than 0.001 ha per ton of carbon per year compared to 0.1–1.7 ha for BECCS plants, depending on the fuel stock) and, according to its advocates, would have only relatively small environmental side-effects, all while producing a verifiable, high-purity stream of carbon dioxide that can be permanently sequestered using existing carbon storage technology (Smith *et al* 2016, Erans *et al* 2022, McCormick 2022). Fuss *et al* (2018) add that DACCS could even be deployed proximate to storage facilities, and it could be co-located with attractive sites for renewable energy, thus minimizing transport and grid costs.

As the carbon capture and storage (CCS) at the end of DACCS implies, direct air capture is coupled closely with carbon capture and storage. Technology needs to be able to capture carbon dioxide (either pre-combustion or post-combustion). It needs to be able to transport it, or in some situations, put pure carbon to use (for food and beverages production, enhanced oil recovery, or other industrial applications). And it needs to be able to safely store or sequester it, most likely in underground salt caverns or aquifers or depleted oil and gas fields.

The total sequestration potential of these systems can be quantified by reference to annual sequestration, or by reference to total cumulative sequestration potential available The gross total emissions that can be stored underground, whether using sedimentary basins or alkaline rocks and mineralization, is well above the total levels of atmospheric carbon that humans have emitted since the industrial revolution (Godin *et al* 2021). There are, however, separate limits on the rate at which carbon can be sequestered in this way, which could be up to 5 Gt of carbon dioxide per year by 2050, with higher potentials possible if currently assumed constraints are proven to be overly cautious (Smith *et al* 2016, Fuss *et al* 2018, Godin *et al* 2021). Used in conjunction with renewable (but relatively intermittent) energy sources, direct air capture sites may be an efficient way to use otherwise curtailed electricity production, ramping up when energy demand is saturated and energy storage is full. To benefit from these advantages, however, direct air capture technology will have to overcome significant challenges with technological readiness, high energy demand, high financial costs, and social acceptance

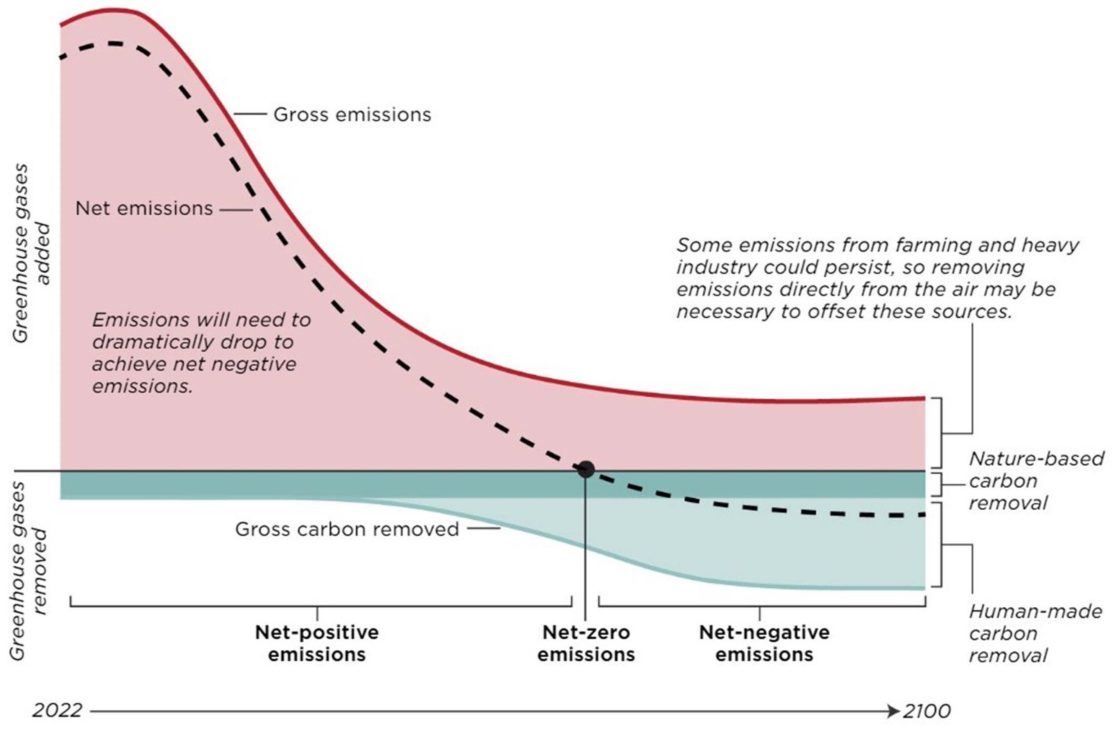

Figure 1. Stylized pathways for greenhouse gas emissions and carbon removal from 2022 to 2100. Source: IPCC *et al* (2022).

(Fasihi *et al* 2019, Budinis 2021, Deutz and Bardow 2021, Erans *et al* 2022).

The first step of the direct air capture process is to intake large amounts of air and put it in contact with a chemical reagent that will remove the carbon dioxide (see figure 2). Appropriate reagents already exist to extract carbon from point-source exhaust gasses in carbon capture and storage systems. Flue gasses—those gases exiting into the atmosphere from power plants and other large industrial point-sources—typically have a carbon dioxide content between 3 and 20%, depending on fuel source and plant design (Packer 2009, Didas *et al* 2015), while ambient air has a concentration of 410 parts per million, or 0.04% (IPCC 2021). This means that a much larger volume of air must be processed, which in turn requires either a very large facility or very large and energy-intensive fans (Kazemifar 2022).

The next step is the chemical process that removes carbon dioxide from the reagent, concentrates it, and recycles the reagent to be used again. For this, there are two kinds of systems: an alkaline aqueous solution or a porous solid-based sorbent (Liu *et al* 2021). The former typically uses a process called a calcium loop, which reacts calcium with carbon dioxide to form $CaCO_3$, then converts this into CaO to separate out the carbon dioxide. The advantage of this approach is that it is relatively simple. The downside, however, is that regenerating the calcium requires process heat of around 900 °C—meaning that most systems of this type will have to burn natural gas, reducing the net carbon capture of the facility, and are forced to recover as much of the released heat as possible to increase efficiency (Realff *et al* 2021). Furthermore, chemical damages and loss of solvent and sorbent over time are currently still problems for such systems (Ozkan *et al* 2022). The Canadian company Carbon Engineering has already built a functioning pilot plant using a calcium loop, using mostly off-the-shelf or slightly modified industrial technologies (Keith *et al* 2018).

A solid sorbent system is an alternative to the liquid solvent approach, which functions by channeling the air through a reactive microporous solid adsorbent. A chemical process is then used to remove this built-up carbon compound, and the sorbent is recycled. Solid sorbents require process heat of only around 150 °C to regenerate and can therefore use a much wider variety of heat sources, including geothermal heat or waste heat from power plants and industrial facilities, leading to higher net carbon removal than with an alkaline aqueous solution system (Gutknecht *et al* 2018, Madhu *et al* 2021). Sorbent-based systems, however, have additional complexity compared to liquid solvent systems (Keith *et al* 2018). Furthermore, a great number of different adsorbents and their composites can be used in principle, but their adsorption capacities vary greatly under different conditions (Lai *et al* 2021, Liu *et al* 2022). Even more, while solid sorbents are constantly improved, they still usually face at least one of three issues: low capture capacity, high capital costs,

