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Original research article

Applying the multi-level perspective to climate geoengineering: Sociotechnical bottlenecks for negative emissions and cloud seeding technologies

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ABSTRACT

Carbon dioxide removal and negative emissions technologies, such as bioenergy with carbon capture (BECCS) and direct air capture with carbon storage (DACCS), may have an important role to play in reducing greenhouse gas emissions (GHGs). Cloud seeding (CS), a controversial form of weather modification, might also help to reduce the severity and intensity of storms and address widespread drought from climate change. Nevertheless, costs, technical complexity, social acceptance, and other unknown risks have so far kept these climate geoengineering interventions at uncertin levels of research and deployment in the response to climate change. Although a large corpus of literature sufficiently deals with the technical aspects underlying such interventions, the nontechnical and social aspects of geoengineering mark fertile research territory. This study applies the sociotechnical concept of the Multi-Level Perspective (MLP)—commonly used for analysis of sustainability transitions—to explore the risks, costs, uncertainties, and complexities of rolling out BECCS in the United Kingdom, DACCS in the United States, and cloud seeding in Australia. We examine the interaction of the MLP across three levels (niche, regime, and landscape), then explore windows of opportunity and technological transition bottlenecks. Specifically, we show that BECCS align with the "stretch-and-transform" transition, DACCS can be construed as "fit-and-conform", and CS can be seen as within the "stretch-and-conform."

1. Introduction

Radical technological interventions have reemerged as potentially vital climate solutions [1,2] following the landmark Paris Climate Agreement in 2015, which is governed by a collective target to stay below 2 °C global average warming by the year 2100. This target implies that between 400 and 1000 GT of CO2 must be captured and safely sequestered in the 21st century [3]. In connection, the Paris Agreement emissions reduction goals now tacitly call for geoengineering solutions and negative emissions technologies (NETs) to "compensate for past and current residual CO2 and non-CO2 emissions" ([4]: 205).

Cloud Seeding (CS) has experienced somewhat of a renaissance as the effects of climate change become more severe, and it is seen as a geoengineering solution that could, among other benefits, stymie widespread drought conditions ([113–117]). In addition, NETs or, alternatively, Carbon Dioxide Removal (CDR) technologies—such as Direct Air Capture with Carbon Capture (DACCS) and Bio-Energy with Carbon Capture (BECCS)—have similarly experienced a revival as governments seek-out backstop technologies should the climate transition proceed too slowly, or the effects of climate change come sooner than anticipated [5,6].

Nevertheless, there is a tangible disconnect between policy ambitions and technological expectations, on the one hand, and technological performance and deployment, on the other [7,8]. These disconnects, furthermore, correspond to a misalignment between social and technical research [9]. First, radical and largely untested climate interventions "will probably be constrained by cost considerations and geopolitical factors, as well as by biological, geological, technological and institutional limitations" ([10]: 17). Second, although these technologies are known to be confronted by social, technological, and economic risks [118], few researchers "grapple with public acceptance" ([11]: 14).

In this article, we address the following research questions: what are

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the sociopolitical and sociotechnical bottlenecks precluding more widespread and rapid development of climate geoengineering interventions such as negative emissions and cloud seeding technologies? Furthermore, what shifts might be needed for negative emissions and cloud seeding to achieve greater political feasibility and flexibility, whilst recognizing the justice, cost, and environmental concerns of upscaling?

We investigate BECCS, DACCS, and CS in the UK, US, and Australia, respectively. Not only do these countries share similar emissions reduction goals, but each country's government has dedicated substantial public funds in recent years and decades to drive innovation in these technologies. To sufficiently explore the sociopolitical tensions germane to three climate geoengineering interventions, we leverage the Multi-Level Perspective (MLP), widely applied to transition studies on energy, climate, and technologies [12–14]. The MLP helps to explain how technologies are incubated in niche, protected spaces; furthermore, within the context of the MLP, the Paris Agreement acts as an overarching landscape pressure, in turn driving more attention and funding. Following an exposition of the technological evolution seen through the MLP, we then explore transition bottlenecks within the context of goals such as the target of 2 °C climate change [15]. Specifically, we show that BECCS in the UK align with the "stretch-and-transform" transition, DACCS can be construed as "fit-and-conform", and CS can be seen as within the "stretch-and-conform."

2. Climate geoengineering technology scope and theoretical framework

This section justifies our selection of three climate geoengineering interventions, and introduces our conceptual framework of the MLP.

2.1. Selection of three climate geoengineering interventions

Although the term is contested, CS, DACCS, and BECCS fall under the broad category of "climate geoengineering" options, which seek to modify natural or technological environments to address climate change [16,17]. Fleming [137] offers a helpful typology of four types of geoengineering interventions: carbon sequestration, albedo modification, climate design or reducing vulnerability. Carbon sequestration interventions store, capture, or sink carbon or other greenhouse gas emissions into geological disposal in landforms or in the oceans. BECCS and DACCS fall into this category. Albedo modification interventions seek to change the earth's albedo—a measure of how much light is reflected without being absorbed— by launching aerosols to the stratosphere, enhancing cloud reflectivity, and modifying land surfaces. Climate design options seek to actively control the climate or environment—otherwise referred to as "terra-forming." Both weather control and cloud seeding fall into this category.

NETs and CDRs such as BECCS and DACCS directly remove then permanently store carbon dioxide. They fall into the carbon removal and sequestration side of geoengineering [16,18]. Though the costs remain very high, they are considered a less risky and an option to reduce negative transition impacts upon industrial and fossil fuel operations [19,20]. BECCS receive the lion's share of research attention as a CDR, especially within Integrated Assessment Models (IAMs) and IPCC Assessment Reports [21–24]. DACCS, somewhat differently, draw CO2 from ambient air using chemicals to break down the gas into liquid form, either to be re-used or stored in geological formations [25,26]. The advantage of DACCS is that they can mitigate emissions from any CO2 emission source [5,17]. Like BECCS, DACCS require safe and efficient carbon capture and storage (CCS) [119]. As promising future geoengineering solutions, these two CDR technologies might be vital should "climate impacts turn out to be more sudden and severe than currently known" ([120]: 2). Moreover, they might be one way to "heal the atmosphere from emissions inflicted earlier" making them attractive to policymakers ([27]: 288).

Nevertheless, although a sobering majority (344 of 400) IAMs assume that a substantial deployment of CDRs are required to achieve net-zero GHGs [28], their uptake has been remarkably slow, and their measurable impact on carbon reductions even more finite [29]. Apart from costs and emissions mitigation potential, there are related calls for a deeper integration of justice architecture, social legitimacy, and social license in technological development. For instance, O'Beirne et al. ([121]: 272) explore the justice implications of both BECCS and DACCS in the UK and find that the denial of public participation could "undermine progress towards net-zero." In addition, they are also seen as distracting solutions that risk distorting net-zero policies [112].

CS is a form of climate geoengineering via weather modification that involves injecting chemicals into the stratosphere or other depths of the atmosphere to induce precipitation or occlude solar radiation [30–32]. Alternatively, it is considered a solar radiation management (SRM) technology defined as "any other current or future technology that could significantly alter the net incoming solar radiation across the Earth's atmosphere in a relatively uniform fashion" and constitutes, as such, a "deliberate human attempt to alter the Earth's climate" ([33]: 48). CS is, in addition, considered a form of water control technologies, which might help with climate adaptation by reducing the severity of drought [16].

CS is garnering renewed interest in policy and research circles because of the expected widespread changes to the earth's climate which demands extensive mitigation and adaptation options [7]. As a backstop technology, it is estimated that CS could delay global warming by 25 years [34,114]. Remarkably, of the myriad geoengineering solutions to arise, CS has the longest history—having first been used for military purposes by the US, Australia, and the Soviet Union in the 1950s [7,17,35], followed by scientific and research interventions from the mid-1960s through the 1980s [31,36,37,122].

