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Effective and fair policy to mobilize industrial carbon dioxide removal

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Abstract
Carbon dioxide removal (CDR), which emerged in climate models as a largely abstract idea, has evolved into a set of specific methods and spawned calls for supportive policies. Industrial approaches through the use of biomass combined with carbon capture and storage (BECCS), as well as direct air capture with storage (DACS) compete for scarce resources. We examine emerging conflicts that shape policy design to mobilize industrial removals by examining ideas, institutions, and interests and their interplay, conflicts, and alignments. We base our analysis on semi-structured interviews and stakeholder workshops in addition to emerging CDR policy literature. Arguably, technology developers, industry, civil society, and policymakers put forward ideas in a way that tends to advance their interests over others. Dominant ideas of CDR methods – including the notion that these would inherently be done at a large scale – have proven challenging to forming constructive policy discussion and made unhelpful generalizations of environmental performance, social desirability, or scalability of entire CDR methods. We outline opportunities and barriers to advance sound policies that scale the removal of CO_2 effectively, efficiently, and fairly by outlining synergies, trade-offs, and conflicts in the current policymaking landscape of BECCS and DACS.

Keywords Carbon dioxide removal · Bioenergy with carbon capture and storage · Direct air capture and storage · Mitigation policy · Political economy · Public acceptance

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1 Introduction – Ideas of removals from categories to technologies

The road to supporting the scaling of carbon dioxide removal (CDR) in climate policy started as an abstract idea of "negative emissions" (Möllersten and Yan 2001) and has been bumpy (Honegger et al. 2021a). As CDR was initially ignored and later vilified as a dangerous distraction (Schenuit et al. 2021), policies supporting it have only recently emerged in OECD countries (Schenuit and Geden 2023). CDR methods are still often summarized in broad categories. Policy discussions increasingly recognize sector-specific support needs (Karlsson et al. 2017), and industrial institutions – startups and incumbents alike – have started advocating for policies that accelerate their respective approaches in biomass processing with carbon capture and storage (BECCS) and Direct Air Capture and Storage (DACS). Acknowledging the broader context of (carbon dioxide) removals (Carton et al. 2020), we focus here on those that include capturing, transporting, and storing CO_2 underground, given that such industrial approaches intersect with the broader theme of "carbon management" and its reliance on effective policy support (Honegger 2023).

The problem this paper seeks to address is the risk of ineffective or unfair CDR policies – which can result from narrow ideas representing special interests dominating the policy discourse. As CDR evolved from an abstract concept in climate models to actual industrial policy the policy landscape remains fragmented due to competing ideas, institutional dynamics, and differing perceptions of CDR's role in climate mitigation. The two primary industrial CDR approaches – BECCS and DACS – compete for scarce resources, raising questions about their environmental performance, scalability, and social desirability. While policymakers, industry players, and civil society actors engage in shaping CDR policies, their priorities and underlying motivations often lead to misalignments and conflicts. This study reveals how ideas, institutions, and interests interact in the policymaking process for industrial CDR, identifying barriers and opportunities for effective, efficient, and fair policy frameworks.

Given its importance within the EU, we focus on Germany as a case study for policy discourse at the national level. Germany has also one of the biggest industrial sectors and influential industry players and has been actively engaged in developing a carbon management and negative-emissions strategy in recent years – accompanied by lively discussions on residual emissions and the role of carbon management practices. Public opposition had stalled carbon management development in Germany for decades, but recent developments point to a decisive shift in policy and public opinion on this matter, making it an even more compelling case to examine.

Through employing the 3-I framework (Hall 1997), this research contributes to ongoing discussions by identifying how different policy instruments—carbon removal obligations, technology standards, emissions trading, subsidies, and procurement mechanisms—can be designed to effectively and equitably scale industrial CDR. By examining the synergies, trade-offs, and conflicts between key actors, the study aims to inform policies that maximize environmental and economic benefits while minimizing unintended consequences.

2 Methodology - examining ideas, institutions, and interests

2.1 Research design and data collection

A multi-method approach was employed for data collection – combining semi-structured interviews, stakeholder workshops, policy archives, and CDR literature as the input data into our qualitative content analysis. Data was collected through expert interviews conducted between August and October 2022, and three stakeholder workshops held in 2022 and 2023. We pursued a qualitative content analysis to interpret and analyze the resulting data – identifying patterns, themes, and meanings – utilizing the organizing structure of the 3-I framework (Hall 1997; see Section 2.2). This process involved identifying key categories of Institutions, Ideas, and Interests and exploring the deeper insights that would flow from such structure.

The study conducted 12 semi-structured interviews with technology developers, industry representatives, policy experts, and academics to ensure diverse perspectives (Online Resources 1, 2). While a broader range of stakeholders (e.g., scientists, international and multilateral organizations, media, the legal and judicial systems, and vulnerable populations) are critical factors to be considered, we only interviewed stakeholders whose expertise is on BECCS and DACCS (Supplementary Material Table 1).

Participants were selected based on their direct involvement in or influence over CDR policy design. Interviews were recorded, transcribed, and thematically analyzed to extract key ideas, institutional roles, and stakeholder interests (see categorization of institutions in Section 4). Participants were informed that no statements would be attributed to their names.

Three stakeholder workshops and a deep dive into the CDR literature of the last decade complemented the interviews (Online Resource 3). The first stakeholder workshop was conducted in person during the United Nations Framework Convention on Climate Change (UNFCCC) meeting in Bonn in 2022, followed by a second online workshop later in 2022. The third and final workshop was organized in Berlin in early 2023. The combination of in-person and online meetings maximized the range of participants in geography and focus, including institutions in international climate governance, CDR experts, and national policymakers. These interactions allowed us to unpack many of the ideas and interests held by various types of institutions spanning environmental NGOs, (German) government agencies, and industries, including notably CDR solution providers, CDR experts, and the interdisciplinary social sciences and humanities team of CDR-PoEt.

The interviews and workshops sought to elicit inter alia views on policy instruments including carbon removal obligations, technology standards, Emissions Trading Systems (ETS), subsidies, reverse auctions for public procurement, and other regulatory measures. Moreover, we sought to identify ideas of CDR and CDR policy more broadly to observe alignments of ideas and institutions and see how ideas may serve to advance specific interests – ultimately identifying how (mis-)alignment of interests may cause synergies and conflicts in policy.