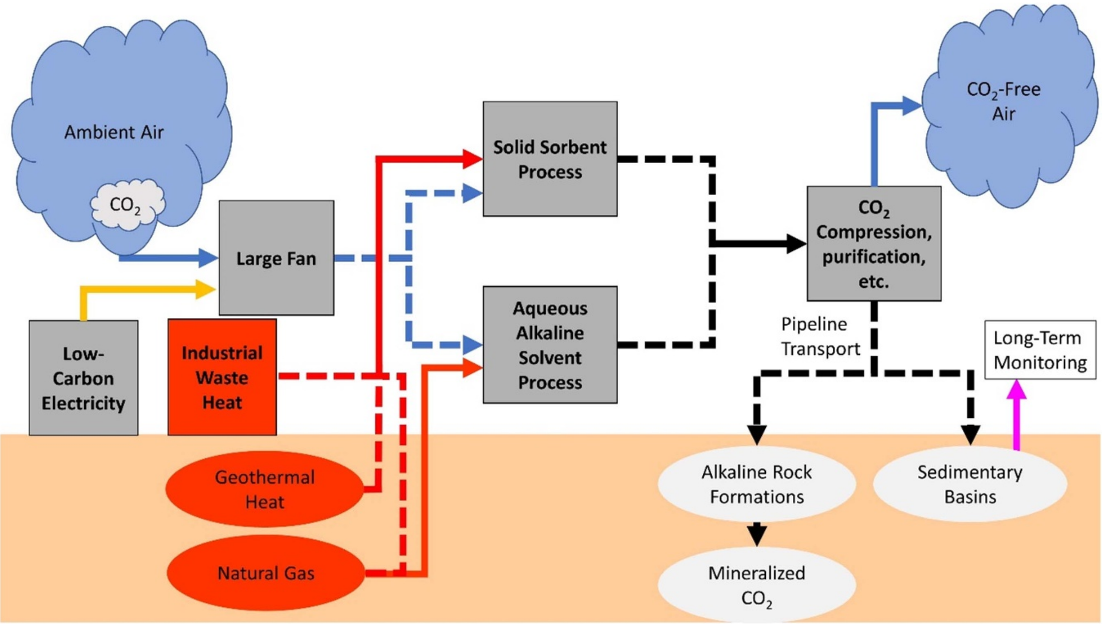

Figure 2. A graphical depiction of Direct Air Capture technologies.
Source: Authors. Note that dotted lines represent alternative rather than parallel options.

Figure 3. The Climeworks 4000 tons yr^{-1} demonstration DACCS project in Iceland.
Source: Authors, during a site visit to ON Power's Hellisheiði Geothermal Power Plant in September 2021.

or high regeneration costs (Ozkan *et al* 2022). There are several companies currently using this process to develop direct air capture technology, including Global Thermostat, Skytree, and Climeworks. The latter of these currently has a plant in Iceland capable of capturing 4000 tons of carbon dioxide per year (see figure 3 and table 1).

Researchers have also investigated completely different, electrochemical approaches, such as a pH swing for carbon dioxide capture. However, such technologies are still in earlier stages of development and have not yet been commercialized. They will therefore require major technological breakthroughs to catch up with alkaline aqueous solution and solid

Table 1. Status of key and upcoming Direct Air Capture technology providers (as of early 2022).

Provider	Project	Location	Start	Technology	Status	Notes
Carbon Engineering[6]		Canada	2015	Aqueous alkaline solution	1 ton CO_2 d^{-1} demonstration plant	
		Canada	2017		1 ton CO_2 d^{-1} demonstration plant	Expansion of the initial pilot plant with new modules for pilot demonstration of synthesizing captured CO_2 into fuels, up to ∼1 barrel fuel d^{-1}
		USA			Design and engineering phase for 1 million tons CO_2 yr^{-1} commercial plant	Currently planning with partner in the USA to start construction in 2022 with no known date of planned start of operation
		Canada	2026+		Feasibility study for 100 million liters fuel yr^{-1} plant	If feasibility is given, construction is supposed to begin in 2023, operation roughly three years later
		Norway			Design phase for DACCS plant removing 0.5–1 million tons CO_2 yr^{-1}	Cooperation with partners in Norway and start of design phase announced end of 2021, no further info yet
	Dreamcatcher	UK	2026		Preliminary Design and engineering phase for DACCS plant removing 0.5–1 million tons CO_2 yr^{-1}	
	AtmosFUEL	UK	2030		Feasibility study for 100 million liters aviation fuel yr^{-1} plant	Start of operation planned for end of current decade.
Climeworks[7]	Capricorn	Switzerland	2017	Solid sorbent	Commercial operation at up to 900 tons CO_2 yr^{-1}	Captured CO_2 is fed into nearby greenhouse. Regeneration at around 100 °C, waste heat used for regeneration, modular approach
	Arctic Fox	Iceland	2017		Proof of technology at up to 50 tons CO_2 yr^{-1}	Proof-of-technology DACCS pilot in cooperation with Carbfix. Regeneration at 80 °C–100 °C, geothermal heat used for regeneration.
	STORE&GO	Italy	2018		Proof of technology at up to 150 tons CO_2 yr^{-1}	Research plant for power-to-gas proof of technology, running for 15 months. Project has ended.
	Kopernikus P2X	Germany	2019		Proof of technology at up to 10 l fuel d^{-1}	Single module used for the first step, i.e. CO_2 source, of power-to-liquid research. Regeneration at 80 °C–100 °C
	NECOC	Germany	2020		Proof of technology for DAC to carbon black plant	
	Orca	Iceland	2021		Commercial operation at up to 4000 tons CO_2 yr^{-1}	DACCS plant in cooperation with Carbfix. Regeneration at 80 °C–100 °C, geothermal heat used for regeneration, modular approach.

(Continued.)

Table 1. (Continued.)

Provider	Project	Location	Start	Technology	Status	Notes
	Zenid	Netherlands			Preliminary design and engineering phase for 1000 l aviation fuel d^{-1} plant	Based on 2019 feasibility study, a proof-of-technology plant is planned. Current phase announced in 2021, no further update since.
		Norway	2024		Design and engineering phase for 12.5 million liters aviation fuel yr^{-1} plant	Part of the Norsk e-Fuel consortium. Construction start is planned for 2023, increase of production by 2026 to 25 million liters.
Global Thermostat[8]		USA	2010	Solid sorbent	Proof of technology	
		USA	2021		Design and engineering phase for 100 000 tons CO_2 yr^{-1} DAC system	Developed by Black & Veach with global Thermostat DAC technology, to be used in Texas, Alabama and Illinois. No date for start of construction or carbon capture.
	Haro Oni	Chile	2022		Construction phase of Power-to-liquid demonstration plant, capturing up to 2000 tons CO_2 yr^{-1}.	Demonstration plant by Highly Innovative Fuels for planned 230 kt CO_2 yr^{-1} Power-to-Liquid plant, planned to be operational in 2025
Carbominer[9]		Ukraine			Prototyping	Small modules for greenhouses advertised. No information on actual state of development or technology used, but looking for partners for pilot testing
Carbon Collect[10]	Mechanical Tree	USA	2022	Ion-exchange sorbent, moisture swing	Prototyping	Passive approach where wind instead of fans is used to transport CO^2 onto sorbent, moisture swing to release it. First prototype operation planned for 2022
Csiro[11]	Airthena	Australia	2020	Metal organic framework	CO_2 generator prototype capturing up to 2 tons CO_2 yr^{-1}	Modules for localized carbon capture and utilization, field trials planned
Hydrocell[12]	Soletair	Finland	2017	Solid sorbent	Demoed as part of a 200 l power-to-liquid research project	
Infinitree[13]				Ion-exchange sorbent, moisture swing	Concept	Passive approach, intended for greenhouses.
Noya[14]		USA	2021	‘blend of clean CO_2 capture chemicals’ in retrofitted cooling tower water	First commercial site retrofitted	Utilizes existing cooling tower infrastructure where fans draw ambient air through cooling water, allowing ambient CO_2 to react with the ‘capture chemicals’, 95% purity

(Continued.)

Table 1. (Continued.)