2.2. Theoretical framework: the multi-level perspective (MLP)

The Multi-Level Perspective (MLP) was developed by Geels [12] as well as Geels and Schot [13], based on the work of Rip and Kemp [38]. It is widely regarded as one of the most successful sociotechnical transitions theories [39]—capable of explaining largescale technological transitions that draw considerable policy attention. Its main thesis is that sociotechnical transition phases are governed by three analytical levels of analysis—the niche, the regime, and the landscape [40]—and each engender different kinds of changes, with interactions between the levels serving to accelerate or delay technological changes [12,41,42].

(1) The niche level provides space for radical innovations that emerge in peripheral niches, which shelter and nurture their development (e.g., where experimentation and testing are done). It consists of "a network of actors (e.g., funding organisations, technology developers) that share a belief in the future potential of a new technology and are willing to invest time and money in its further development" ([43]: 880).

(2) The regime level, which also encompasses incumbent systems, consists of interlinked sociotechnical elements such as technologies, practices, policies, business models, cultural meanings—that develop incrementally along predictable trajectories (i.e., the deeper sociotechnical structures that involve technologies, infrastructure, institutions, users, markets, and industries).

(3) The landscape level, wherein companies, society, governments, and policies interact in dynamic ways to steer, or inhibit, sustainability transitions [40], imparts pressure from exogenous sources (e.g., global climate change goals and policies, severe drought, or foreign wars) [44].

Collectively, the interactions across the three levels are as follows. While the sociotechnical regime is characterised as a "coherent complex of scientific knowledge" including "regulatory requirements, institutions and infrastructures" ([38], p. 338), radical innovations that develop in the niche can, in turn, exert pressure that eventually changes the regime (niche innovation- > regime). In addition, landscape pressures might alter the trajectory of the regime (landscape- > regime trajectory). For instance, the sociotechnical *landscape* can exert "pressure on existing *regimes* and create windows of opportunities for *niche* innovations" ([123]: 492). In turn, this enables "new technologies to pry in," wherein modular and add-on technologies make incremental improvements in system components and changes in the "system architecture" [45]. It is a suitable framework in this setting since these technologies require the incubation of innovations in "protected spaces" as a "locus for radical innovations" ([39]: 4)—and consequently require policy attention since market forces, on their own, are not yet capable of driving requisite innovations [123].

While uncommon, several studies have explored some of the interactions of MLP levels for geoengineering solutions. Schelling [46] raises attention to the landscape and regime pressures involved in geoengineering because it "totally transforms the greenhouse issue from an exceedingly complicated regulatory regime to a simple—not necessarily easy but simple–problem in international cost sharing" ([46]: 305). Stirling [47] furthermore highlights the role of landscape pressures from global actors—such as intergovernmental institutions like the IPCC and the UNFCCC—which create and revise IAMs with geoengineering becoming ever more central to technological predictions [48]. Vergragt et al. [27] claim that BECCS emerged in a research niche and as an outgrowth of the fossil fuel regime. Innovations were also induced *vis-à-vis* landscape pressures from the IPCC's 4th assessment report in 2007 [124]. McLaren [125] advances this line of reasoning, by arguing that centralised planning protocols, dominated by incumbent regime actors—even within the IPCC—are inherently paired with geoengineering solutions, even though their widespread deployment remains highly uncertain [49].

None of these extant works has, nevertheless, looked at deployment patterns nationally, within national case studies, nor have they looked at BECCS, DACCS, and CS through country case studies, as we do here. Furthermore, the study can be distinguished from prior research in at least four ways because we: include cloud seeding and thus a form of solar geoengineering; provide analysis of three countries and three climate interventions; develop a sociotechnical rather than purely technical or policy-based analysis. Finally, after grounding our study in the Multi-Level Perspective, we then delve deeper into three transitory features: fit-and-stretch, stretch-and-conform, and stretch-and-transform, for each of the three technologies.

3. Research design and case studies

This section discusses the research design and methods of the study before introducing our three cases studies.

3.1. Research design

We develop three national-level case studies, based on prior literature [50,51]. Given the costs and uncertainties involved in these three technologies [49], governments have to date been heavily involved in incubating, funding, and driving innovations in geoengineering interventions [9,52,53]. Though not a comparative case study, we trace the evolution of three geoengineering solutions across three correspondingly large economies; indeed, the UK, the US, and Australia follow similar financial, political, and policy pathways with respect to climate technology support—and have similarly committed to net-zero by 2050 in line with the Paris Agreement. Finally, national level transitions have demonstrated a remarkable degree of coherence as nation-states are the formal units involved in the UNFCCC process, and a distinct unit of analysis meriting investigation [54].

3.2. Bioenergy with carbon capture and storage in the UK

Bioenergy with carbon capture and storage (BECCS) seeks to harness specific energy crops (e.g., perennial grasses, or short rotation coppicing) or increased forest biomass to replace fossil fuels, then capturing and storing consequent carbon dioxide [55]. There are currently six commercial BECCS facilities operating around the world, with fifty-six in developmental stages [56]. While the first major BECCS project was developed in 2011 in Illinois, with an estimated 1 Mt. CO2 per annum capture rate [11], technologies are evolving rapidly. According to the IEA [57], Fuel-BECCS has the highest Technology Readiness Levels (TRLs). Syngas BECCS, thermochemical Fuel, and Hydrogen BECCS are in demonstration phases [57].

The UK government expects that between 43.9 and 111.9 MtCO2 of negative emissions will be achieved by 2050, with BECCS accounting for 90 % of these [112]. Much of the differences in estimates are due to varied estimations of future technological innovation. Starting in 2012, Drax began to convert six coal-fired boilers to biomass, aiming to become "carbon negative." When fully operational in 2027 these plants are expected to capture 4.3 Mt./CO2/year using post-combustion chemical absorption [58]. Drax's North Yorkshire power station is deemed the UK's "Flagship BECCS Project"—targeting 8 Megatons per annum (Mtpa) capacity [56].

Demonstrating its capacity for niche innovation, Drax has cooperated with several start-up companies: Deep Branch Technology aims to study the production of proteins using the Drax station's CO2 and Econic Technologies Ltd. aims to produce plastics from CO2. Drax hopes to, in Phase 2 of the BECCS-H2 technology programme, demonstrate the technology in Wednesbury. Peel NRE and the Bioenergy Infrastructure Group have plans to build out a massive BECCS facility in North West of England, connected to a 28.5 MW Ince Bio Power Facility in Cheshire [59]. An emerging niche technology, Syngas, is being developed by Syngas Solutions Ltd., based in Wales, which received funds to develop synthetic gas from hydrogen, carbon dioxide, carbon monoxide, and methane—hence, it is in an incubation phase within a niche, protected space. Another BECCS facility, which receives much less attention, is the Cargill wheat processing CO2 purification plan Trafford Park, Manchester. It has been operational since 2016 and can capture 0.1 megatons of carbon per year.

3.3. Direct air capture and storage in the USA

Direct Air Capture (DAC) technologies capture carbon dioxide from the air via engineering or mechanical systems and, using solvents or other techniques, sequester carbon safely in reservoirs (e.g., DACs with CCS, or DACCS) [2,55,60]. To date, 27 DACCS plants have been commissioned worldwide with 130 in planning stages [58]. DACCS are appealing since they produce a product, carbon dioxide, albeit with much of the current demand confined to the oil industry for enhanced oil recovery [25]. Although DACCS technologies have been researched and discussed since the 1980s, their commercial deployment is yet to expand outside a handful of countries (Iceland, Japan, Switzerland, the US). Nonetheless, momentum for DACCS is accelerating. From 2010 through 2022, an estimated $4.1 billion in total public investment for RD&D was directed to CDRs and DACCS [29], with $200 million in capacity investments between 2020 and 2022 (ibid).