The study also conducted a comprehensive policy and literature review to track emerging CDR policies and regulatory frameworks over the past decade. The policy tracking was done at the global level, with particular attention to Germany. The literature review contextualized findings from interviews and workshops within the broader academic discourse.

2.2 Analytical approach

This article analyzes the interconnected ideas, institutions, and interests of BECCS and DACS. We examine qualitative data gained through expert interviews, stakeholder workshops, and tracking of emerging policy initiatives with an approach inspired by the three "I" frameworks (Fig. 1). We unpack diverse technology ideas associated with BECCS and DACS in Section 3. We then map private and public sector institutions and their interests in Section 4. In Section 5, we discuss where synergies and conflicts might arise in policymaking. While we recognize that institutions legitimately pursue their interests, including by advancing certain ideas over others, our conclusion (Section 6) aims at preventing ineffective, inefficient, or unfair policies and incentives.

Our qualitative content analysis is structured by the *3-I* framework: its focus on the interplay of "ideas", "institutions", and "interests" in the political economy (Hall 1997) allows the identification of patterns linking categories of institutions with a set of ideas and associated interests (Kuckartz and Rädiker 2023). In the realm of *ideas*, we unpack contradictory constructions of BECCS and DACS as technologies or categories. Focusing on *institutions*, we examine not merely established institutions e.g. of governments and civil society organizations, but also those emerging as start-ups and incumbent industries moving into removals as a new business opportunity. Thirdly, we examine the respective *interests* that may be ascribed to those institutions based on our observations as well as judging by their economic ambitions (Fig. 1).

3 Ideas

We start by unpacking the ideas involved in the notion of carbon dioxide removal (CDR) itself, which embeds ideas of BECCS and DACS.

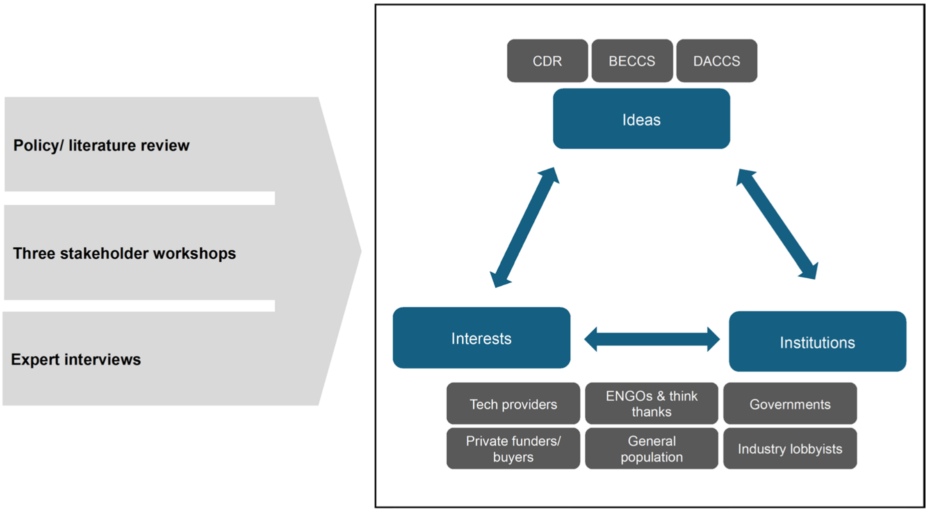

Fig. 1 Our methodological framework for analyzing the dynamics in CDR policy development through the 3-I framework. Source: Authors expanded Hall (1997)'s 3-I framework

3.1 Unpacking ideas of CDR

Moving away from the earlier concept of climate engineering, participants framed carbon removals in two ways: as a *mitigation result* (cf. Honegger et al. 2021a, b) or as a *technology*. The *mitigation result* perspective focuses on measurable removal outcomes, distinguishing them from emissions reductions or avoided emissions. This approach requires evaluating the full lifecycle of an activity to confirm its impact (Tanzer and Ramírez 2019). The *technology* perspective, on the other hand, is reflected in acronyms like BECCS or DACS, which describe technological value chains. Related terms such as Carbon Capture and Storage (CCS), Carbon Capture and Utilization (CCU), or Carbon Capture, Utilization, and Storage (CCUS) follow the same logic but do not specify the carbon source.

While industrial stakeholders use both perspectives, civil society organizations tend to prioritize the mitigation result perspective (Bellona 2022). Their focus is on demonstrating tangible removal outcomes while ensuring environmental integrity (Honegger et al. 2021a, b).

3.2 Unpacking ideas of BECCS, BiCRS and BCCS

The idea of using biomass to remove carbon from the atmosphere first appeared in integrated assessment models in the early 2000s. Initially, it was referred to as "biomass-based sequestration technologies." Later, it became known as "BECCS" in climate models and scenarios used by the IPCC (IPCC 2007). While technical audiences are well aware, it is important to highlight that numerous paths lead to combinations of biomass utilization resulting in usable energy (electric power and heat) from waste incineration, biomass cofiring (e.g. in cement plants) to dedicated biomass powerplants or even biochar production plants.

Some stakeholders have sought to emphasize the removal results of such activities and even go so far as to remove the notion of energy generation by introducing the idea of 'Biomass with Carbon Removal and Storage (BiCRS)' (Sandalow et al. 2021). The BiCRS acronym blurs the lines of CDR ideas (see Section 3.1) by describing technology and results in a single term – in contrast to the common acronyms (BECCS, CCS, and CCU), which more modestly focus on technology chains. A simpler terminology such as BCCS would avoid this.

Among most stakeholders, the common idea of BECCS is the greenfield construction of a power plant. This idea implies a growing demand for biomass, which is at the roots of most civil society organizations' rejection of BECCS – reminiscent of first-generation biofuels and their rejection a decade ago (Honegger and Reiner 2018). Such a view is reinforced by those cases where increasing biomass energy demands may indeed have triggered unsustainable logging activities (Miller 2021).