Provider	Project	Location	Start	Technology	Status	Notes
Prometheus Fuels[15]	Titan Fuel Forge	USA		Ethanol synthesis via carbonic acid	Prototype construction for 900 tons CO_2 yr^{-1}	The 'Titan Fuel Forge' is intended to be a modular system capturing CO_2 and directly synthesizing it into alcohol, then fuels. Synthesizer prototypes already exist, the 'carbon salvage tower' prototype is currently in construction
Skytree[16]	ERSA		2021	Solid sorbent, air scrubber	Prototyping	Air scrubber for improved air quality, including carbon removal, in cars based on ESA technology, implemented into a test car in 2021. Plans to apply technology to CCU in the future.
Soletair Power[17]		Dubai	2021	Solid sorbent	Power-to-*X* demonstration	Smaller office air scrubbers are already commercially sold. Outdoor Power-to-*X* and indoor office HVAC air scrubbers planned.
		Germany	2021		Commercial operation at up to 21 kg CO_2 d^{-1}	DAC unit running 12 h per day, creating 98% pure CO_2. Modular design. Provided to Hydrogen and Fuel Cell Center ZBT. Based on Hydrocell's design.
Verdox[18]		Norway		Electrochemical absorption in electrode stack	Design and engineering phase for flue gas	Technology is meant to work with flue and ambient gas, currently focused on aluminum smelter exhaust, planning for industrial scale by 2030. No thermal energy needed.

[6] carbonengineering.com.
[7] climeworks.com.
[8] globalthermostat.com.
[9] carbominer.com.
[10] mechanicaltrees.com.
[11] csiro.au.
[12] hydrocell.fi.
[13] infinitreellc.com.
[14] noya.co.
[15] prometheusfuels.com.
[16] skytree.eu.
[17] soletairpower.fi.
[18] verdox.com.
Source: Compiled by authors.

sorbent systems, which are in use already and will likely be scaled up in coming years (Sharifian *et al* 2021).

The final step is to transport the captured carbon to a site where it can be securely stored for the long-term. Primarily discussed and tested options for this are deep geological storage of the gas at high pressure in sedimentary basins, and mineralization in mafic rock formations, rich in alkaline earth metals (Bickle 2009, Cuéllar-Franca and Azapagic 2015). The former can lock the carbon dioxide in saline aquifers or cavities under a relatively impermeable cap rock, much like how oil and natural gas are trapped in underground reservoirs. Depending on the specific site and rock properties, the carbon dioxide may also be fixated through capillary trapping in porous rock formations and solubility trapping in brine (Bickle 2009, Cuéllar-Franca and Azapagic 2015). Indeed, spent oil and gas fields are already used for this kind of carbon capture and storage, and the injected carbon can be used to increase the recovery factor of these fields ('enhanced oil recovery') (Godin *et al* 2021). Such enhanced oil recovery could even become net zero if oil is only extracted at a rate equivalent to the amount of carbon that is being removed from the air.

While these storage options are promising on long time scales, there are risks to this kind of sequestration. If the cap rock fails, the gas could leak—possibly at a rate that would be dangerous to anyone or anything on the surface—and aquifers may transport brines and carbon dioxide to the surface, necessitating monitoring and thorough hydrogeological assessments (Bickle 2009, Godin *et al* 2021). There are also risks of seismic effects (Kazemifar 2022), not to mention questions around how this might affect social acceptance for these projects (Cox *et al* 2020, Jobin and Siegrist 2020, Wenger *et al* 2021, Sovacool *et al* 2022).

The alternative to this is to inject the gas into mafic rocks, such as basalt or peridotite, causing a chemical reaction between the carbon dioxide and the silicate minerals in the rock, mineralizing the carbon. This reduces the risk of leakage and has already been applied in Iceland at the CarbFix project, with promising initial results (Gutknecht *et al* 2018). However, overall, this remains an unproven technology, with many uncertainties and risks. It is possible, for example, that there are limits on how quickly the carbon dioxide can be injected while the mineralization reaction occurs, though research in this area remains inconclusive (Sanchez-Roa *et al* 2021, Cartier 2022).

Regardless of the method of sequestration, there is ample potential worldwide for underground carbon sequestration. In either sedimentary basins or alkaline rocks, it would be (theoretically) possible to store more carbon dioxide than humanity has emitted over its entire history (Snæbjörnsdóttir *et al* 2020, Godin *et al* 2021, Kazemifar 2022).

Another option for direct air capture would be to utilize the carbon, rather than injecting it. Carbon dioxide can be used to rapidly grow algae or greenhouse plants, it can be incorporated into cement, or it can be used to produce liquid fuels from the air, which could make these fuels effectively zero net carbon (Godin *et al* 2021).

In most cases, captured carbon dioxide will have to be transported by pipeline from the capture to the sequestration site, adding additional costs both for pipeline construction, and also for purifying and pressurizing the carbon stream for transportation. Carbon dioxide pipelines already exist across much of North America, where they are used for enhanced oil recovery projects, but significantly more would have to be built to enable widespread use of direct air capture (Gür 2022, Kazemifar 2022).

2.2. Challenges and projections of affordability

Direct air capture systems face two important challenges. The first of these—and for many potentially interested parties the primary concern (Erans *et al* 2022)—is money. Cost estimates for direct air capture are contested in the literature, ranging from $30 per ton CO_2 captured to $600 at the high end, with most estimates falling in the multiple hundreds (de Richter *et al* 2013, Godin *et al* 2021, Gür 2022). This is in addition to sequestration and transportation costs. Under optimistic assumptions, if the direct air capture follows the cost reduction trajectories of comparable technologies such as solar power, there would be significant economies of scale and possibly innovations which could bring prices down and make direct air capture economically viable (Lackner and Azarabadi 2021, McQueen *et al* 2021). Lackner and Azarabadi (2021) argue for this comparison since direct air capture would, like solar power, be scaled up through the increasing production of small-scale modules and efficiency improvements instead of increasing size, as is the case with larger power plants. However, for such a buy-down to happen, a significant financial entry barrier beyond initial profitability needs to be overcome to start this process.

It is not clear where the money to sequester gigatons of carbon dioxide could come from under the current global economic structure. One approach may be to incentivize carbon capture and storage as part of a carbon tax or emission trading system, where negative emissions are credited, as suggested by Stavins (2008). Others propose to expand or replace current carbon pricing schemes with a carbon removal or takeback obligation. Bednar *et al* (2021) describe a system where carbon tax revenues are partially retained and invested to finance carbon removal at a later point in time, which may foster earlier and less aggressive deployment of carbon removal than scenarios without such obligations. Jenkins *et al* (2021a) envision industrial obligations to remove emitted carbon. Since the inherent price of carbon is not set through policies but dependent on the availability and cost of removal technologies, such a scheme may foster investments into increasing efficiency and reducing costs of carbon removal. We will indeed return to this debate about pricing in section 4 when presenting our ten principles for DACCS policy.

The second major challenge is the energy requirements of the technology (Madhu *et al* 2021). Sequestering gigatons of carbon dioxide using direct air capture will require enormous amounts of power, some of which may have to come from fossil fuels. Energy demands can reduce the carbon capture efficiency of direct air capture projects, put pressure on efforts to decarbonize the electricity supply, and also put constraints on the location of direct air capture plants. The list of places in the world that are in close proximity to both good sources of renewable energy and to suitable injection sites is much smaller than the list of places in the world that have access to carbon sequestration sites alone.

McCormick (2022) adds that drawbacks include the concern that DACCS cannot reach large-scale deployment without a profitable business model, in which the cost of building and operating DACCS facilities is offset by revenue from one or more sources. This is particularly challenging for DACCS because it does not produce a product or service that has any economic value in absence of government intervention, such as through carbon pricing schemes (Stavins 2008). This sets it apart from some other negative emissions technologies, such as Biochar and BECCS. Fuss *et al* (2018) note four challenges including capital investment costs, energy costs for capture, energy costs for regeneration, and costs related to sorbent loss and expensive maintenance.