The US has been a technology leader in this domain, first developing DACCS in a niche incubation space at Los Alamos National Laboratory. Yet DACCS soon got out of the lab, with earlier innovative companies—led by Klaus Lackner who worked at the lab—such as Global Research Technologies, Kilimanjaro Energy, Carbon Sink, and Infinitree. The US DoE also funded Global Thermostat's DAC technology development since 2020, which has now become involved with ExxonMobil on a joint project. Recent developments are also promising. In 2021, the DoE's Pacific Northwest National Laboratory was funded to develop new DAC's technologies with AVNOS Inc. as its main partner, demonstrating a niche-regime interaction. Texas is quickly becoming a hotbed for DACCS-based investments and technologies in the last several years. Carbon Engineering, Occidental Petroleum (Oxy), and 1PointFive plan a large DACCS Hub, with at least three massive DACCS projects in the Texas Permian Basin [56]. An additional three DACCS hubs are in advanced development stages: Project Bison, Climeworks Gulf Coast, and Cypress DAC Hub. [58]. Indeed, the US Department of Energy (DoE) tabled $3.5 billion for four regional Direct Air Capture hubs under Biden's IRA (2021).

One of the world's first DAC firms, Climeworks, is involved in two major projects in the US: at the University of Illinois and as part of the Gulf Coast Sequestration DACCS hub. In 2019, Carbon Capture Inc. became involved in several high-profile projects in the US, including the $12.5 million Wyoming Direct Air Capture Hub. Heirloom was also selected for $600 million in federal funding under the DACCS Hub program, with funding matched by Gate's Breakthrough Energy Ventures, among other investors. Carbfix and Removr are two emerging start-ups that have received $3 million for R&D funding by the US DoE. AirCapture received part of $14 million adjacent to a nuclear powerplant in Alabama, and it is also a key player in Texas and California. A total of 14 DACCS projects have been announced since the Biden's Inflation Reduction Act (IRA).

3.4. Cloud seeding in Australia

Australia's first foray into cloud seeding (CS) began in the Snowy Mountains, as the Snowy Mountains Hydroelectric Authority sought to produce more rainfall in the 1950's, although earlier niche experiments by The Commonwealth Scientific and Industrial Research Organisation (CSIRO) were deemed uneconomical [61]. Experimentation and public funding continued through the 1980s: from 1988 to 1991, the Snowy Mountains Hydroelectric Authority received another public grant, which was again extended through to 2005 when Snow Hydro Ltd. received $4.02 million to continue its experiments. In addition, CSIRO experimented with CS to ameliorate drought in Tasmania, the Midlands and along the East coast in 1995.

From 2002 to 2003, CS was carried out in the Tasmanian Central highlands under the TASCO program. Other projects demonstrate how the government worked with private companies to experiment with CS—with government providing oversight and funding, and the private sector undertaking experimentation in niche spaces. For instance, a feasibility study, the Southeast Queensland Cloud, was an initiative by Weather Modification Inc. in 2008, which experimented with aircraft-based CS. Also in 2008, WeatherTec AG sought to use cloud ionisation technology to increase rainfall. It was supported by a subsidiary, the Australian Rain Corporation. WeatherTec's main technology attempts to chance the charge of climatic aerosols–using aerosols to transfer negative charges to clouds—powered by renewable energy powered ground-based stations. From 2010 onward, Hydro Tasmania flew 12 to 31 seeding flights per year over the West Coast and Tasmania. There are currently two major CS projects ongoing and planned in Australia.

4. Results: climate geoengineering from the multi-level perspective

Using the MLP, we outline the sociopolitical evolution of BECCS, DACCS, and CS, attending to the niche, regime, and landscape interactions over time, organised by country.

4.1. BECCS in the UK

As remarked above, a main benefit of BECCS is that they can be affixed in a modular fashion in "hard-to-abate" sectors and can also mitigate emissions elsewhere [27]. Their widespread deployment, however, is faced by several fundamental risks. Indeed, critics have been vocal in their opposition to BECCS in the UK, with some researchers countering the carbon neutral claims of Drax and related, high-profile projects. First, they are exposed to fluctuations in energy prices. In addition, the sustainability of wood pellets, as well as their embodied emissions, are not well verified [62].

Taking the example of Drax's operations, it is difficult to ensure that negative emissions are not double-counted because the "entire system is contingent on the country that is producing that biomass robustly and accurately […] [yet] we have no enforcement capacity over another country to robustly and accurately report those land use change emissions to the UNFCCC" (Dr. Quiggin Testimony, [62]). Similarly, the Climate Assembly [63] found that the Drax plant's "biomass burning is currently using trees from the United States where […] They have been known to fell old growth forests to chop down into wood pellets to burn – so actually by burning such wood this carbon is released back into the atmosphere that would otherwise have been stored in the trees." Notwithstanding technological critiques, it is also unclear if the vast public subsidies—estimated at around £31.7 billion over 25 years [64], or between £155 and £181 cost per megawatt hour [65,66]—will pan out in the face of growing public resistance.

Despite these critiques, UK policies have sought to catalyse it to become a front-runner and "first-mover" in the BECCS technology domain [67,68], as outlined by its Business Model Consultation for BECCS [59] and its Biomass Strategy [136]. Several publicly-funded BECCS projects are at or very close to full operational capacity (see Table 1). It is worth reiterating that the future of BECCS as an important climate solution relies on the successful deployment of CCS [27]—which remains significantly undeveloped in the UK case.

The UK has at first focused on power and industrial BECCS—with the former nearing commercialisation via the Drax plant in North Yorkshire. Since 2018, government has sought to catalyse niche innovation by recognizing three main technology vectors: post-combustion CO_2 (from wood, waste and agricultural residues); capturing CO_2 streams from conversion processes such as gasification or steam reformation to be used for sustainable aviation fuels or hydrogen; and capture of CO_2 emitted from biological processes such as fermentation and anaerobic digestion ([70]: 122).

Government policies are also beginning to pay greater attention to hydrogen and fuel-BECCS through its industrial decarbonisation policy initiatives, which envision one industrial carbon capture and two EfW facilities—ensuring that these "could be some of the first projects in the UK to deliver BECCS" ([70]: 140). To accelerate niche technologies and innovations, it is applying landscape pressure via the target to achieve 10 GW of low carbon hydrogen by 2030. This is supported by its Net-Zero Innovation Portfolio (NZIP), which includes the Hydrogen BECCS Innovation Programme. Support will also be given to technologies that "can produce hydrogen from biogenic feedstocks and be combined with

Table 1
Planned and operational bioenergy with carbon capture and storage (BECCS) projects in the UK.

#	Name	Location	Partners	Capture (MT CO_2/year)
1	Drax Pilot	Selby	Drax Power, Mitsubishi Heavy Industries, C-Capture	365 tons per year [69]
2	Drax BECCS Project (Phase 1)	North Yorkshire	Storegga, Chrysaor, Shell and Total	4.3 (planned)
3	Drax BECCS Project (Phase 2)	North Yorkshire	Storegga, Chrysaor, Shell and Total	3.7 (planned)
4	Ince Bioenergy Carbon Capture and Storage (InBECCS) phase 2	Net Zero Northwest Cluster	Bioenergy Infrastructure Group (BIG), Peel NRE	NA (planned)
5	CCH2: Carbon Capture and Hydrogen Production from Biomass	Birmingham, UK	KEW Technology	NA (planned)
6	Cargill wheat	Manchester	CO2 purification	0.1 Mtpa

Source: (IEA CCUS projects database, [58]).

carbon capture ([70]: 124). Furthermore, landscape pressures can be observed in its specific technological performance targets, such as its commitment to 5Mtpa of engineered GGR by 2030. A total of 22 projects received £5 million each under the programme. Phase 2, launched in June 2023, earmarked an additional £21.2 million.

