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Carbon dioxide removal: Perspectives from the social sciences and humanities

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Carbon dioxide removal: Perspectives from the social sciences and humanities

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Editorial: Carbon dioxide removal: perspectives from the social sciences and humanities

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Editorial on the Research Topic
Carbon dioxide removal: Perspectives from the social sciences and humanities

Introduction

In recent years, carbon dioxide removal (CDR) methods have been increasingly recognized as crucial in climate policy and scientific contexts (Abegg et al.). According to the latest Intergovernmental Panel on Climate Change reports, the 1.5-degree target is unattainable without rapid and substantial investments in CDR. These methods are also crucial to counteract emissions overshoot and residual emissions. Currently, integrated assessment models (IAMs) and techno-economic research dominate the interpretive space for understanding and deliberating the future of CDR methods and translating these understandings into policy and political action (Hansson et al., 2021). A criticism of this dominance is that many important perspectives on technical development, socio-ecological challenges, local political contexts, and other complexities are relegated to a marginal role. If large-scale CDR is portrayed as achievable through its incorporation into mitigation scenarios and climate policies, this might justify less focus on crucial short-term challenges.

Against this backdrop, we aimed to invite theoretical and empirical contributions from the social sciences and humanities about CDR-related policy design or analyses of recent policy developments, construction of knowledge in scientific discourses, historical and contemporary experiences of CDR in different contexts, and political and public debates over CDR. The Research Topic has gathered contributions that provide puzzle pieces that nuance, deepen, or challenge previous research through empirical case studies, theoretical engagement, literature reviews, policy and governance analysis, or analyses of perspectives from the public, experts, or industry. Specifically, the contributions approach this by asking questions like: how does the adoption of a "net" framing reconstruct the goals, processes, and mechanisms of climate policies (McLaren and Carver)? What is the industry's view on residual emissions assumed to be compensated for in the future (Brad et al.)? What could a research agenda capable of supporting a more responsible evaluation of CDR methods look like (Healey et al.)? How is foresight knowledge produced and used among policymakers with the help of emission scenarios (Andersson)? What are the gaps and barriers for a specific CDR method to be integrated into a national policy regime (Cortinovis et al.)?

Carbon dioxide removal policy from sub-national to international levels of governance

Since the early 2020s, there has been a surge in research on policies to incentivize CDR deployment, a trend also reflected in this Research Topic. Focusing on the UK, Healey et al. report on stakeholders' views of CDR, which, despite a tendency toward negative opinions, do not rule out any CDR options. Stakeholders request further research and deployment to gain experience. Two policy pathways emerge from their analysis: contracts for difference and producer responsibility obligations. However, Healey et al. underscore the importance of developing appropriate incentive structures from the bottom up, "built one at a time, jurisdiction by jurisdiction." They caution that even well-regarded CDR methods could be rejected if paired with unfavorable financial incentives. Top-down policy analysis requires complementary bottom-up analysis to ensure feasibility, or policies risk backfiring.

Bottom-up analysis of policy instruments may be cumbersome but beneficial. Incorporating multiple perspectives can lead to more robust policy by identifying potential trade-offs between diverse objectives. Günther and Ekardt emphasize this, showing how CDR policy is subordinate to emissions reductions in international climate law, while conservation measures are paramount in international biodiversity law. They argue that safeguarding biodiversity should take precedence if trade-offs are identified. Policymakers must address both climate change and biodiversity loss through coordinated land-use strategies, considering the negative impacts of large-scale land-based CDR on ecosystems and food security.

This is no simple feat. The shrinking solution space necessitates CDR to avoid costly loss, damage, or extreme adaptation measures, including risky solar radiation management. Policymakers must also juggle sector-specific interests involving powerful lobby groups like chemical, steel, cement, and fuel producers. Brad et al. show how trade associations largely support the EU's climate goals, including CDR integration. However, the EU's net targets for 2030 and 2050 leave room for residual emissions from unspecified sources. Trade associations make vague claims to residual shares and highlight CDR's technical potential to argue against the need for rapid emissions reductions. Brad et al. work similarly to Healey et al. by assembling industry claims to reveal a bigger picture where the equation does not compute. Their analysis highlights the challenges in designing CDR policy that is effective, overcomes trade-offs, and avoids promoting overstated future CDR potentials that can be used to delay necessary emissions reductions.

Construction of scientific knowledge and communication of carbon dioxide removal

IAMs are pivotal in the scientific and policy debates on CDR methods. Their quantitative analyses of emissions scenarios form the foundation of IPCC assessments of mitigation options, placing CDR at the forefront of global discussions on achieving net-zero targets. Therefore, it is important to examine, from a critical social scientific perspective, the roles that modeling frameworks like IAMs play in shaping scientific knowledge on CDR and broader climate policy. Andersson and Wilson contribute significantly to this endeavor.

Andersson examines how model-based scenario analyses inform foresight knowledge relevant to Swedish climate policy. These simulations, despite their deep uncertainties and long-term outlooks, guide policy decisions by defining common problems and suggesting cost-effective mitigation pathways. However, Andersson highlights that focusing solely on economic efficiency may limit policy effectiveness by neglecting transformative changes in cultural norms and behaviors.

Meanwhile, Wilson explores the challenges of measuring CDR technology effectiveness, particularly in California's forest offset program. He critiques current measurement practices reliant on baseline projections, which often overestimate carbon removals due to inaccurate representations of carbon dynamics. Wilson advocates for alternative measurement targets less dependent on counterfactual scenarios to ensure genuine long-term carbon reductions.