New ideas of BECCS, however, emerge with key variables including (a) the type of biomass (including focussing on biomass already in circulation or sustainably sourced), (b) the type of energy use (if any), and (c) the sector involved in its implementation. In principle, any economic activity with biomass can be combined with carbon storage. Biomass-processing sectors include agriculture, forestry, pulp and paper, construction and furniture production, energy, municipal waste processing, and productive industries including notably cement and chemical industries. Emerging ideas of BECCS in those sectors include:

- Power plants and or heating furnaces utilizing waste biomass only with CCS.
- Waste incinerators that also produce power and heat (i.e., waste-to-energy) with CCS.
- Pyrolysis for biochar production with utilization of heat and additional capture of carbon for storage.
- Industrial processing of biomass for heat (e.g., cement industry) or other production processes (e.g., chemical industry) with carbon capture and storage.
- Production of low-carbon fuels e.g., biogas (methane) or hydrogen from biomass with carbon capture and storage.
- Biomass-fuelled cement plants with capture and storage.
- Residues and wastes from forest harvesting or forest industries (e.g., sawmill residues and black liquor) as a source of biomass.

This shows that environmental performance, social desirability, and actor interests vary significantly. As a consequence, the idea of BECCS may need to evolve from a single technology to a category. Stakeholders are beginning to adopt such nuance – noting for example the environmental benefits of retrofitting existing waste-incineration plants with CCS (i.e., achieving emissions reductions and removal of CO_2 without altering biomass flows). Yet, our engagements showed that many civil society organizations remain invested in the idea of BECCS as a technology to be rejected for sustainability concerns.

3.3 Unpacking ideas of DACS

Ideas of "DACS", direct air capture and storage (or sometimes "DACCS" – direct air carbon capture and storage), are perhaps more homogenous than those of BECCS. The idea of DACS is similarly becoming more complex and gradually including novel technological options. DACS has emerged from a handful of innovators developing thermo-electric capture technologies via liquid solvents (L-DAC) or solid sorbents (S-DAC). Ideas of DACS diverge conceptually regarding storage, whereby a default would be the same CCS-based storage in geological formations as in BECCS or fossil-CCS, but other options have been advanced including mineralization in basaltic rock or recycling concrete (a form of CCUS).

The dominant idea of DACS characterizes it as a cost and energy-intensive and therefore niche form of removal. Yet land and water requirements vary significantly as some DAC technologies, for example, even gain water from ambient air (McQueen et al. 2021). DACS is often seen as a "pure" CDR technology as it does not produce any goods other than the service of carbon removal (Beaumont 2022). This has earned it a particular view among NGO stakeholders and in public perception. Incumbent companies in the CCS space, however, emphasize the small volumes that current DACS plants can process.

The idea of DACS is loaded with an expectation of cost reductions (Lackner and Azarabadi 2021; Realmonte et al. 2019) where insiders emphasize opportunities including proximity to storage sites. While many expect the cost of DACS to drop to about USD 200–300 per tCO_2 (Climeworks 2023b; Favasuli 2022), unexpected cost increases (Climeworks 2022) and estimates between USD 226/tCO_2 and USD 1000/tCO_2 for commercial plants (IEA 2022a; Plumer 2023; Sievert et al. 2024) cast doubt. To some, the feasibility of DACS is symbolic of the challenges of CDR overall, given its public-good nature and lack of revenue sources other than carbon markets or subsidies (Michaelowa et al. 2023).

Radically new types of approaches (e.g., Heirloom) blend CDR categories by leveraging the chemistry of enhanced weathering to achieve a new type of DACS.

Forms of DACS – planned or future – include the following possibilities:

- **Solid DAC (S-DAC)**: renewable energy sources (e.g., geothermal, heat pumps, industrial waste heat, or other sources of lower quality thermal energy) due to its lower temperature heat requirement at the separation phase (i.e., 90–100 °C). S-DAC is modular and more suitable for a small scale (i.e., 50 tCO_2/year per unit). Maintenance can require regularly replacing sorbents for S-DAC (IEA 2022a; McQueen et al. 2021). *Examples: Climeworks*, *Global Thermostat*.
- **Liquid DAC (L-DAC)**: often relying on natural gas for heat due to its higher temperature requirement. While L-DAC is more suitable for large-scale operations (e.g., 0.5–1 $MtCO_2$/year), it requires potassium hydroxide, calcium carbonate, and water (IEA 2022a; McQueen et al. 2021). *Examples: Carbon Engineering*.
- **Emerging DAC technologies**: Multiple start-ups aim at increasing energy efficiency (e.g., Heirloom, Avnos, Carbyon) or the use of different sorbent/solvent materials (AspiraDAC, Calcite-Origen).

One area of divergence related to the *idea* of DACS regards the term itself – i.e., whether the method should be described as DACCS or DACS. The former conceptually links DAC with CCS, thus establishing a connotation with past attempts at decarbonizing fossil fuels (e.g., coal plants) or ongoing use cases of carbon dioxide for enhanced oil and gas recovery, as well as efforts to lower emissions in the oil and gas industry. The latter (DACS) is advanced by DAC technology providers to distinguish this CDR method more sharply from the CCS term, which they see as problematic for public perception.

4 Institutions and interests

Based on our observations we group institutions in the emerging BECCS and DACS ecosystem as follows: (1) technology providers (including BECCS, DACS, carbon storage and transport), (2) private sector credit buyers/funders, (3) governments/regulators, (4) lobbyists and industry representatives, (5) environmental NGOs and think tanks, and (6) various publics. In this section, we examine the structure of interests, their ability to influence, and potential conflicts among the identified categories of institutions to better understand the dynamics of influence on the development of public policy (Table 1).

Boettcher et al. (2023) have mapped CDR-policy relevant institutions in Germany and the EU based on discourse analysis. We consider a broader range of institutions in the international landscape of BECCS and DACS to explore how their ideas and interests might influence policy. Most activities are based in North America and Europe, hence we considered institutions in these regions. However, there is also emerging interest in the Global South (e.g., DAC in Kenya with respect to its geothermal energy and desire to access carbon markets). This section reports on findings from the interviews and workshops that were conducted, particularly representing the views of stakeholders on how they portray their roles and interests and those of other institutions.