Demonstrative of government attempts to establish a niche-incubation space for BECCS are programs to catalyse novel biomass feedstocks, such as from algae and seaweed— as well as Biokerosene (SAF) BECCS which is supported through the Advanced Fuels Fund [70]. Notwithstanding broad policy support for experimentation and innovation, the more radical technological niche solutions are not eligible for existing subsidy schemes [59]. Recent industrial decarbonisation policies and mechanisms envision a prominent role for hydrogen BECCS—specifically the Net Zero Hydrogen Fund and hydrogen business model (ibid). Here we observe niche-regime interaction, governed by the Net-Zero GHG target applying landscape pressure. Though the government assumes a prominent role for BECCS to meeting net-zero goals, by its own admission they are underperforming at scale [70]. Consequently, they are yet to fully emerge from a niche, protected space. As Fig. 1 depicts, BECCS remains a top-down and regime-led process as its flagship projects rely on substantial government policy and financial support. Fig. 1 also shows how UK's recent policies, and its vast financial support for Drax, have sought to propel the nascent technologies from the niche into the regime space.

4.2. DACCS in the USA

Although in the past "top-down" climate regulations on emissions in industrial sectors—so-called "sticks"—largely failed, the Biden Administration's IRA (2022) and IIJA (2021) focus squarely on so-called "carrots" [126]—or rewards for compliance, and generous grants for research and demonstration. Three main pieces of legislation affect DACCS in the US: (1) The Chips and Science Act—the "brains"—which includes $54 billion for innovation in clean technologies; (2) The IIJA—the "backbone"—which directs $98 billion for clean technology and industrial decarbonisation infrastructure; (3) the IRA—or "the engine"—which is expected to result in more than $360 billion for clean technology R&D, infrastructure, and demonstration projects ([71]: 12). Under the IRA, DACCS are looking increasingly more attractive to private firms and investors [72]. For example, the Biden Administration has increased the reward to $180 per ton of CO2 captured, providing a strong policy "carrot" to direct attention to the US. Though access to carbon storage can be a major constraint on DACCS development [27], the US already has ten commercial facilities in operation situated adjacent to functional storage facilities, and twenty planned [69], as depicted in Table 2.

Evidence that DACCS is stradddling both the niche and incumbent regime can be found in the firms involved in the projects in the US (see Fig. 2), with several large Oil and Gas (O&G) firms vying for early dominance. We can, indeed, observe several niche-regime-landscape interactions. Specifically, the IRA's $180 per ton tax credit for carbon captured, in addition to landscape pressures such as the US commitment to net-zero GHGs by 2050, are providing niche-landscape interactions. As Nemet et al. [11] predicted, DACCS are rapidly becoming an entrepreneurial niche market space and are the most protected intellectual property in the CDR arena. Evidence for this can be found in the explosion of interest from smaller start up companies—e.g., CarbonCapture and 1PointFive (Table 2 above). Finally, though entrepreneurial players are numerous, most are supported by regime actors from the fossil fuel industry (e.g., Occidental Petroleum), as DACCS are seen as a potential way to stay in business for the next 100 years for the O&G industry [73]. Given the significant attention from small and big players, the IRA is beginning to provide a niche space protected from markets, as DACCS remain unprofitable without public support.

4.3. Cloud seeding in Australia

Cloud Seeding (CS) has a contested history, with a fair share of supporters and detractors. Farmers and hydroelectric companies, faced with drought, got behind earlier projects in Australia. Though the US used it as both a diplomatic and military tool, this does not appear to be the case in Australia ([7]: 306).

Cloud seeding in Australia emerged in a niche-regime space because the government has been involved in every major project since the

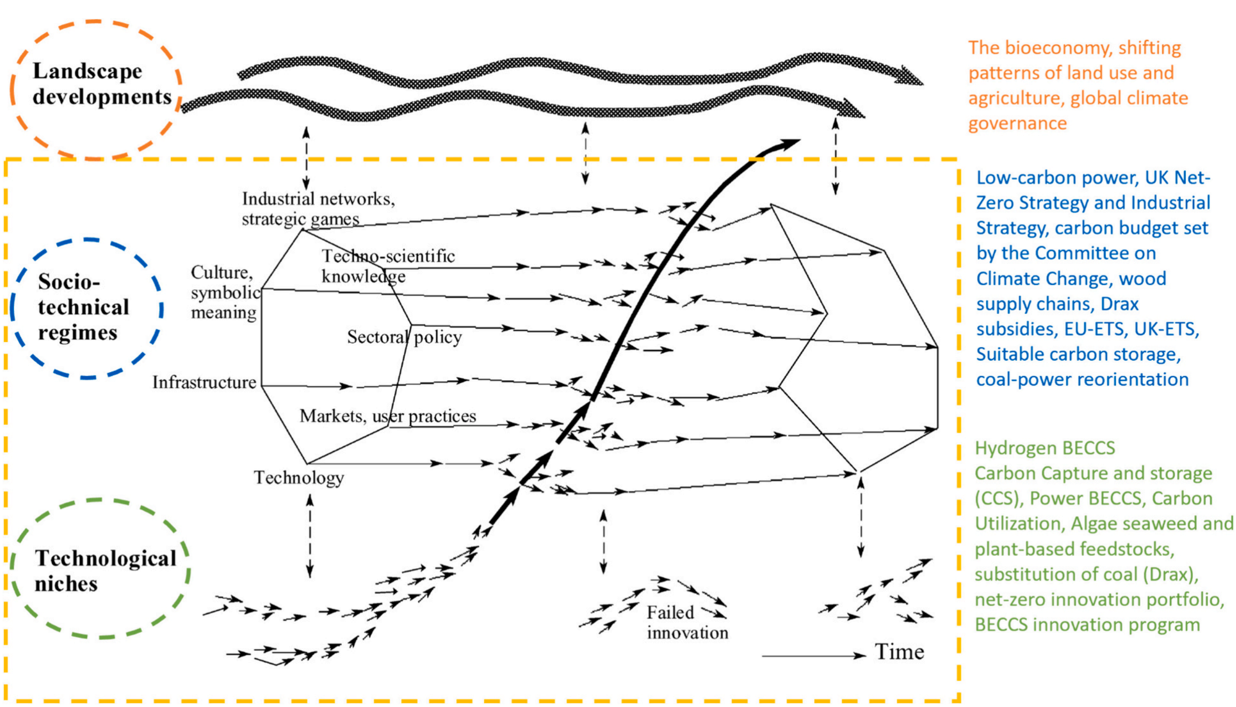


Fig. 1. The Multi-Level Perspective applied to Bioenergy with Carbon Capture and Storage (BECCS) in the United Kingdom.
Source: Authors.

Table 2
Planned and operational direct air capture projects in the United States.

#	Name	Location	Partners	Capture (MT CO2/ year)
1	AirCapture DACU	Nutrien Kennewick Fertilizer (WA)	AirCapure, Nutrien	NA (planned)
2	AirCapture Nuclear DAC	JM Farley Nuclear (AL)	Southern Company, Battelle, AirCapture LLC	NA (Planned)
3	Carbon Engineering Constellation Nuclear DACS	Byron Generation Station (IL)	Constellation, 1PointFive, Worley, Carbon Engineering, PNNL, U of IL	0.25
4	CarbonCapture DACU Carbon Cure	Gary Works (IN)	CarbonCapture, CarbonCure, US Steel	NA (planned)
5	Oxy CE DAC	Kleberg County plants (TX)	Occidental, 1PointFive, Carbon Engineering	1 (planned)
6	Oxy 15 CE DACs plants	Kleberg County (TX)	Occidental, 1PointFive, Carbon Engineering	2 (planned for 2030)
7	Oxy 15 CE plants expansion	Kleberg County expansion 2035	Occidental, 1PointFive, Carbon Engineering	3 (2035 planned)
8	Climeworks DAC	Brawley Geothermal (CA)	University of Illinois, Climeworks	NA (planned)
9	Climeworks Gulf Coast	MoU (LA)	Climeworks, Gulf Coast Sequestration	1 (planned)
10	DAC-1	Ector County (TX) train 1	Occidental, 1PointFive, Carbon Engineering	0.5 (planned)
11	DAC-1	Ector County (TX) train 2	Occidental, 1PointFive, Carbon Engineering	0.5 (planned)
12	DAC City	Silicon Valley (CA)	for industrial use, e. g., for use in greenhouses. The CO2 capture approach is based on a porous ceramic layer of monolithic rock.	
13	Avnos Demo	Southern California	Pacific Northwest National Laboratory; US DoE; Office of Naval Research	0.03
14	Bison Project	Wyoming	CarbonCapture; Frontier Carbon Solutions	10

Source: (IEA CCUS projects database, [58]).