3. Research design: qualitative expert interviews

The literature on direct air capture thus shows that the process works in principle, but that there are serious unanswered questions about the technical and economic realities of what a gigaton-scale direct air capture system might look like. If DACCS is intended to become a serious option for carbon removal and climate change mitigation, policies must address these issues, support research and development, and incentivize investments, e.g. through carbon credits or other measures to include negative emissions effectively in carbon pricing mechanisms. Aggressive policy measures will moreover be necessary to help it overcome its financial and technical hurdles.

Despite the recent growth in pilot and demonstration DACCS projects around the world (see table 3 above), policy mechanisms supporting DACCS remain nascent at best. In the United States, the Energy Act of 2020 offered $800 million in funding for programs looking at carbon storage and an additional $280 million for carbon utilization, but the Department of Energy had not yet (as of early 2022) established its proposed Carbon Removal Program nor formed its Carbon Dioxide Removal Taskforce. The United Kingdom considers DACCS in its roadmap to net zero but makes no specific commitments. The European Union indicated possible interest in advancing a framework for carbon removal certification in its Circular Economy Action Plan, but nothing more substantial. Meckling and Biber (2021) suggest that meaningful policy sequencing for DACCS would extend far beyond these nascent efforts and would need to include more active support that cultivates niche markets, offers strong incentives, and steers regulation though mandates. McCormick (2022, p 2) also cautions that 'the technological promise of DACCS will be largely irrelevant to the climate crisis' if proper policies cannot answer the question of 'who will pay for it,' and notes that policy is 'tremendously important' and 'needed to enable DACCS to scale.'

It is with these gaps in mind that we conducted a large expert interview exercise where we explicitly asked a pool of international experts several questions about DACCS scaling, innovation dynamics, policy, and governance dynamics. Justification for such an interview approach is grounded in two sets of literatures. First, expert interviews are widely used within the social sciences, arts, and humanities fields (AbdulRafiu 2022) and have been extensively documented as a critical methodology within the energy studies, justice and climate policy fields as well (Itayi *et al* 2021, Jenkins *et al* 2021b). Second, such interviews have been used as an original method for multiple studies published in *Environmental Research Letters*, with recent examples including research on forestry (Ceddia *et al* 2022), new smart home technologies (Sovacool *et al* 2021), and climate adaptation (Sietsma *et al* 2021)—all areas similar in many respects to DACCS technologies.

3.1. Data collection and sampling

Our recruitment and sampling of experts for this paper has been deployed in Baum *et al* (2022), Sovacool *et al* (2022), and Low *et al* (2022), as part of the 'GeoEngineering and NegatIve Emissions pathways in Europe' project, containing the following elements. To ensure a diverse spread of perspectives, we focused on a mix of advocates and critics of different DACCS configurations—alongside other forms of negative emissions, as well as a suite of sunlight-reflection methods, or solar geoengineering. Our project justifies an integrated assessment of negative emissions (including DACCS) and solar geoengineering from two angles: that carbon dioxide removal at particular scales can be a form of transboundary climatic intervention (Caldeira *et al* 2013, Sovacool 2021), and that portfolios of both strategies are increasingly considered to reduce the

Table 2. Summary of expert interviews conducted in May–September 2021.

Summary information	No
No. of experts	125
No. of organizations represented	104
No. of countries represented	21
No. of academic disciplines represented	34
Cumulative years spent in the geoengineering industry or research community	881
Average years spent in the geoengineering industry or research community	7.8
No. of experts whose current position falls into the following areas:	
Civil society and nongovernmental Organizations	12
Government and intergovernmental Organizations	8
Private sector and industrial associations	12
Universities and research institutes	94
No. of experts from the Global South	12

Source: Authors.

Table 3. Interview question sets.

1. Innovation	Which particular options have high or low innovation potential in technical, communication, societal appraisal, and policy dimensions?
2. Coupling	What energy systems or other sociotechnical systems could or should be coupled to carbon removal?
3. Business models	What business models and markets could carbon removal create or disrupt?
4. Risks	Which serious risks (e.g. social, political, military, ethical, environmental) may arise?
5. Sustainability	What are the synergies and trade-offs of deployment for the Sustainable Development Goals and other societal objectives?
6. Justice	What vulnerable groups could be affected, positively or negatively?
7. Actors	Who are the relevant (or most important) actors (or stakeholders/networks), e.g. for commercialization, development, and/or acceptability?

Source: Authors.

risk or damage from climate change in post-Paris climate governance.

Of the total sample of experts ($N = 125$), 90 participants have expertise in the assessment, policy, or technological development of multiple carbon removal approaches, and a large and multidisciplinary plurality has concentrated expertise in the current applications, projected pathways, and governance mechanisms for DACCS. To ensure the credibility of our knowledge base, we invited only those who have published high-quality peer-reviewed research papers on the topic, or published patents and intellectual property, within the past ten years (from 2011 to 2020). Table 2 provides an overview of the demographics of our total sample of expert interviews. Data from these interviews is presented here as anonymous with a generic respondent number (e.g. R010 for respondent 10, or R110 for respondent 110). The full list of interview respondents is shown in annex I as supplementary online material.

Our engagement technique of semi-structured interviews asks participants a set of standard inquiries, while allowing for novel directions and areas to be explored in an emergent fashion. We structured our questioning to cover key areas of innovation and sectoral interconnections and gaps, risks, justice and sustainability dimensions, and governance needs, actors, and instruments (table 3).

We see this method as appropriate for the following reasons. DACCS is an emerging topic, where experts and technologists play clear and substantial roles in thought-entrepreneurship and steering with regards to the assessment, innovation, and policy discourses. Accordingly, we seek to facilitate a more targeted discussion between expert views, to comprehend complicated programs or events (and their potential consequences), as well as how they intersect with experts' perceptions, beliefs, and values. We moreover engage with a rapidly expanding topic, and see interviews as a rigorous, real-time collection of prospective thoughts, points of view, and plans of action that could take months or even years to materialize. In this regard, employing interviews provides timely insights at an early stage of the discourse, and without having to wait for such other sources of information to become publicly available.

3.2. Data analysis

Given that interviews were completed over a three-month period, blocks of interviews were sent to a professional transcription service as they were completed. Upon being returned, all transcripts were then cleaned by authors before being entered in the qualitative data-analysis program NVIVO, where transcripts of all 125 interviews were coded. Using this program, new nodes (and sub-nodes) were iteratively created in order to capture the diverse perspectives of the expert sample, including, for instance, to reflect where different understandings of specific aspects of DACCS (policy, governance, technology) arose. The resulting dataset thus presents a structured coding of the interview data, which can be simultaneously utilized to explore both consensus views across experts and significant differences of opinion or perspective.

3.3. Limitations

Our use of a large sample of expert interviews provides crucial and diverse insights into the potential, challenges, and possible shortcomings of DACCS as a solution to the climate crisis. At the same time, our research approach, and our decisions of how to report on the data, have some shortcomings. First, while our emphasis on anonymity proved crucial to encourage our respondents to feel that they could express themselves without thought of retribution or negative consequences, this presents difficulties for the potential replication of our findings, given to the issue of correlating the identity of respondents with particular interviewee statements. For this reason, we do provide a full list of all our participants (with one exception) in the appendix as well as make frequent reference to specific quotes as support and justification for our findings. Moreover, we took an ethnographic approach that did not correct or problematize responses, so we present the views of participants, even if they may have had misperceptions on specific points about DACCS or policy. In this regard, we take the decision to not impose ourselves too much on their claims, other than perhaps offering context where deemed appropriate, as it is not our place to determine or set bounds on their self-assessed expertise. This research therefore offers a mapping of the current perceptions of experts regarding preferable policy and governance principles of DACCS, but such findings are still based on expert opinion and subject to intersubjective interpretation.

4. Ten principles for direct air capture policy

This section presents ten core recommendations for DACCS policy arising from our expert interviews, which are supplemented with a review of the recent literature.