Table 1 The structure of interests according to institution types in BECCS and DACS

Institutions	Interests	Capacity to influence	Potential conflicts
DACS technology providers	Compete with other removal technology providers on the ground of universally implementable and highly innovative technology with credible permanence to justify the very high price	*Technical*: intellectual property on processing, capture, transport and storage technologies, R&D choices, expertise	Competition with cheaper technologies over limited funding
BECCS technology providers	Compete with emission reduction technologies as well the higher cost removal technologies	Link to agricultural interests that are politically powerful	Conflicts with landowners; conflicts with ENGOs
Transport and storage	Coordinate with both carbon removal and point-source carbon capture technology providers	*Technical*: transport and storage technologies	Potential issues having to compensate other stakeholders for leakage related revenue lost
Private funders/credit buyers	Access high-quality removal credits to strengthen public standing and/or pre-empt costly regulation	*Economic*: Allocation of funding. (Voluntary) norm-setting as the first mover (e.g. determining quality standards)	High cost; shareholder pressures
Governments/regulators	Alignment of national targets (e.g., net-zero) with removals; prevent scandals (i.e., from low-quality projects)	*Political*: setting of regulatory or fiscal incentives *Administrative*: storage exploration, infrastructure permitting	Pressure from ENGOs, private companies, and general population on regulations, credit purchase quality, or taxpayer cost-burden
Industry lobbyists	Unlock revenues for represented industries; avoid costly regulation.	*Political*: influencing the policymaking process	Special interests conflicting with public interest or ENGO views Conflict between industry groups (representing different removal categories)
ENGOs and think tanks	Specific focus issues (nature, nature-based solutions, specific ecosystems, renewables, etc.)	*Political*: influencing the policymaking process	Trade-offs with other sustainability targets (particularly for BECCS); fear of mitigation deterrence
Public and landowners	To be satisfied with the proposed measures; to prevent infringement on property, to generate revenue from providing land to removal technology providers	*Political*: voting power *Administrative*: land permits	NIMBY attitude to CDR infrastructure, particularly if perceived as dangerous (CO_2 pipelines/storage)

The first cluster is industry institutions including those that possess intellectual property or otherwise a relevant capability to build or operate (parts of) a BECCS or DACS value chain. Having a direct stake in the scale-up and future revenue from BECCS or DACS and in some cases also of industrial decarbonization with CCS, such stakeholders desire policies and market conditions that enhance demand for CDR and maximize profits and long-term viability (Honegger and Reiner 2018). The shared interest of capture operators as well as transport and storage operators is the continued revenue generation from carbon markets, government payments for results, or other forms of subsidies or support: While technology providers have a great chance of benefitting together if the pie of financial incentives is growing, they also compete over the resources available at any given time. Similarly, there are partial overlaps and differences across the other institutional groups in their interests – as listed in Table 1 and laid out in the following.

4.1 DACS technology providers

Direct air capture is not stemming from an existing industry sector. Thus, key companies are often spin-offs of major universities or have academic backgrounds (e.g., ETH Zurich – Climeworks, Columbia University – Global Thermostat, University of Calgary, and Carnegie Mellon University – Carbon Engineering). While the three leading companies mentioned above were founded in 2009 and 2010, most of the current 25–30 technology providers are relatively new in the field and are concentrated in North America and Europe. Most have developed and own proprietary technology, some of whom are setting out to operate it themselves and partnering with storage providers (e.g., Climeworks partnering with Carbfix or 44.01) while others seek to license their technology to prospective operators. Finally, start-ups may also become acquired by larger corporations, as recently seen with the case of Carbon Engineering's acquisition from Occidental Petroleum. DAC start-ups have long lacked lobbying channels but are now making up for this by spearheading the foundation of dedicated lobby groups such as the European Negative Emissions Platform and the German Association for Negative Emissions.

A key challenge for DACS is the considerable amount of required energy for its operation and the handling of CO_2 incurs an energy penalty (Bui et al. 2018; Prado et al. 2023). The high demand for zero emissions power of DACS may pose a systemic challenge. Our stakeholder workshop similarly noted that the energy penalty of DACS is challenging given the persisting energy insecurity across the world. Stakeholders highlighted that once issues in the electricity and energy sectors improve (e.g., grids, renewable energy capacity), then the general confidence for DACS would be increased.

One interviewee noted the "climate crisis is an energy crisis", implying a resource conflict over limited zero emissions power capacity. However, not all interviewees seemed to worry about the high energy demands of DACS in the long term as DACS diversifies energy demand patterns. Another interviewee noted that DACS could help accelerate renewable electricity if combined with on-site hydrogen generation from local wind farms (Interviewee I).

Further, given the currently strong price difference between DACS and BECCS-based credits on voluntary carbon markets (VCMs), DAC providers have sought to differentiate themselves based on their independence from sustainability issues related to biomass.

Joint planning of energy projects and direct air capture facilities or limiting DACS to use surplus power (e.g., during nights, or when grid capacities are reached) might be a way forward (Interviewees J, K). Cooperation between governments and grid operators would be critical (Interviewee I).

4.2 BECCS technology providers

BECCS understood as situated in the power sector is relevant to utilities, which are known for their influence on national policymaking (Interviewee D). Indeed, most operators are well-established energy utilities (e.g., Stockholm Exergi in Sweden, Drax Group in the UK) and some produce bioethanol (e.g., Archer Daniels in the US Midwest), though waste service providers are joining the group (Interviewee G).

The political economy of BECCS involves a heterogeneous set of industry sectors ranging from forestry to woody biomass, to agriculture for other biomass, to power, to waste, and to the fossil fuel industry holding key expertise in pipelines and underground storage. Given the diversity of institutions and low levels of trust of the general population in this technology cluster linked to the key institutions for the deployment (CITE), greater efforts to ensure consistent approaches to monitoring, reporting, and verification appear an absolute necessity to overcome public opposition, which may serve as the key driver to bring these institutions together.