1950s. Also, the unique Australian climate is well suited to deployment given that, unlike other locations around the world, silver iodide seeding efforts can have impacts that span months, rather than days [127]. The penetration of several private firms (Australian Rain Corp., Snow Hydro Ltd., WeatherTec, and Weather Modification) suggests that the niche is impacting the regime by proving technical feasibility (see Table 3).

Even though CS has a longer history of research and deployment than BECCS and DACCS, niche experimentation dynamics are still evident [74]. The accuracy and efficacy of CS deployment in Australia depends on precise understanding of the natural microphysics of clouds that are seeded, as well as how both clouds and precipitation patterns alter across geographic regions, and across different seasons and time periods (ibid). Understanding of weather patterns is reliant on radar designs that can derive and assess factors as diverse and diffuse as precipitation flux, the water mass of storms, the duration of weather events, and the size of CS particles. The Australian program continues to experiment with dual-polarization, dual-wavelength, and dual-Doppler radar capabilities, which all give different resolution (and have varying degrees of effectiveness in local contexts) [128]. This leads to an emphasis in Australia on real-world experiments, and also randomized research designs that have control groups of seeded versus non seeded clouds and different types of modified aircraft (ibid).

Given its history and technological know-how, CS is emerging from the niche and may soon settle on a favoured technology. Furthermore, since Australia has suffered major droughts in recent years—as well as forest fires from these droughts—it is being more seriously considered. Pressures on hydroelectricity production are pressing government and private players to find a solution to increase rain fall (see Fig. 3). Nevertheless, though the “governance of cloud seeding” [75] is garnering attention, civil society backlash is also growing in tandem with its prospective deployment.

5. Discussion: interactions, opportunities, and bottlenecks

In this section we discuss the emergent sociopolitical and cross-cutting themes from the three technologies and cases. These are on niche technological development and windows of opportunity, first, then followed by the concept of “fit and stretch” [76], which is demonstrative of the nuanced embedding of each respective technology within the regime, and finally transition bottlenecks.

5.1. Interactions of MLP levels and coevolution

In general, CS, BECCS and DACCS interventions are at very different phases of sociotechnical development (see Fig. 4). Nevertheless, all have emerged in niche spaces through coordinated actions by both regime and niche actors, guided by landscape pressures such as global climate change and the Paris Agreement. As shown in our case studies, a small group of firms are responsible for most of the innovations, garnering substantial public funding support.

On the other hand, CS resides in a landscape-driven regime space. In the local-global rendition of niche-landscape interactions, local niche experiments evolve to the global level as local outcomes are aggregated into more generic lessons and rules, thus allowing for more (global) actors to be enrolled and previous expectations to be adjusted [77]. Here we can observe spatial interactions from landscape pressures and niche developments stemming from the “local-global” (ibid). CS is nevertheless constrained by global landscape pressures that are constraining weather modification because of potential unknown and long-lasting consequences. Though the Environmental Modification Convention (1977) sought to preclude unilateral intervention into the climatic system, localised pressures such as drought—which negatively impact both agricultural and hydrogen energy processing in Australia—mean that these solutions might go forward without global support. This risks a “moral hazard” [55] that might “encourage behaviour that is individually advantageous but not socially optimal” ([17]: 276), especially at the global level.

We are beginning to witness interesting interactions and opportunities within and between sociotechnical systems, bringing attention to whole-systems approaches [78]. Getting back to climate interventions—which are, to be sure, technologies that have, and are currently, developing within the niche—it is clear that *landscape pressures* (climate change and the quickly decreasing carbon budget) impact the search for radical technologies in *niche spaces*. It is more difficult, however, to locate the collective *regime* for geoengineering technologies. While we have shown that BECCS in the UK and DACCS in the US are led by government and entrepreneurial firms—the latter are largely funded by incumbent firms or large private investors such as Bill Gate’s Breakthrough Energy Ventures—demonstrating the growing role of private and corporate interests actors, but also potentially reducing open debate and dialogue for geotechnologies [79].

In line with earlier MLP studies ([38,80]), we contend that BECCS and DACCS, and to a greater extent CS technologies, have thus far been

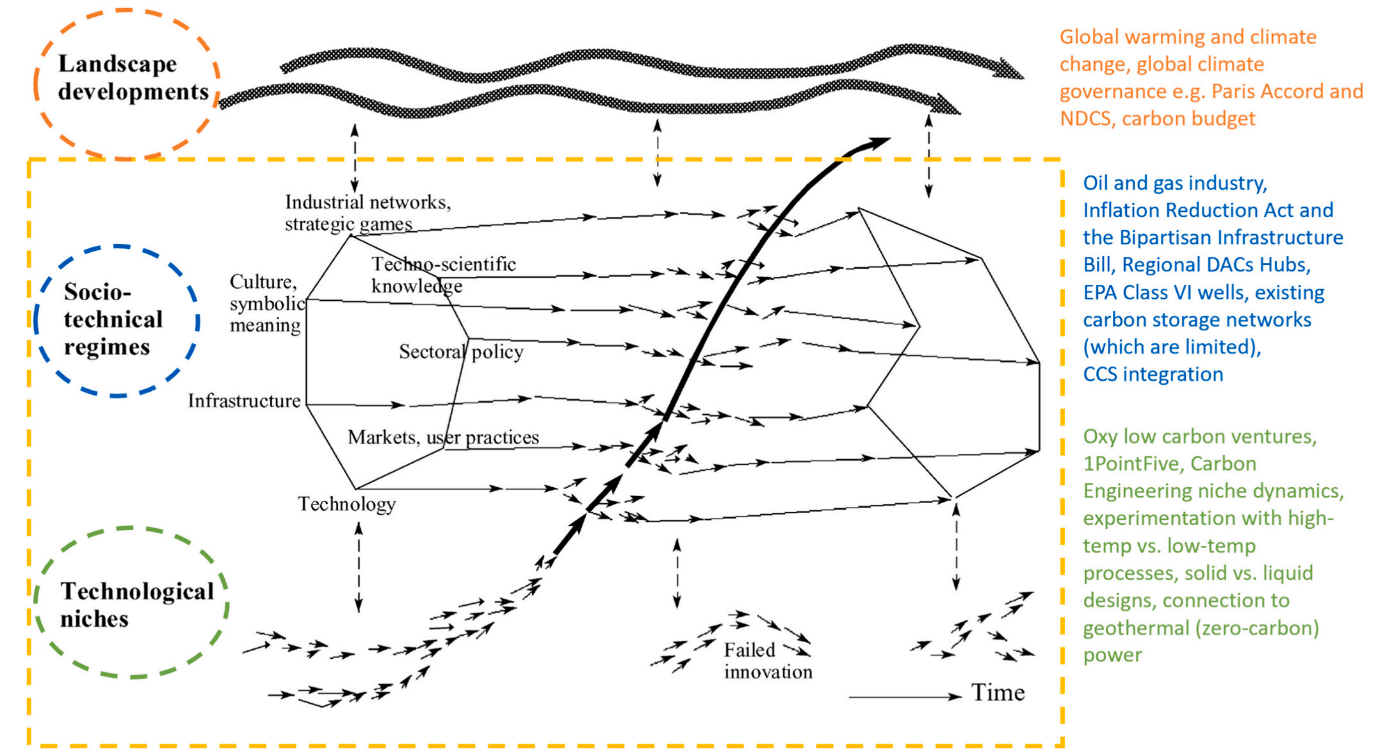


Fig. 2. The multi-level perspective applied to direct air capture in the United States.
Source: Authors.

shielded from mainstream selection pressures. Owing to both their costs and technological immaturity, they have until recently remained within niche incubation spaces—yet there is some evidence of impending "path-breaking innovations" ([81]: 1027). While BECCS was considered a "new niche" over a decade ago [27]—characterised as "emerging through overlap of the CCS niche and the biomass niche-regime" ([27]: 288)—evidence from the UK case suggests that it is emerging as a dominant industrial decarbonization technology—spearheaded by a network of industrial and central government actors, though costs and sustainability considerations loom large. While costs for DACCS remain prohibitive, the handsome subsidies on offer in the US have seriously changed the landscape. Though it is difficult to predict when DACCS might be survive in the absence of government support, carbon targets and subsidies for CCS are seen as continuing to drive innovation and exploration [82,83].