4.1. Follow key principles for ensuring ‘negative’ emissions

Our first recommendation summarizes four underlying governance principles for DACCS and negative emissions deployment (Tanzer and Ramirez 2019, Preston Aragonès *et al* 2020). R109 explained these principles succinctly:

> *Principle 1 is to emphasize collection of CO_2 from the atmosphere. Principle 2 is to store it in a manner intended to be permanent—see also the need to prioritize utilizations which are more durable. Principle 3 is that monitoring, reporting, and verification approaches must look at all upstream and downstream emissions (regarding both the full life cycle of the product or process and along supply chains), as well as to comprehensively estimate and include them in the balance. Principle 4 is, at the end of the day, to remove more CO_2 than is emitted.*

Schenuit *et al* (2021) also argue that deployment of carbon dioxide removal technologies like DACCS need policy mixes that actively enforce net-zero policies and couple diffusion with national net-negative emissions targets.

4.2. Prioritize long-term carbon storage

Our second recommendation is that removal and long-term storage of carbon dioxide from the atmosphere should take precedence over less durable/more immediate uses of removed carbon (McLaren 2020). Utilization should focus on where it is important to move away from fossil or atmospheric carbon to sustainable carbon (Bruhn *et al* 2016, Patricio *et al* 2017).

Issues of long-term storage intersect with other aspects of risk including permanence, leakage, liability, and the pursuit of a more circular economy. To highlight how limited the effective removal and utilization of carbon is at present, R013 drew parallels to the case of BECCS:

> *If you look at the direct air capture and storage, they aren’t doing anything with the carbon dioxide they’re capturing yet. [And then look at] Drax, which is the biggest bioenergy plant we’ve got in the country [the United Kingdom]. That technology is capturing just one tonne of carbon dioxide per day. In fact, they’re just putting it in barrels on site now currently because they really don’t have an idea about what to do. We have to really get some idea about the way the whole thing will work from one end to the other one.*

R039 expanded on this risk of CCS and second-life uses by noting how:

> *Based on the flow of carbon, essentially you can have something labeled as part of the circular economy which in the end still results in additional emissions. In other contexts, circular economy is taken to represent a form of CO_2 removal, which it might not be. And so there is a risk of obfuscating, from an atmospheric carbon perspective, what is actually happening.*

The National Research Council (2015) has already argued that some carbon dioxide removal options, including DACCS, could generate pure, ready-to-use streams of carbon dioxide for industrial application. Rather than being put underground, these could be used instead for enhanced oil recovery, chemical production, or other uses (Wilcox *et al* 2017).

Thus, according to this logic, DACCS—if implemented without constraints, or considerations for net-zero reductions—would not be sequestering carbon, but putting it to uses where carbon-intensive oil is combusted and carbon re-enters the atmosphere and, in some cases, could contribute to fossil fuel extraction and associated emissions. McCormick (2022) notes the potential for strong market demand for such pure carbon, citing that very recently both the United States and the United Kingdom have confronted repeated shortages of industrial CO_2 due to fragile supply chains. Furthermore, many ongoing and upcoming DAC projects focus more on utilization in fuel synthesis than storage, as shown in table 1.

We recommend against such uses of DAC, however. Notably, we stipulate against the endorsement of its uses for enhanced oil recovery, i.e. given how it prioritizes near-term applications over long-term consequences for the climate and the potentially adverse impact on social acceptance (see section 4.10), but do endorse use of feedstock for building materials (e.g. concrete) or synthetic aviation fuels, in the scope of sustainable aviation fuel mandates.

Nevertheless, there is a caveat to this stipulation. There could be cases where near-term enhanced oil recovery could still result in net reductions of carbon dioxide, either by generating revenues needed by incumbent firms which can be utilized or reinvested in net-zero options, or that enhanced oil recovery is needed to clear out reservoirs to make space for carbon storage. In simpler terms, near-term usage of enhanced oil recovery could still result in net, longer-term storage of carbon. In these situations where enhanced oil recovery results in significant net reductions and storage of carbon, it deserves more serious consideration as a deployment option. Such consideration will, however, have to take account of complex knock-on effects beyond just the carbon sequestered while extracting the oil, and released while burning it. Further lock-in of oil-dependent infrastructure, or political legitimization of economies based on oil extraction might be unintended consequences of such an approach.

4.3. Appreciate scale and incentivize experimentation

Multiple respondents spoke about the importance of scale. As table 4 summarizes, this included the notion that policies must steer innovations through the '*Valley of Death*' within research and development, and that DACCS could be the ultimate '*game-changer*' if economies of scale were to be achieved. Respondents also spoke about how '*getting in now*' could be very profitable for investors, and that we '*need this now*' in terms of experimentation and scaling effort to the point where it is as '*big as the car industry*', as well as policies that '*speed up the discovery process.*'

Based on these statements, and in view of the amount of carbon removal required as per the recent IPCC reports (IPCC 2021, IPCC *et al* 2022), we believe policy should set an aspirational objective of gigatonne-scale permanent carbon removals by 2030. Further, there is a need to move towards large-scale demonstration for first-of-a-kind installations, with possible matching support at a domestic level from institutions such as the EU Innovation Fund and Breakthrough Energy Catalyst, or the Energy Systems Catapult in the UK, or the Advanced Research Projects Agency-Energy (or the U.S. Federal Government's network of national laboratories) in the United States.

Furthermore, experimentation with a view towards scaling up and incentives towards larger-scale demonstration projects are necessary for tackling what was broadly seen by our set of experts, and more generally in the literature (Beuttler *et al* 2019, Fuhrman *et al* 2021, Madhu *et al* 2021, McQueen *et al* 2021, Erans *et al* 2022, McCormick 2022) as the key limiting factor for DACCS deployment: cost. Indeed, the experts in our sample (e.g. R002, R004, R008, R012, R059, R071, R082, R093, R109, R120, R124, R125) repeatedly highlighted the need for per-tonne costs to come down—though with some disagreement about how far costs would need to decline for DACCS to be viable. Pointing to its potential reliance on government support, R057 for instance underscored the risk of DACCS '*draining the treasury if costs do not come down*', with likely follow-on effects for its social acceptance legitimacy (see section 4.10). In addition, while energy use was a recurring theme in these discussions (see section 4.6), high costs of DACCS were also a result of the high water use of some approaches, the strong need for capital infrastructure as well as the costs for processing the materials that were the outcome of DACCS. On this point, R081 lamented the inability of those outside of companies to subject DACCS processes to closer inspection:

> *Direct air capture might be a problem, but nobody knows because this technology is shrouded in secrecy. It's all patented; we don't know.*

More broadly, R046 was critical of how much the current cost numbers around DACCS could be trusted in view of what they deemed to be inconsistencies:

> *I just don't trust any cost numbers, well, any of these future cost numbers out there, because I think most of them are*

Table 4. Summary of expert statements concerning the importance of scale and experimentation for DACCS.