Energy from BECCS can replace or complement other energy sources. In the United Kingdom, bioenergy represented about 13% of the country's electricity supply in 2021 (Booth and Wentworth 2023). Furthermore, BECCS can replace natural gas 'peaker' plants with CCS to balance the intermittency issues of renewables (Bistline and Young 2022; Prado et al. 2023). At high carbon prices (e.g., in the range of USD 145 to 215/tCO_2), BECCS could become a competitive option in the electricity market compared to existing natural gas power plants (Sproul et al. 2020). However, integrated assessment models show that the uptake of BECCS could increase fossil fuel use with CCS as the rollout of BECCS caps the carbon price at a relatively lower level in the long term (Fajardy et al. 2021). On the other hand, coal-fired power plants can be retrofitted to run on biomass with CCS (Fan et al. 2023). A holistic power sector plan seems crucial to balance incentivizing CDR and phasing out fossil fuels.

One of the biomass feedstocks for BECCS could be municipal solid or liquid waste with CCS, which has not received much attention in the literature to date. Municipal solid waste, which includes biogenic sources, presents different opportunities and challenges as a resource for bioenergy. The examples include municipal solid waste incineration with CCS and landfill gas combusted in a gas turbine with CCS (Pour et al. 2018). One of our interviewees noted that any technology that changes biomass or biological material from waste or non-viable product into something viable is a critical technology (Interviewee L). As of now, the most common type of waste sector engagement in CDR is waste incineration with CCS (e.g., Fortum Oslo Varme plant in Norway). Retrofitting existing waste to energy plants with CCS, especially if located near potential CCS hubs, can reshape the waste sector although the success would depend on the CCS infrastructure availability and economic and technical viability (Muslemani et al. 2023).

4.3 Transport and storage providers

The transport and storage of captured CO_2 are expected to become increasingly important for BECCS and DACS, with these activities generally seen as service providers within the broader CDR value chain. The cost of CO_2 transport depends heavily on distance and the mode of transport. Less capital-intensive transport options such as roads, waterways, and rail – have lower financial stakes, and the institutions involved are not expected to play a major role in shaping policy. In contrast, pipeline operators, which rely on significant policy support due to high capital costs, are likely to exert greater influence. While pipelines offer one of the lowest-cost transport options at scale, their development requires substantial upfront investment and faces uncertainties related to public acceptance and permitting.

Currently, most of the world's 9,000 km of CO_2 pipelines in operation (IEA 2022b) are concentrated in the United States and primarily serve enhanced oil recovery, operated by 17 companies in the oil and gas industry [1] (US DOE 2015). This strong association between carbon management infrastructure and the oil and gas industry has fueled concerns among stakeholders.

While several storage sites are coming online in the coming years, it is unclear whether this growth will meet demands induced by net-zero objectives and policies. There is a clear need for a faster permitting process and operationalization of storage sites. For instance, across the United States, there are only 2 fully permitted "Class 6 wells"[2] in Illinois, while 90 permits are "pending" as of June 2023 (US EPA 2023). While the United States has focused on expanding its onshore CO_2 storage capacity, European countries expect to focus on offshore storage. An interviewee sees a need for more funding for research, development, and demonstration to accelerate storage infrastructure (Interviewee J). At the same time, stakeholders noted that the pace of DACS deployment would not be guaranteed even with the availability of CO_2 storage capacity due to differences in domestic political stances on DACS disrupting continuity in subsidies or carbon markets. Investments and partnerships needed for transport and storage infrastructures have a multi-decade time horizon and the demand outlook would thus match these time horizons. Cooperation between Nordic countries is crucial as shown in the European Nordic countries, which engage in exemplary strategic cooperation involving significant state support for storage – blurring the lines between private and public institutions in providing underground storage (in Denmark and Norway).

4.4 Private funders and buyers

To date, uncertainty in long-term funding prospects appears to be limiting BECCS and DACS scale-up. CO_2 removal funding currently comes from voluntary carbon markets, mostly in the form of advance purchase agreements and private sector investments mainly through venture capital like Clean Energy Ventures, Carbon Removal Fund, and Breakthrough Energy Ventures; many high-end purchases are essentially philanthropic donations (Honegger 2023). Such funding is volatile and viewed as illegitimate by many due to concerns of greenwashing flowing from an erosion of trust in carbon markets. The limitation of funding from private funders and buyers resonated during the stakeholder workshops as VCMs would not be sufficient to scale DACS in the medium to long term. One of the workshop participants noted that the VCM should turn into compliance markets where governments set the standards to make it stringent enough that there is enough demand to reach the price reduction of DACS.

[1] Oxy Permian, Kinder Morgan, Denbury Resources, ExxonMobil, Apache, Anadarko, Devon, Chaparral Energy, XTO, Dakota Gasification, Chevron, Trinity CO_2, Merit, Whiting, Hess, TransPetco, Core Energy, LLC. (as of 2015, in the United States)

[2] Class 6 Wells are used for geological sequestration of CO_2, not for enhanced oil recovery.

Buyer clubs lower the barrier for buyers accessing credits from novel CDR methods by sharing the transaction costs (Interviewee J). Examples include Frontier – composed of multiple companies, led by Stripe and having signed agreements with at least 16 CDR projects, and the US-based First Movers Coalition launched in the lead-up to COP26 (WEF 2022).

Voluntary carbon market demand grew from zero transactions in 2019 to USD 8 billion in 2024 (CDR.fyi 2025). Demand for removal credits with inherent storage durability may be growing on the back of recent controversy regarding forestry projects with ESG-related shareholder pressure. However, given their high cost only companies in high-margin sectors (such as digital services and consultancy) have engaged (Interviewee I). Nevertheless, buyers expect that more would be done on standardization and transparency in voluntary carbon markets (Interviewee J) so that carbon credit prices increasingly reflect the true value of removal results (Interviewee I).

Stakeholders are ambiguous on the longer-term role of private support: Some see a continued need for scaling venture capital to advance early-stage solution providers (Interviewee E). However, most see private involvement as limited to the early stages and count on public policy to induce compliance demand to scale, as discussed by Honegger (2023).

4.5 Governments

Stakeholders see governments move toward supportive policies for industrial removals domestically and abroad – given pressure to meet net-zero pathways and improve public perception, although approaches vary. For instance, while the former Trump administration broadly supported CCUS in the United States, the Biden administration added conditions for just and equitable development (The White House 2022) and the Inflation Reduction Act increased tax credits for DACS (The White House 2023). This "changed the atmosphere and direction of the industrial perspective associated with CDR" (Interviewee I) and encouraged a much more positive narrative for CDR policy.