5.2. Windows of opportunity

The MLP envisions that landscape pressure on existing and emergent regimes "create windows of opportunities for niche innovations" ([123]: 492). In this context, major policy changes—e.g., conformity to the Paris Agreement—both shapes and directs "support for industries […] and economic frame conditions" ([129]: 46). The Paris Agreement has, accordingly, opened a window of opportunity for radical geo-engineering solutions, which are now "directly in the spotlight of many climate change mitigation discussions ever since" ([84]: 3). This in turn helps to build awareness to, and induce need for, new technologies such as CDRs and SRMs [130].

Specifically, the Paris Agreement's carbon budget and 2 °C temperature target are landscape pressures opening opportunities for BECCS and DACCS. We can observe, especially for social acceptance of BECCS and DACCS, the "weakening reproduction of core regime elements" [129]—especially considering the reluctant but eventual acceptance by incumbent fossil fuel companies. Changes to the structure or architecture of sociotechnical systems [85–87], finally, are less relevant for DACCS as they are for BECCS or CS since the former can be situated anywhere there is water and power.

5.3. Fit, stretch, conform, and transform

We build on the discussion above by introducing three concepts: "fit-and-stretch," "fit-and-conform," and "stretch-and-transform"—which are derived from transition and innovation studies [76,131]. In early phases of technological transitions, technical form and design, and user context and functionality, are the predominant forces. Emerging from the niche, in this setting, implies that both technical and social benefits must be harmonised [88]. Following Geels' [76] example, in the early 20th century automobiles were designed as "horseless carriages." Over time, designs embedded new materials and technologies, but maintained a "fit" that was familiar to the users' preferences. In another example, General Electric designed the light bulb to resemble gas-fired streetlamps to ease the embedding of the strange new technology into existing regimes [132].

Moreover, harking back to the MLP, Smith and Raven [81] argue that new innovations need to properly utilise a "protective space" during a "nurturing stage" to leverage learning, expectations, and networks. Sovacool et al. [89] advance this perspective by arguing that radical climate technologies demand that the "existing socio-technical regimes" often involve a "stretch-and-transform" pattern since their diffusion requires adjustments in wider contexts, which are likely to be more difficult, entailing various struggles. On the other hand, less radical niche innovations can be "fit" easily into current regimes [90,91]; "The implication is that the niche innovation is developed in such a way that it fits into and conforms to a relatively unchanged selection environment" ([81]: 1030) and are more likely to be supported by incumbent actors [89]. This requires "Limited institutional change, implying that niche-innovation needs to compete in existing selection environment ('fit-and-conform') and "incremental adjustment and layering" (Geels et al. [90].

Since BECCS are integrated into existing systems, they can be seen as

Table 3
Planned or operational cloud seeding projects in Australia.

#	Name	Location	Partners/sponsors	Type
1	CSIRO	Snowy Mountains	Government	CS first experiments (1947–1956)
2	CSIRO	New England, Warragamba, South Australia	Government	1955–1963
3	Tasmania I	Tasmania	Local government	1964–1971
4	Tasmania II	Tasmania	Local government	1979–1983
5	Tasmania III	Tasmania	Local government	1992–1994
6	CSIRO Emerald	Queensland		Experiment, 1972–1975
7	CSIRO Victoria	Victoria		Experiment, 1979–1980
8	Wheatbelt CS	Australian Northern Wheatbelt	Western Australian Weather Research Association, Western Australian Government, School of Physics and Geosciences at the Western Australian Institute of Technology	Dry ice at cloud tops Experiment, 1980–1982
9	Tasmanian Cry-Ice (DICSE)	Tasmania's Central Plateau	Government, Hydro-Electric Commission Tasmania Australia (1975–1984) and 1992–1994	40 KG dry ice/h to clouds
10	Melbourne Water Wintertime Cloud seeding	Melbourne	Melbourne Water Corporation	40 KG dry ice per hour in clouds 120 km east of Melbourne, Experiment, 1988–1992
11	Snowy precipitation	Snowy Mountains	Government, Snowy Mountains HydroElectricity Authority (SMHEA)	Enhanced snowfall (1988–1991)
12	Drought relief cloud seeding	NW of New South Wales	Local and central Government	Dry ice cloud brightening, 1994
13	Midlands Drought relief project	Tasmania, the Midlands, and the East Coast	Australia Gov (1973–1995)	Clouds seeded with Agl 5 KG in 1995
14	Tasmanian Area cloud seeding	Tasmanian Central highlands	TASCO (gov.). Australian gov (1998–2003)	14 KG cloud seeding in 2003; 20 KG cloud seeding in 2002 with aircraft
15	Snowy mountains cloud seeding	Snowy mountains	Snowy Mountains Hydroelectric Authority; Snow Hydro Ltd. CSIRO, Snowy Mountains Hydro-electric Authority, New South Wales Government, Snowy Hydro Ltd., NSW Natural Resources Commission	Cloud seeding program (1950s to 2005)
16	Southeast Queensland Cloud Seeding (CSRP)	Queensland	Weather Modification Inc.	Aircraft cloud seeding (2007–2009), $7.6 Government funds
17	Hydro Tasmania Cloud seeding	Tasmania and the West Coast	Australian Gov (since 2010)	12 to 31 Cloud Seeding flights per year since 2010
18	WeatherTec Australia	Brisbane	WeatherTec and Australian Rain Corp. Australian Government / National Water Commission. Further partners/ sponsors: University of Queensland, University of Wollongong (2007–2008)	Increase precipitation with cloud ionisation technology; negative charges to clouds with aerosols (2007)

Source: adopted from [61]. * Commonwealth Scientific and Industrial Research Organisation (CSIRO).

stretching and transforming into low-carbon power. In this sense, BECCS in the UK are developing within an "active niche space" and supported by regime actors, enabling it to stretch into existing systems. BECCS aligns to the "stretch-and-transform" transition pathway and, hence, is governed *vis-à-vis* "changes in mainstream selection environments in ways favourable to a path-breaking niche innovation" ([92]: 2).

DACCs can be construed as "fit-and-conform" niche technological developments as they largely fit within "unchanged selection environments"—e.g., not too much pressure to change the regime required for widespread development DACCS, which can be deployed wherever there are reliable power and water resources, are not disruptive to the incumbent regime. Should their scaling-up lead to substantial usage of energy and water, however, DACCS could well lead to widespread civil backlash.

CS can be seen as within the "Stretch-and-conform" space. Though CS technologies can be deployed, it is hoped, without changes to sociotechnical structures and environments, it also must conform to strict international guidelines and protocols (e.g., Article 5 of the UN Convention on the Law of the Non-Navigational Uses of International Watercourses). Consequently, it is the riskiest from a civil society perspective, as they are the most likely to "tamper with nature" [53]. For CS, technology lock-in would matter in a future scenario where all other technologies fail to effectively confront climate change. The question remains, however, if DACCS and, to a lesser extent CS technologies, can be sufficiently "escape the niche-level and be incorporated in the ST-configuration" (see Fig. 5).