Respondent	Statement
R064	*So, I think we are working on it now because we need to scale up to mid-century, but I think we do not really know what the technology will look like in mid-century. It may or may not resemble the stuff that's being talked about now. We do not know which of those technologies will get through the 'Valley of Death' of innovation. I think the same thing applies to the other major technological approaches to carbon removal.*
R037	*If it were possible, that could be a game-changer, because it scales and it is not dependent on using the land and suchlike. That could be a remarkable way forward.*
R048	*In terms of investment, if you are investing in direct air capture and—it is a really early stage in that field—if the technology improves and the costs go down, and carbon per tonne pricing makes it feasible, I think that will scale up. Getting in now can be a really profitable investment opportunity.*
R051	*There's a limitation on policy funding at early stages. We need this now; otherwise, we will not get to gigaton scale, no chance. If you want direct air capture to scale to gigaton scale and become cheap, you need about a decade to make it an industry. Think of it like the car industry, the things are built by hand in Switzerland or we have made a Tesla Roadster and we need to make a Model 3. Also, more crucially, the Gigafactory for the Model 3. You cannot switch that on overnight. The same story with battery electric vehicles, the same story with wind and solar, it will take time. We need to push now and not wait until it is needed in the models because it will not be there, if that makes sense … I think if you look at the IPCC climate models, and go back to it becoming gigaton scale, this has to become bigger than the car industry or the oil and gas industries. It is massive. … it is also one of the industries that's not massive. It has to become massive; otherwise, we will not make the goals.*
R058	*The sorbents themselves, again, similar to BECCS, there needs to be innovation in the scale-up and the making-cheaper of the sorbents in both cases of lower-temperature amine sorbents and the higher-temperature strong-base hydroxide sorbents. Again, that will come from essentially the chemical engineering innovation that comes from manufacturing stuff at greater and greater scales, hopefully benefiting from the economies of plants-scale, the supply-chain economies that will come from sourcing the chemical inputs at larger scales and so on.*
R082	*This is used almost as a buzzword, and to be at climate-relevant scales, you need large plants. So in our analysis, for example, we consider a 100 kilowatt per year plant and a 1 mega-tonne per year plant to look at the cost differences, and it appears that solids costs do not change as much for the smaller plants. So the scaling is more or less linear. But for liquids, they definitely benefit from larger plants.*
R120	*We need to develop new technologies that do the same job but better, but that's a known unknown where we know these kinds of new technologies will be invented, but we just need to speed up the discovery process.*

Source: Authors, based on expert interviews ($N = 125$).

> *self-serving. We have a lot of experience that, until you get to the commercial stage, the price usually rises from your cost estimates as you start dealing with reality.*

The issue of the costs of DACCS will remain a live topic for the foreseeable future, therefore making further experimentation and demonstration especially crucial.

4.4. Co-develop with point-source capture, transport, and storage

New DACCS approaches rely on much of the same energy, storage, and utilization infrastructures as point-source carbon capture—which was already introduced to climate policy in 2005, and upscaling of which has been slow to date (Martin-Roberts *et al* 2021). Deploying DACCS requires building out CO_2 transportation and storage infrastructure (Bui *et al* 2018, Haszeldine *et al* 2018, Lane *et al* 2021). R117 suggested that this could begin with the capture of flue gasses:

> *Capturing flue gases is the essential thing we should be doing way more of, right now, today with no question. That is where we should start. Eventually, hopefully, we remediate all the flues that we can and now we have got no alternative but to start capturing from direct air. But it should be in that order. We should not be horsing around with direct air capture- we shouldn't be trying to scale it now anyway, maybe we should be trying to exploit technologies. Either way though, however we capture the carbon, there is then the whole backend infrastructure of pipelines and sequestration facilities that is needed to be stood up at the same time, in order to make the capture step meaningful.*

Such an approach would also add financial longevity to pipelines, thereby encouraging much-needed investment into this space through the security afforded by being connected to a growth sector like DACCS. Indeed, many experts (e.g. R115 and R119) highlighted its sizable requirements in terms of transport and substantial infrastructure as a crucial, albeit underappreciated challenge for DACCS. On this point, R119 enumerated how:

> *Using it at a scale where you're pumping 1000 tonnes per second of CO_2 underground—worldwide, that's as much as we're emitting right now—so say we get to 100 tonnes per second worldwide, so it's… You know, if you have 1000 facilities you're still doing a tonne every 10 s. It just is mind-boggling and that's only 10% of our current emissions. I mean just flat out mind-boggling.*
>
> *… I think that the studies are fairly reliable, the capacity for large-scale safe storage is there but the infrastructure and the capacity and even the technical development of how to do that safely at that scale is huge.*

4.5. Phase in a carbon price and sustained governmental support

Carbon is ultimately a waste product, with a limited scope of cascading uses (Bruhn *et al* 2016, Patricio *et al* 2017), and as such needs to be treated, and adequately priced, as a pollutant—in order to reduce its occurrence and to encourage its removal. The history of pollution control suggests that waste removal must be treated as a public good, or it will not occur. According to this recommendation, DACCS deployment therefore demands a suitably high carbon price to provide a signal to markets and encourage innovation, upscaling, and economies of scale—such activities and aims must be underpinned by strong government funding, incentives, and regulation (Honegger and Reiner 2017, Cox and Edwards 2019, Schenuit *et al* 2021, Meckling and Biber 2021). As a promising sign, in 2022, voluntary carbon markets began differentiating by type of activity or offset and gave the most value to carbon removal projects. The average carbon credit price for carbon removal (about $20 per ton) was more than twice that for nature-based removal ($10) and about four-times more than renewable energy (about $5 per ton) (Sustainable Finance Lab 2022).

Alternatively, direct air capture technology could circumvent market incentives altogether through direct state investment. Among other benefits, such support would be essential for speeding up the discovery process and enable start-ups in this space to get through the 'Valley of Death' mentioned in section 4.3.

R106 argued in favor of consistent international market policy by suggesting that:

> *Policy makers always think they can switch off, switch on, these markets as they wish, but this will not work in the long term.… Again, it's clear that any option that is linked to geological storage just incurs cost. There is no commercial benefit of any of these geological storage options.*

R086 concurred and said that:

> *It's the regulation [which is crucial]. For actors to thread the needle on how to get to scale. You need all these different pieces. We're doing as much as we can on our business model, our technology, all these, the predictability of the revenues of the plants to make it easy to borrow. All those things all have to come together to get to scale and to get over the 'Valley of Death', or the chasm, whatever you want to call it. We think that's really the challenge we have, so far more than just technology, right?*

4.6. Couple with renewables

In the near to medium term, there could be trade-offs between uses of renewable energy to power either new DACCS systems or global energy needs (Beuttler *et al* 2019, Creutzig *et al* 2019, Realmonte *et al* 2019). Moreover, upscaling renewable energy would require tremendous material and spatial resources (Fuhrman *et al* 2020). Global renewable energy capacities must be built up to present synergies between DACCS and other needs. In the nearer term, DACCS systems must be piloted and scaled in areas with surplus renewables, in part, as stressed by many experts (e.g. R008, R047, R051, R071, R082, R086, R121), as a way to keep the costs of DACCS down by making use of cheap sources of available energy. Innovative couplings of direct air capture with hydroelectricity in Canada and Norway and with geothermal energy in Iceland are already being developed or even deployed, along with potential couplings with wind energy in Texas and solar energy in New Mexico. Regional deployment across the UK must consider other geographically relevant couplings with renewable energy, possibly in line with the devolved powers, for instance with wind energy in Scotland or even tidal and marine energy in North Wales. Our respondents expressed strong concerns about DACCS and renewables in table 5, noting that renewable energy '*makes more sense*,' that it must be coupled to renewables to be environmentally sound, but also that policymakers need to account for some of the possible negative externalities from renewables, especially solar photovoltaics (PV).

4.7. Harness hub deployment

Sufficient capacity for CO_2 storage is only available in certain countries, and social acceptance will differ by location. Underscoring the differences in national

Table 5. Summary of expert statements concerning renewable energy and DACCS.