In Germany, policymakers have made a 180-degree turnaround in terms of their position on CDR and wider carbon management policies after years of political gridlock. Former German federal and state governments firmly ruled out possibilities of pursuing carbon capture and especially storage, while only permitting geological storage for small-scale research purposes. However, in light of a considerable mitigation and ambition gap and increased pressure from industry and even civil society (BDI 2024) the new federal government made recent announcements and initiated three concrete policy packages relevant to BECCS and DACS: the Carbon Management Strategy, the Long-term Strategy for Negative Emissions, and the National Biomass Strategy. Taking these packages together, Germany intends to build a sound foundation for CDR approaches, while assessing what regulatory, governance, and economic drivers are required and how specific targets could be set. The policy-making processes for CDR in Germany are characterized by strong inter-agency relations, stakeholder engagement, and cross-sector interactions between research, industry, and civil society organizations. Although the outcome of these processes remains to be seen, also in light of Germany's election results in 2025, a deliberative approach is needed for informing fruitful discussions on the EU level as well as UNFCCC negotiations on the Long-Term Low-Emission Development Strategies (LT-LEDS). Vice-versa, governments are influenced by international environmental law, including the expectations created under the Paris Agreement toward climate change mitigation, which extends to CDR (Honegger et al. 2021a).

All interviewees see an important role for the government to help accelerate BECCS and DACS and many pointed to risks along the way should supportive policies be interrupted. Given the very large investment needs in BECCS and DACS value-chains, government policies are seen as critical in generating (future) demand for removals through regulation as well as in defining accounting and monitoring, reporting, and verification rules (e.g., EPA's regulations on storage, EU Carbon Removal Certification).

Three primary types of policy instruments are discernible: (1) regulations (e.g., carbon removal obligations, standards, certification), (2) market-based incentives (e.g., carbon credits in compliance markets), and (3) subsidies/grants (e.g., tax credits, reverse auctioning). These categories have also been observed toward accelerating mitigation technologies such as solar and wind (Gallagher and Xuan 2019), although the range of policies for BECCS and DACS is less diverse to date compared to the range employed for renewables.

There is a consensus in the literature that cross-border export of CO_2 for storage is seen as particularly challenging requiring clarification through contractual arrangements, carbon accounting systems, and international agreements. A key hurdle stressed by many interviewees is that the accounting frameworks for different types of BECCS are not clearly defined in the IPCC Guidelines for National Greenhouse Gas Inventories (Interviewee G). While carbon accounting features less prominently in broader discourses on DACS on assumptions that as a black-box engineering process carbon flow quantification may be more straightforward, it may nonetheless be an important component to accelerating DACS (Interviewees J and K).

Stakeholder views on the role of governments align with the literature. Meckling and Biber (2021) find that "financial incentives (e.g., subsidies or tax rebates) and deployment or performance mandates" could be effective in broadening political support for large-scale deployment of direct air capture. Sovacool et al. (2022) highlight the role of certification and compliance systems and the lack of a demand-pull in carbon markets especially for the costly DACS.

4.6 Industry lobbyists

Industry lobbyists such as the Carbon Business Council and the World Business Council for Sustainable Development represent industries in the conventional mitigation space. Specialized institutions exist for CCS (e.g., Global CCS Institute and Zero Emissions Platform), and more recently also for CDR (e.g., Negative Emissions Platform, Coalition for Negative Emissions, Carbon Removal Alliance, the German Association for Negative Emissions, and similar national associations).

We address them separately as technology providers, private buyers and funders, and industry lobbyists can deviate in their interests. While CDR industry lobbyists share an interest in policies that induce long-term revenues for removals, they can differ in the prioritization of CDR methods (e.g. those with inherently durable storage versus those situated in the bioeconomy in agriculture and forestry). Competition for support and access to storage separates CDR and CCS lobbying as the latter emphasizes industry and energy-sector decarbonization. What can the respective industries gain or lose from specific policy designs? So far, CDR interests have often aligned for advancing all forms of CDR, but also for advancing industrial removals with inherently high storage stability. The Carbon Business Council and over 100 CDR experts pushed the UNFCCC to recognize the inherent durability of storage in the context of international carbon markets and asked it to remain technology-agnostic with transparent criteria rather than pre-determined categories (Carbon Business Council 2023). Similarly, the Negative Emissions Platform pointed to a need for balance in the "representation of engineered CDR benefits" and the need to address "discrepancies in CO_2 quantification, and misrepresentation of long-term storage benefits" (Negative Emissions Platform 2023).

These organizations thus empower industries to take an active role in shaping policies even when the issues become increasingly technical with progressing policy development. With innate differences in CDR methods and relevance to sectors, CDR interests will likely start to diverge more clearly when policy is moving toward regulation and incentives.

4.7 ENGOs

Stakeholders understand that Environmental NGOs (ENGOs) play a key role in shaping public opinion and policy by highlighting environmental and social problems (Honegger and Reiner 2018; Schenuit et al. 2021). They raise concerns about biodiversity (Schenuit et al. 2021) and emphasize the co-benefits of "nature-based solutions" (Boettcher et al. 2023). For example, in the case of DACS, many ENGOs in Iceland focus on protecting the country's vulnerable ecosystems and pristine landscapes (Eberenz et al. 2024). Participants discussing Iceland's DACS efforts highlighted the country's long history of environmental activism, particularly in protecting rivers, wetlands, waterfalls, and lava formations from infrastructure projects like hydropower plants. This aligns with the broader role of ENGOs, which have traditionally focused on environmental conservation, with climate change mitigation emerging more recently as an advocacy priority – primarily emphasizing domestic action. However, few ENGOs have actively supported CDR, often expressing concerns that it could divert attention from their preferred mitigation strategies. These concerns were evident in both interviews and discussions during our stakeholder workshop.

Nevertheless, acceptance of DACS among ENGOs appears to be growing. A representative from a major ENGO network noted a tension between supporting mitigation efforts and remaining skepticism of CDR. Some see DACS as aligning with the *polluter pays principle* and producer responsibility, which strengthens support. On the other hand, concerns persist due to its reliance on technology, which contradicts the paradigm of reducing human interference in nature.