5.4. Transition bottlenecks and risks

We draw attention to bottlenecks that are revealed through the MLP, such as risks of technological lock-in of inferior solutions [27]. Climatic problems that are elevated to global policy agendas, however, can lead to "transition bottlenecks" which can be used as a "methodological aid to focus socio-technical scenarios" ([15]: 3). Furthermore, consistent with Geels [12]—when new "elements are introduced in the regime, they may trigger further changes if changes at the landscape level create pressure and new opportunities"—we have identified how the 2 °C temperature target in the Paris Agreement is acting as a landscape pressure in each respective country, as reflected in their NDCs.

For BECCS, the broader claims of inefficiency point towards potential negative lock-in solutions [93]. BECCS, like CCS, has been bolstered by "the backing of a segment of the scientific community" ([27]: 287)—though it remains a contested technology (Climate [63]). While the UK Climate Change Committee (CCC) report specified that the UK target should be 20 MT/year for carbon captures using BECCS, the report was mired in controversy related to the close ties with industry, with Dr. Rebecca Heaton from Drax forced to step down from the Committee. The

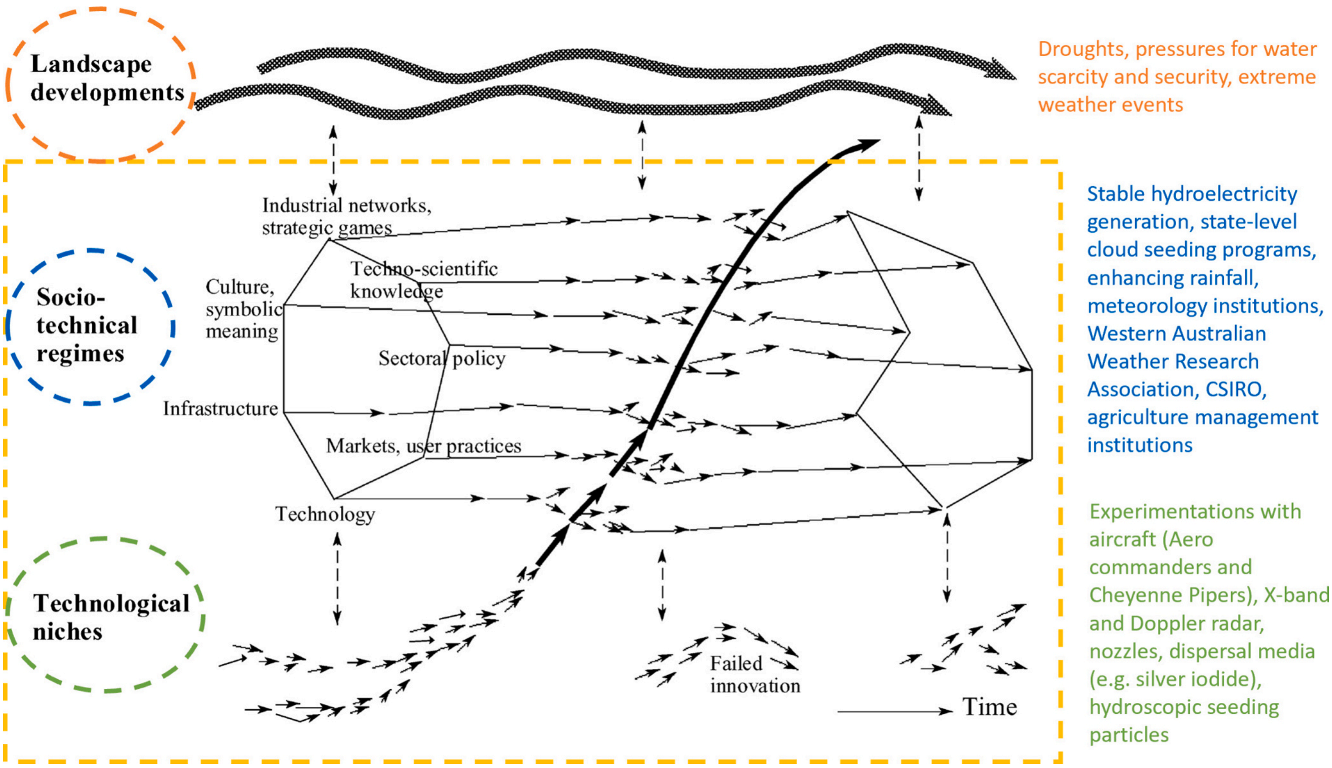
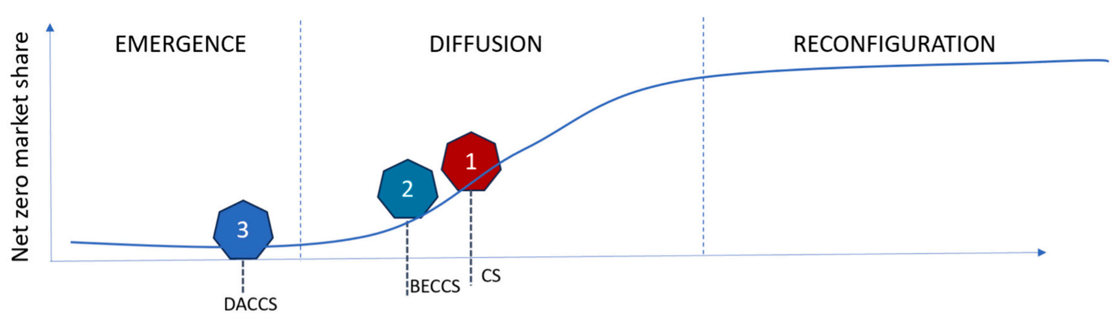


Fig. 3. The multi-level perspective applied to cloud seeding in Australia.
Source: Authors.



Sector	Emissions & Stage of transition	Nature of the problem now	Priorities for international action	Priority for institutions
1	Cloud Seeding DIFFUSION Eighteen projects, history of experimentation and deployment	High costs and uncertainty Global commons issues Moral hazards	Climate-induced drought affecting agriculture and hydroelectricity	Collective planning and deployment Stepwise and measured experiments
2	Bio-energy with CCS EARLY DIFFUSION Six commercial plants, fifty-six planned	Tracking embodied emissions High costs, inefficiencies	Carbon-embodied feedstocks Proof of origin and sustainability Carbon-border adjustments	Ensure transparency on public funds Continually monitor GHG reductions
3	Direct Air Capture EMERGENCE Twenty-seven plants, 130 planned or developing	Technological immaturity Few reuse outside EOR High cost, energy and water usage	Cross-country R&D Pool resources Track GHG reductions at origin	Monitor energy, storage, and water resources

Fig. 4. The sociotechnical dynamics of BECCS, DACCS, and CS in comparison.
Source: Authors. DACCS = Direct Air Capture with Carbon Storage. BECCS = Bioenergy with Carbon Capture and Storage. CS = Cloud Seeding.