Respondent	Statement
R115	*For DAC, it is really just getting that very dilute, all the volumes of very dilute air, in contact with the material. That's the challenge. Then, ultimately, making sure we have enough renewable energy to do this all, and making the determination: if using renewable energy to power a DAC system actually makes more sense than using renewable energy as just the energy source, because eventually there'll be a competition if we really see wide-scale deployment of DAC systems.*
R059	*I think with DAC, what that means is, given the enormous quantity of energy that a very large-scale DAC could mean in terms of energy usage, we need to be very aware of what the broader environmental impacts of the energy sources that are specifically used for DAC might be, and there I think about mineral resources and so on that go into wind-turbine manufacture. I think about local environmental degradation that might come from massive manufacture of PV panels.*
R027	*Certainly, there is a very strong argument to say that direct air capture is not even a thing without renewable energy provision on a scale that we do not currently have.*
R032	*The Carbon Engineering approach is seeking to replace existing energy pathways to shift from liquid fossil fuels to liquid zero-carbon fuels. In contrast, something like Climeworks' method in the long run is going to need a low to zero-carbon energy source, because of course you use very large amounts of electricity, which is one of the reasons it remains expensive. And in the long run, for that to scale up, it will need to tap into scaled-up zero-carbon energy, or at least low-carbon energy. So, what systems even direct air capture could couple with depend upon the particular techno-economic pathway that is envisioned.*

Source: Authors, based on expert interviews ($N = 125$).

conditions that exist, R017 contrasted the storage potential of Japan and Saudi Arabia:

> *In the case of Japan, there's not much high potential of storage potential. So, storing CCS in Japan is very limited, so it comes to the question of where to dispose the CO_2 to. Many of the government experts are actually arguing to send the CO_2 to some other countries, which sounds ridiculous and it sounds very costly.*
>
> *… It doesn't make sense, economically, to deploy DACCS in Japan and send the CO_2 somewhere to store it. I feel it's better to actually deploy the DACCS in Saudi Arabia and the Japanese government or a Japanese company pays for that, to help and store that. That's more economical and politically viable.*

For those experts focused on countries where storage potential was greater, however, there was much to discuss about how this might occur. Looking at the UK, R065 stated that:

> *I think [the UK] government sees that the locations that are most likely candidates for CO_2 transport and storage clusters, tend to be areas where you have legacy industries. Where, in the leveling up agenda, you would target investment. So, there is seen to be quite a nice potential alignment between development of transport and storage and zero and potentially negative carbon industries with the leveling-up agenda, definitely.*

R012 added that:

> *In the UK, the decarbonization of industry is what's driving where the CCS clusters are being developed. That's what's driving it and so your BECCS is then fitting into that after the event, so a bit like in the US with their established bioenergy there. Your established systems will also shape how and why. It's those couplings will mean certain BECCS or DACCS routes, or certain natural carbon storage routes, will flourish in certain environments that are a lot harder in others because of pre-existing infrastructure, pre-existing skills base, technology skills base. Like, the US has a lot of potential because of the amount of EOR, the amount of pipe networks with CO_2 to switch quite quickly to BECCS and DACCS, but obviously you need the political will, as well, to make that happen in that context.*

Hubs and spokes—where a large storage site serves as a hub or anchor for a region, with different spokes transiting carbon to it—should therefore be envisioned, cultivated, and then utilized. Hubs and spokes could be used to transport and store CO_2, including through the kind of 'Projects of Common Interest' approach utilized for renewable energy facilities, cross-border electric transmission networks, or smart grids—which identifies critical cross-border projects for energy infrastructure, providing them with more streamlined procedures for permitting and environmental assessment as well as access to financial assistance (European Commission 2021).

Greater freedom of distribution could thereby be created for CO_2 transportation and storage infrastructure by developing a similar framework, with possible support occurring under the auspices of the Trans-European Networks for Energy Regulation, or the Leveling Up agenda in the UK (UK Government 2022).

4.8. Maintain separate targets

Metrics and emissions baskets should distinguish between permanent carbon removal and conventional-emissions reductions, in order to prevent fungibility between measurements of carbon removal and mitigation activities and avoid the impression that the former can be understood to substitute for the latter (McLaren *et al* 2019). R055 noted that:

> *Then the whole question of overshoot, I guess, just neglects so many different dimensions of the difference between direct emission reductions and CDR. So, it's not so much cheating as kind of convenient and creative accounting… by investing all your faith in these equivalencies that you have to come up with things like additionality guarantees, to make the equivalence work, that are impossible to do.*

R098 added that:

> *I proposed it early on as well … to make a clear delineation between emissions reductions and removal targets so that you don't create the illusion you're just going to build up a second system that removes all the stuff that you continue to put into the atmosphere.*

R065 also supported the idea that:

> *You should have separate targets for emissions reductions and removals. In order to manage some of the risks, primarily about removals being used in place of emissions reductions in a non-optimal manner—however you want to define optimal.… there's quite a lot of confusion sometimes between offsets as a traded unit. So, carbon-offset credits and removals … you need transparency over the plans to achieve targets. You need to set out how much removal, how much emissions reductions, from which technologies, how much offsetting. What are you going to do with the carbon you're storing? And then that addresses risks across the whole portfolio and it's not an emissions thing or a removal thing.*

Net targets must therefore be accompanied by ambitious mitigation action in the near term and safeguards for the role of high-integrity, permanent engineered carbon removal (Smith 2021).

4.9. Embrace certification and compliance

Metrics and emissions baskets should distinguish between carbon capture taking place at different locales, through different means, and for different lengths of time, to avoid 'false equivalences' (Carton *et al* 2021). We must develop systems for monitoring and management of captured CO_2, whether this occurs through nature-based methods like afforestation or soil management, along supply chains, and/or between sectors (Clery *et al* 2021, Terlouw *et al* 2021). R103 elaborated on this theme, noting that:

> *We need broad assessments, so, when you're evaluating CDR, that the carbon accounting is only one dimension. All these side-effects that come up from what we call the 'misplaced fungibility' of assuming that a ton of carbon in a forest in the Congo is the same as a ton of carbon in a field in Britain or a ton of carbon drawn out of the atmosphere in Canada.*

R115 added that:

> *Lifecycle analysis is critical too because we don't want to act like we're actually removing CO_2 from the atmosphere, but, when you look at it from the lifecycle perspective, you're actually not doing that. If you're using a solid sorbent system, and you're stacking these fans up and it's taking acres and acres, or tens of acres, hundreds of acres of land, all of the emissions—lifecycle emissions that are going to come from just producing all that material—all need to be factored in.*

Certification should be sufficiently granular to differentiate on the source of CO_2 and the degree of permanence of storage. Robust certification is essential given the narrow timeline for climate mitigation, the need for transparency and trust, and so that integration into compliance frameworks for high-integrity, sufficiently permanent carbon removals can be attained by 2025. In carbon accounting and accreditation, it is important to ensure that 'residual' emissions from 'hard-to-abate' sectors are robustly calculated (Buck 2021b). Many industries will have incentives to conduct 'creative

Table 6. Summary of expert statements concerning DACCS and social acceptance, involvement, and equity.

Respondent	Statement
R006	*Certainly, there's an environmental justice component here [with DACCS], for fence-line communities. But yes, I think the workers would be stakeholders, obviously. The industries themselves, both the DACCS companies and whatever companies are presumably paying them to offset their emissions or offset their historical emissions, in the case of Microsoft.*
R029	*If you are thinking about something like direct air capture, where there is going to be new siting for these things, or if there are going to be land-use changes that are having to be widespread, I think siting concerns are going to be a big policy consideration of how are we going to decide where these go and how are we going to work with communities in a way to get them to accept it.*
R056	*At the moment, the best scheme seems to be to put it under ground. So, you have to find places where the communities do not mind that you are going to put this stuff underground. Climeworks are doing it in Iceland and there are various surveys in the States, for example, of individual states which have access to underground storage.* *So, I am guessing that, depending where those places are, the communities would say, 'Well, we do not really like that underground.' Certainly, in the EU, I think the feeling is that they do not want to store carbon dioxide under land. So almost certainly, what will happen is, they will pipe carbon dioxide to the North Sea and store it in undersea formations below the North Sea. I can see there being a community concern about storing carbon dioxide under land.*
R065	*People, when you talk to them about DAC, yes, they can accept it, but with reservations, and it tends to be A, 'Well, are you using this as an excuse to not do what you should on emissions reduction?' And B, it is not dealing with the root cause.*
R068	*I think my general feeling is we tend to get ourselves in trouble if we think we can just rush forward without including local communities, so I would be worried about what's the thing? Once trust is lost, it is hard to rebuild. That's what I would worry most about, is that all it takes is one project going awry. That will be amplified in news and social media and can sour other projects, as well.*
R052	*I think understanding the job and workforce opportunities associated with having these plants built and maintained nearby and also just how integrated… how accessible is this technology? Can it be integrated into a community in some way where there's interface or is it going to be something that is removed from a community, a very sterile piece of technology in the middle of the desert and then we have people drive there to work, but there is not, kind of, that interface? So, I think that some of these social perceptions of it will seem, kind of, like soft parameters, but, at the end of the day, can shape a lot about its political viability and even, kind of, the future of how this technology looks.*

Source: Authors, based on expert interviews ($N = 125$).

accounting', exacerbating the double-counting and limited additionality of emission reductions (Carbon Market Watch 2021).