For BECCS, widely shared concerns about its impact on land use (Interviewee K) – particularly competition for land, biomass availability, and biodiversity – have limited its acceptance beyond a few countries like Sweden. These concerns align with findings in the literature, which highlight issues such as limited feedstocks, conversion losses, and high land and water demands (Brack and King 2021; Fridahl et al. 2020; Mulligan et al. 2020; Realmonte et al. 2019). Given these challenges, ENGOs tend to favor regulatory approaches that place direct obligations on polluters to fund or facilitate carbon removal, reinforcing accountability for emissions (Interviewee C).

4.8 Publics and landowners

Public perception is understood to strongly influence policy, and local acceptance may be decisive for the feasibility of necessary infrastructure projects (Stauffacher et al. 2015). Local rejection is often associated with a low perceived local benefit associated with permanently storing CO_2, which is inherently a global public good. Stakeholders are conscious of limited public awareness as confirmed by surveys (Cox et al. 2020) similar to CCS since 2008 despite a long history in expert debates (Wallquist et al. 2010). Stakeholders are aware that laypersons do not understand the mechanics of DACS as also observed by Cox et al. (2020).

The findings from the literature align with the insights we gained from our interviews. For instance, one of the interviewees noted most people are also not familiar with BECCS or expect that BECCS and DACS would fully counteract all emissions – expressing that “all of this is already done” (Interviewee L). When compared to approaches perceived as more natural such as afforestation and reforestation (Jobin and Siegrist 2020; Wenger et al. 2021) public support for BECCS and DACS appears to be low (Cox et al. 2020; Wenger et al. 2021; Wolske et al. 2019). Likely owing to its roots in forestry or other biomass sourcing, BECCS appears to be considered more realistic, natural, and greener by laypeople compared to DACS (Cox et al. 2020). This suggests potentially greater support for the currently mainstream ideas of BECCS among the general population – in apparent contrast to the inverse views among ENGOs.

While laypeople appear to be moderately supportive of CDR as a category (Wenger et al. 2021), some express negative sentiment associated with CDR “not addressing the root cause of emissions” and deepening “fossil fuel dependency” (Cox et al. 2020). Such phrasing may indicate the influence of ENGOs many of which have criticized BECCS as a distraction from “deeply altering our entire relationship to energy consumption” (Donnison et al. 2023). Similarly, a study in Iceland (Eberenz et al. 2024) highlighted that DACS can contribute to climate change mitigation if it does not displace emissions reductions.

While there may be some observations that apply internationally, it is important to not underestimate the influence of cultural and historical experiences. The case of DACS in Iceland shows the need to minimize the visual footprint of technology on landscapes and ecosystems and urges that all development of BECCS, DACS, and other carbon management infrastructures be constrained to current industrial areas (Eberenz et al. 2024). This aligns with studies showing a link between CDR skepticism and specific ideas of the environment (Arning et al. 2019) and perceived risks of interfering with nature (Jobin and Siegrist 2020).

Nuances in how infrastructure projects are introduced can determine public support. In particular, landowners are key stakeholders in CO_2 pipeline development as their rights often impose considerable power to stop pipeline or powerline projects. When CO_2 pipelines cross private lands, conflicts are often inevitable, which was echoed in our interviews. For instance, the excavation of land for the installation of pipelines might not only degrade farmland but also elicit a sense of intrusion threatening farming communities’ sense of social and cultural identity closely tied to the land they cultivate (interviewee L). This was observed for DAC (Scott-Buechler et al. 2023) as well as CO_2 pipelines where the crossing of private land often causes conflict with landowners to the point of prioritizing road transport despite dramatically higher cost (Wallquist et al. 2012). For CCS projects, von

Rothkirch and Ejderyan (2021) show that contextual "place-factors" – population density, fossil fuel extraction, environmental impacts, and a lack of regulation of CCS – can limit its acceptance. Context thus influences which types of stakeholders may turn out most influential: opinions can differ starkly between communities local to storage sites and outside experts – flowing both from respective interests and prior knowledge (Bellamy 2022; Cox et al. 2020; Scott-Buechler et al. 2023; Wolske et al. 2019). Negotiations with individual landowners are seen as time-consuming and costly especially if leading to longer routes. This may increase acceptance and avoid broader "not in my backyard" (NIMBY) sentiments although there could be exceptions. For instance, Scott-Buechler et al. (2023) find that communities close to geologic storage or carbon-intensive industries may be open to local DAC deployment – arguably for its meaningfulness and fit with local conditions and the potential for undoing harm from local pollution. Likewise, some farmers in the US are supportive of BECCS if it could bring economic benefits (Cox et al. 2020).

5 Discussion

Policies that target BECCS, DACS, and other forms of CCS are evolving: Starting from a highly heterogenous base with a focus on subsidies in the US and on the development of rules for market mechanisms in the EU. Incentives are often lower than costs for most technologies in both contexts, (i.e., the exception would be direct DACS subsidies in the US), and fail to provide long-term solutions for BECCS, DACS, and CCS. Further, BECCS and DACS are competing for policy support and the availability of finance and storage sites. BECCS, DACS, and other CCS players have different interests in making a clear distinction between CDR and emission reductions given the strongly differing prices for credits for these two forms of mitigation. While DACS companies appear most supportive of a very strong distinction (given their unique standing as a high-cost, "pure" CDR technology (see e.g. Climeworks 2023b), BECCS companies have been much more lackluster or even outright in favor of viewing removals on a continuum with emissions reductions. The latter can be explained by the physical sharing of infrastructures as well as the possibility of combining removals and emissions reductions in a single plant where there are parallel biomass and fossil inputs (e.g., waste incineration). Storage providers also appear to be against a firewall division given that they provide the same service to BECCS, DACS, and CCS technology operators.

However, it is worth noting that there is room for coordination and cooperation between BECCS and DACS as they both need transport and storage to scale CDR. Harnessing synergies in transport and storage would contribute to lowering the costs with potential spillover effects even for point-source capture technology. Interviewees converged on a need for coordination between or even integration of capture and storage. BECCS and DACS should be "woven" into the CCS infrastructure within existing industrial footprints or carbon storage sites.