CCC [94] estimated BECCS could reach 45–95 Mt./CO2/year by 2050. On the other hand, the Climate Assembly [63] found that "Only 42% of assembly members 'strongly agreed' or 'agreed' that" BECCS and DACCS "should be part of how the UK gets to net zero, while 36% (BECCS) and 39% (DACCS) 'strongly disagreed' or 'disagreed'" (Climate [63]: 26). In addition, the CCC [94] also admits that only 40 % of members supported

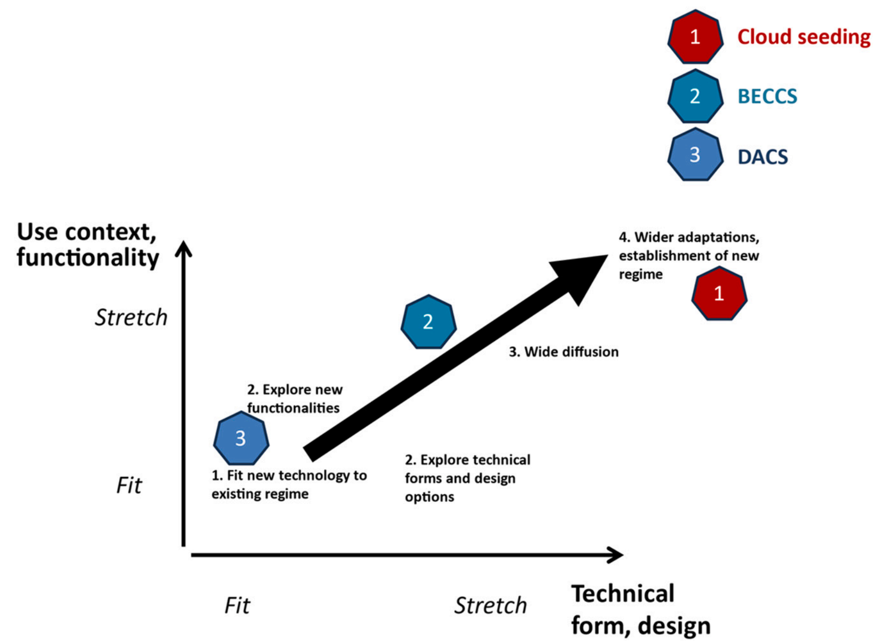


Fig. 5. Fit-stretch dynamics for cloud seeding, BECCS and DACCS.
Source: Authors, modified from [76] and from Dijk et al. [111].

DACCS and BECCS owing to concern about carbon storage as a "magic solution which doesn't get to the crux of the problem (reducing emissions)." For DACCS, energy and storage constraints—as well as costs—feature as predominant bottlenecks (Fig. 6).

There is indeed one immense technological and infrastructural constraint to both BECCS and DACCS: their reliance on suitable carbon capture and storage options. This also means that these technologies are still embedded within the fossil fuel regime [27]. Consequently, "The failure up to now of policy to advance CCS [...] provides additional insights as to effective DAC policy. Governments have spent billions to attempt to advance CCS on fossil-fuelled power" ([83]: 4). In other words, the question is: are governments simply putting wine in old bottles [95]? Concerns related to the geological storage potential for carbon [133] are buttressed by other risks with respect to their technological readiness [28], as well as broader justice issues [134]. Much debate continues to surround these issues since the subsidies of CCS, for example, are largely being provided to conventional energy industry actors [11,84,96]. The hope is that innovation will enable it to break free from public subsidies, though expectations of future technological performance remain largely unknown [11], especially given the physical, financial, and technological risks [79].

Finally, geoengineering technologies such as CS are being legitimated "through speculative, evolving assessments implicitly or intentionally support novel technologies" ([97]: 2). This can lead, nevertheless, to technocentric reliance, leading to blind spots in policymaking [98]. While such technologies could buy time for climate policymakers and incumbent industry players [97,99,100], they can potentially siphon off limited public resources and subsidies away from proven technologies [101]. In this vein, another issue—which promoters of geoengineering solutions largely fail to address—are GHGs besides carbon dioxide, such as methane emissions, with a Global Warming Potential of 82.5 carbon equivalents using a 20-year conversion method [72,102,103].

6. Conclusions and policy implications

In this article we explored two carbon dioxide removal (CDRs) technologies—bioenergy with carbon capture (BECCS) and direct air capture carbon capture (DACCS)—and one geoengineering intervention technology, cloud seeding (CS). As there is still limited curtailment of greenhouse gas emissions in all sectors, these technologies are becoming increasingly more relevant as potentially viable, backstop solutions. We developed three national case studies, exploring BECCS in the UK, DACCS in the US, and CS in Australia.

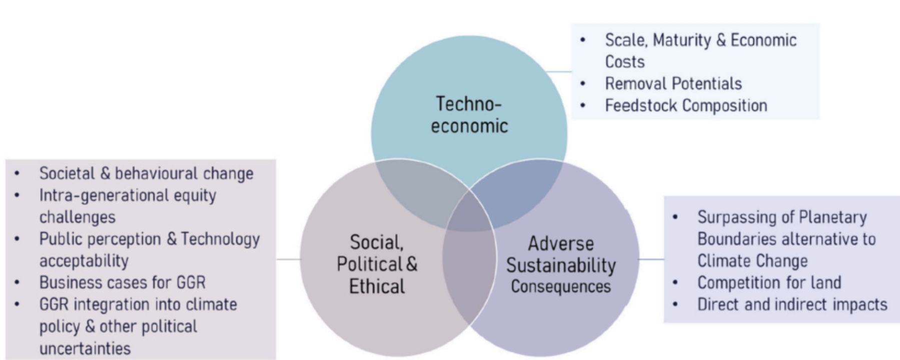


Fig. 6. Summary of risks facing BECCS, DACCS, and CS.
Source: Authors, adapted from Mendez et al. [112]. GGR = greenhouse gas removal.

While prior geoengineering and CDR research predominantly focuses on technology readiness and emissions mitigation potential [11], here we focused on sociotechnical and sociopolitical issues that, so far, have precluded what otherwise might be a more rapid and widespread deployment of these technologies. We applied the Multi-Level Perspective (MLP) to tease out the interacting landscape, regime, and niche levels germane to each technology within its sociotechnical embedding and demonstrated a series of interactions between the MLP's three levels. We then placed each technology within a fit, stretch, and conform context. The analysis showed that landscape pressures will continue to exert exogenous shocks on the search for geoengineering and CDR solutions as the world rapidly approaches 2050. Myriad regimes and power dynamics will also continue to be important. Finally, the niche—and the successful incubation of radical technologies within these protected spaces—are likely to determine how regimes will change over time.

We close with several implications for policy and future research. From one perspective, future innovation and deployment of renewable energy technologies might weaken the fossil fuel regime. The latter favours CDR, NETs, and similar climate interventions because they will, in general, fit within, or be able to stretch into, current regimes and technological systems [48]. Yet, should renewable and clean energy technologies prove capable of driving significant and drastic GHG reductions, emerging geoengineering regimes as well as niches will likely weaken—especially since, unlike DACCS and cloud seeding, renewable energy produces a usable product that already has weaned itself off public subsidies in many countries. Future research might also consider the implications of global technology spillovers for geoengineering technologies, and the implications for rates of innovation [104–106].

Furthermore, the landscape pressures from global climate policy circles—including the Paris Agreement and IPCC reports—might be exerting *undue* pressure to search for niche geoengineering solutions—leading to a focus on intractable technological solutions [107]. Indeed, the necessity to include geoengineering solutions in Integrated Assessment Models (IAMs) that predict technological needs until the year 2100 is somewhat precarious as none of these technologies yet exist at scale [48]. The result might well be an "over-reliance on carbon removal strategies, which may enable business as usual rather than the drastic scaling back of fossil-fuel use" ([10]: 17).

This also begs the question of whether the 1.5 or 2 °C temperature target is helpful—or whether it is high time for a radical rethink on this target, and a move away from carbon budgets [108–110]. In other words, should researchers and policymakers consider models to adjust the temperature target to well below 2 °C [11,97], and integrate technologies that already or soon will be scalable and deliverable? This means shifting the debate back to the obvious dominance of the fossil fuel regime, which might help moving towards solutions and models not dependent on the hope that negative carbon emissions will become a reality [135]. In addition, by revisiting the main source of GHGs, efforts might focus more on localised technical solutions—such as in the food sector and wetlands—which could become a more effective point of departure for climate policy and regulation. In this vein, it need not be a "deploy or not deploy" dichotomy about certain technologies, but rather a more open debate about varying degrees of deployment consistent with different sociotechnical niches and regimes.

CRediT authorship contribution statement

Kyle Herman: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Benjamin K. Sovacool:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

We assert the following:

- All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.
- This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.
- The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Data availability

Data will be made available on request.

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