4.10. Recognize issues of social acceptance, legitimacy, and justice

DACCS will not thrive in areas where it does not have social acceptance or a social license to operate, whether from those in the 'fence-line communities' around plants in operation or those living in the vicinity of pipeline infrastructure or storage locations (Wolske *et al* 2019, Cox *et al* 2020, Jobin and Siegrist 2020). This could entail avoiding fraught associations of DACCS with offering support to the fossil-fuel industry, for instance, through its being used for enhanced oil recovery, or that it substitutes for, and reduces the necessity of, emissions reductions (Cox *et al* 2020, Jobin and Siegrist 2020, Wenger *et al* 2021). Germany and Austria offer examples where the issue of CO_2 storage is fraught, limiting the potential for transportation and storage services up to the North Sea (Schumann *et al* 2014, Buck 2021a, Merk *et al* 2022), not to mention of developing the kinds of supply chains for DACCS to attain economies of scale and become cost effective. Table 6 raises a host of concerns around social acceptance, legitimacy, justice, community involvement, and equity.

Public and regulatory engagement in line with the principles of a just transition and devolved powers (in the case of countries with a federal type of government) is thus crucial for building legitimacy and trust. This connects back to the need for engaging sectors and locales in transition out of the fossil-fuel economy, whereby carbon can be transported out of areas where storage may not be possible, and fostering novel connections and supply chains at the heart of a post-carbon society. Further, the issue of public acceptability demands that considerations of equity and justice be brought to the fore, notably, by ensuring that one group or geographic region not be overly burdened with costs or risks entailed by DACCS, but rather promoting a more globally and societally equitable sharing of risks as well as benefits (Pozo *et al* 2020, Batres *et al* 2021, Lenzi *et al* 2021, Mohan *et al* 2021).

5. Discussion and conclusion

In sum, a preponderance of evidence from our global expert-interview exercise suggests that for DACCS technologies to scale, accelerate, be used

Table 7. Summary of ten recommendations for Direct Air Capture policy.

No.	Recommendation	Explanation
1	Follow principles that ensure ‘negative’ emissions	Ensuring atmospheric carbon removal, permanent storage, monitoring across the lifecycle and net reductions of CO_2
2	Prioritize long-term carbon storage	Giving precedence to long-term storage of CO_2 over short-term applications like enhanced oil recovery
3	Appreciate scale and incentivize experimentation	Moving towards large-scale demonstration projects with ambitious and binding targets
4	Co-develop with capture, transport, and storage	Investing in access CO_2 transportation and storage infrastructure. It also adds financial longevity to pipelines, given it is a growing industry
5	Phase in a carbon price	Setting a robust and reliable carbon price so that carbon removal has a more substantial value proposition and market value
6	Couple with renewables	Integrating DACCS with locally appropriate and renewable sources of electricity and heat
7	Harness hub deployment	Utilizing hubs and spokes and Projects of Common Interest-style approaches to transport and store CO_2
8	Maintain separate targets	Separating metrics and emissions baskets between permanent carbon removal and conventional-emissions reductions
9	Embrace certification and compliance	Establishing robust certification for carbon removal and integrate into compliance frameworks
10	Recognize social acceptance	Recognizing DACCS deployment will not occur without social legitimacy and acceptability

Source: Authors, based on an expert interview exercise ($N = 125$). DACCS = direct air capture with carbon storage. CO_2 = carbon dioxide.

safely with fewer risks, and to meet climate goals, while not undermining climate-mitigation activities, it needs to be steered by at least ten interlacing policy reforms and engagement activities, summarized in table 7. These create an integrated policy mix of mechanisms, governance arrangements and policy support at a range of scales, and stakeholder outreach.

Given that table 7 offers a comprehensive architecture for DACCS policy, it can also be interpreted, subtly, as a way to understand what should *not* be done, that is, policy mixes that are not synergistic or could result in less effective governance or minimal social acceptance. That is, DACCS pathways and policy incentives should avoid doing the inverse of our recommendations, which could culminate, *inter alia*, in a poor governance regime and deployment in the absence of social legitimacy and social license to operate which would likely see DACCS mismanaged, governance fail, and the risks outweigh the benefits, with the former likely falling unequally across societies and around the globe. A sub-optional policy mix or toolkit would therefore involve implementing DACCS while:

- Ignoring governance principles and focusing only on market drivers or competition issues;
- Prioritizing near-term applications (enhanced oil recovery, industrial applications and uses of CO_2) with little regard for long-term consequences on the climate;
- Seeking to ambitiously overscale or scale up DACCS projects without providing adequate support for learning and experimentation;
- Treating DACCS research and deployment as isolated from carbon capture, transport, and storage;
- Attempting to deploy DACCS systems without a stable or reliable price on carbon, or other form of robust policy support to make the technology financially viable;
- Coupling DACCS with fossil fuels (coal, oil, natural gas) or brown or blue forms of hydrogen;
- Pursuing discrete DACCS projects rather than employing interconnected hubs or projects of common interest to leverage more comprehensive gains, including for areas and sectors in transition;
- Conflating targets for climate mitigation with the use of DACCS at the risk of weakening or even counteracting incentives to decarbonize;
- Working out transparent and reliable schemes for certification and compliance only after deployment reaches a certain scale;
- Failing to recognize community and social concerns, leading to strong opposition and even moratoria in particular locations as well as foregoing the potential for local co-benefits.

Following these detrimental practices would likely result in DACCS deployment that could either be halting or never occur (in the absence of adequate learning and experimentation, scaling, and innovation), or would unnecessarily aggravate the climate crisis if it did occur. It could also result in fractious conflicts with host communities and become quickly stigmatized as a technological debacle.

Critically, our article only examines suggestions for policy and governance at the local, national, and regional level, that is, what planners and policymakers at these various scales can or should do to steer DACCS deployment. We do not however consider global or transregional issues such as geopolitics or the differential potential of carbon removal across nations to a great extent, in part given the lack of discussion of such issues among our expert sample. We do nonetheless encourage future research teams to explore such topics. It could very well be that future DACCS governance is also shaped by distinct energy or decarbonization 'cultures' that mediate the interrelationships of policy-related attributes with other normative, material, or institutional attributes (Stephenson *et al* 2020). Or, that DACCS deployment is strongly influenced by 'architectures of constraint' such as its dependency on fossil fuel extraction or coal, a lack of democratic norms or exposure to corruption, or a lack of public climate awareness or low levels of trust (Lamb and Minx 2020). Analysis in these directions would complement ours and lead to a deeper comprehension of both the political economy and global governance dynamics of DACCS.

Nevertheless, at this pivotal moment for both climate policy and the nascent state of DACCS technology, which bundle of governance and innovation practices, best-case or worst-case, will accompany and accommodate future pathways is greatly unknown. And therein lies the promise of stronger DACCS policies, and the peril of failing to implement them.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Ethics statement

The research was conducted in accordance with the principles embodied in the Declaration of Helsinki and in accordance with local statutory requirements, including double ethics approval granted by Aarhus University as well a the European Research Council. All participants provided informed consent to participate in the study. No children under the age of 16 were involved in data collection. In order to protect participant anonymity, we do not attribute any of the qualitative quotes used in the article.

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