Yet, there are concerns about power imbalances within the value chain – between capture and storage providers – and between countries with varying storage availability (Interviewees G, F). Some of this is linked to regulatory differences, where for instance permits for offshore storage in the Baltic sea are restricted by the Helsinki Commission (HELCOM 2013).

Another tension flows from public perception and concern with the dominance of oil and gas in storage operations. Some capture operators such as Climeworks have sought to keep their distance by finding new forms of CO_2 storage (i.e., mineralization in basaltic rock, as piloted by Carbfix in Iceland). It will remain to be seen whether a new storage industry emerges within or separate from oil and gas companies given that some policies still yield significant revenue for this powerful sector (i.e., Inflation Reduction Act tax credits for enhanced oil recovery with DAC). Going forward, stakeholders in capture-, transport- and storage may find their interests increasingly intertwined as revenues accrue from the overall removal value chain. Multi-user CO_2 pipeline networks (being developed in Canada, the United States, and Europe) and hubs and clusters may lower the barriers to accessing transport and storage infrastructures also for BECCS and DACS (IEA 2022a), yet they require complex new institutional arrangements.

Ideas also appear to be evolving. Ideas of BECCS are expanding into entirely new sectors for example the waste sector. In some countries, this is manifesting in dedicated policies, such as the Swiss government signing a voluntary agreement with the solid waste sector that effectively leads to the construction of CO_2 capture (Federal Office for the Environment 2023). The German Environment Agency also coined the term Waste-CCS (WACCS) for the combination of CCS with thermal waste treatment plants (Purr et al. 2023) in an apparent attempt at further establishing this as a distinct CDR method and to move the discussion away from the historically controversial CCS and BECCS. The continued emergence of additional forms of BECCS and DACS seems likely – requiring openness in policy designs that allow advancing novel and unexpected methods across all sectors.

This evolution is expected to be shaped by the continued interaction of ideas and interests variously shared by and negotiated among technology providers, NGOs, broader public and private sector buyers and funders, industry lobbyists, and governments. It remains unclear where this evolution is headed, though some trends in the US and EU reveal some distinct shortfalls and areas for continued improvement that pursue the public good, rather than narrow and short-term particular interests. The observed diversification of institutions, ideas, and interests may indicate an increasingly healthy ecosystem that can achieve this. However, continued care is required, and the challenges ahead remain large.

Stringent frameworks on carbon accounting are needed as a basis for any CDR policy instrument to avoid bias. The lines between emissions reductions and CDR should be kept as clear as possible – even when both arise from the same activity (e.g., from applying CCS to a municipal waste plant or a cement plant that co-fires biomass). Clarity on locally and regionally appropriate biomass utilization is crucial to ensure sustainable results with a holistic view. The different resource demand profiles within BECCS require careful deliberation. Finally, a holistic embedding of DACS into energy systems is essential to prevent the perpetuation of unsustainable energy consumption or undermining energy security.

6 Conclusion

In this paper, through the 3-I framework, we analyze the interplay of ideas, institutions, and interests that influence the policy development of industrial CDR, particularly BECCS, and DACS based on interviews, stakeholder workshops, and policy/literature review.

Our analysis shows that CDR policies, specifically for BECCS and DACS, have been shaped by different stakeholders' interests, which do not necessarily lead to effective, efficient, and fair outcomes. However, as shown in Section 3, shared ideas and precise terminology are essential to avoid ambiguity and inconsistencies that can blur the lines between desirable and undesirable policy outcomes (achieving removals or increasing emissions). Further opportunities to improve the outcome exist in the following areas of policy development.

First, governments could use a balanced set of demand-pull policies (e.g., carbon contracts for difference, procurement) and supply-push policies (e.g., R&D investment) to enable the initial deployment of BECCS and DACS on a national scale. This would de-risk the sector and help to create demand for CDR technologies. However, at the same time, governments need to avoid locking in windfall profits from "lavish subsidies" through frequent evaluation of actual costs and subsequent reduction of the subsidy rate for future CDR activities. If the public policy on BECCS and DACS continues to be tech-agnostic and focuses on market competition instead of considering the effectiveness of targeted interventions, it will just benefit incumbents and prevent the development of a wide range of technologies. Under the condition that the emergence of "subsidy paradises" for "eternally promising" but never performing technologies is prevented, balancing support between less mature and mature technologies within the landscape of BECCS and DACS is crucial with new entrants being able to demonstrate novel technology approaches even in the presence of incumbents that have already scaled up their technologies. International carbon markets could become key sources of revenue and reduce the need for governments to provide subsidies, as the subsidy level could be set to make the revenue from carbon credit sales close the viability gap (Michaelowa et al. 2023).

Second, policy instruments should be strategically used to ensure that CDR is not locking in fossil fuel use with CCS. For example, the design of a carbon takeback obligation should prevent oil and gas companies from deciding which CDR technologies are used to capture and store CO_2, as they have an interest in applying those technologies that are consistent with their current business model, such as enhanced oil recovery (EOR). The obligation could thus exclude technologies that lead to locking in. If this is impossible due to lobby pressure, minimum shares for specific technology types such as basaltic mineralization would be the second-best option.

Policy measures should comprehensively consider the co-benefits and negative impacts along the overall value chain of different types of CDR. This would be particularly relevant in the case of BECCS given the strongly differing potential impacts related to biomass feedstocks, to favor low-impact options using biomass waste and being integrated into existing systems, such as waste-to-energy plants.

Generally, a stringent carbon accounting and MRV process of carbon removal activities in BECCS and DACS should be required when granting incentives (e.g., tax credits, subsidies) to technology operators.

By unpacking the ideas, interests, and institutions involved in BECCS and DACS we have identified distinct types of synergies, trade-offs, and conflicts. To mitigate conflicts and maximize synergies, designing effective policy instruments representing a long-term commitment is pivotal. Awareness of the built-in political performativity of ideas and categories as well as their potential strategic use by institutions to further their specific interests is crucial to avoid letting their performativity unfold unchecked. Balance in the process and outcomes of policy development geared toward effectiveness but still allowing the competition between and emergence of new technologies is crucial to foster a favorable environment for different stakeholders to achieve the large-scale deployment of an ensemble of various methods including forms of BECCS and DACS in a wide range of sectors.

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