Both Andersson and Wilson underscore how scientific knowledge construction through modeling and measurement shapes CDR policy discourses, while also warning against systemic biases and exaggerated promises in climate mitigation strategies. In contrast, Bellamy and Raimi highlight communication challenges surrounding CDR strategies, emphasizing the need for responsible communication that addresses public awareness gaps and frames CDR in broader social and policy contexts. They argue for inclusive communication strategies that consider diverse implementation scenarios to enhance public understanding and support for CDR technologies.

Historical and contemporary experiences of carbon dioxide removal

Cortinovis et al. highlight the IPCC's general lack of inclusion of national characteristics such as financial, technological, social, and political acceptance in their scenarios. They address this gap by analyzing emerging policy frameworks for Direct Air Carbon Dioxide Capture and Storage (DACCS) in Canada, identifying policy deficiencies and proposing tailored strategies to integrate them with existing frameworks and support technology scaling. They emphasize the challenge of short-term national energy policies in Canada, focused on local needs and strengthening current energy systems through investments in Carbon Dioxide Capture and Storage (CCS). The authors argue that while DACCS holds promise, political efforts are needed to effectively integrate it into energy and climate policies as it appears the dominant interests use the promise of DACCS to justify only marginal energy transition.

Hilser et al. similarly examine national contexts, focusing on empirical observations from the Dominican Republic, a small island developing state. They conduct an in-depth study at a field trial site relevant to understanding CDR, cautioning against bioenergy and afforestation projects that may lead to land grabs and exacerbate climate vulnerabilities. They stress the importance of climate justice in CDR interventions, advocating for participatory approaches that include vulnerable groups and build trusting relationships. In contrast, Fink and Ratter study local attitudes toward CDR in Germany, a developed country without ongoing implementation projects. While justice perspectives are less prominent in their analysis, they underscore the importance of transparency, inclusion, and co-creation of knowledge in shaping local perceptions and strategies for implementing CDR technologies. These studies collectively underscore the necessity of considering national contexts and justice perspectives in CDR implementation, whether in policy frameworks, empirical studies, or local community engagements.

Contested carbon dioxide removal framings and discourses

One key theme in the Research Topic is the contentious public and political debates surrounding the role of carbon dioxide removal and storage in climate policy. Authors in this Research Topic emphasize that analyzing these debates is crucial because dominant framings, concepts, and discourses actively shape the goals, processes, and mechanisms of CDR development and governance.

McLaren and Carver illustrate how the concept of "net-zero" has reshaped climate policy by framing it as a balance between emissions sources and carbon sinks. This framing has entrenched the idea of "residual" emissions requiring CDR, reinforcing the inevitability of CDR in international climate governance. They argue that the turn to net policies reflects a broader neoliberal perspective, emphasizing quantification, commodification of the environment, and economic justifications for policy solutions, promoting notions of economic freedom and green growth. Beyond critiquing neoliberal impacts on CDR, McLaren and Carver draw lessons from historical net policy effects. They advocate for shifting away from market-driven narratives and propose principles for fairer and sustainable CDR policies.

Similarly, Rodriguez explores framings in scientific literature on carbon dioxide enhanced oil recovery (EOR) in the North Sea, identifying contrasting views. One framing presents EOR as a bridging strategy facilitating carbon storage, while another views it as incompatible with climate mitigation, exacerbating fossil fuel use and carbon emissions. The analysis reveals conflicts between EOR and point-source or atmospheric carbon capture and storage (CCS) for climate mitigation, emphasizing the dominance of economic interests in EOR discourse. Rodriguez suggests policy solutions to prevent carbon lock-in, such as promoting alternative carbon storage methods without EOR, restricting EOR use, and mandating transparent knowledge sharing on monitoring and safety.

These studies underscore the importance of dissecting framing effects in shaping CDR and climate policy discourses, advocating for policies that navigate conflicts and promote sustainable, equitable approaches to climate mitigation.

Conclusions

The Research Topic has underscored the importance of fostering diversity in scientific and political processes to comprehend CDR's societal role. Despite empirical and theoretical differences among studies, temporal aspects at the systemic level have emerged as crucial for further investigation. For instance, how do CDR methods influence the speed of climate transition and the preservation of existing structures?

Aligned with Bellamy and Raimi's argument advocating for a broader or more comprehensive discourse, we hope this Research Topic can enrich the public debate on the role of these methods in societal transformations.

Author contributions

AH: Writing – original draft, Writing – review & editing, Conceptualization. SA: Writing – original draft, Writing – review & editing, Conceptualization. MB: Writing – original draft, Writing – review & editing, Conceptualization. MF: Writing – original draft, Writing – review & editing, Conceptualization.

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Conflict of interest

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

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Storing carbon dioxide for climate's sake: contradictions and parallels with enhanced oil recovery

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An increase in carbon capture and storage (CCS) projects, including bioenergy with CCS (BECCS), has led to an urgent demand for storage sites, and Norway stands out for its ongoing and planned geological storage sites in a European context. Even though there are no commercial carbon dioxide enhanced oil recovery (CO_2-EOR) projects in Norway and the North Sea, there is scientific literature linking CO_2-EOR and CCS in this geographical region. CO_2-EOR utilizes CO_2 to extract additional oil, counteracting the climate change mitigation purpose of geological storage. This review article explores how CCS is represented in the scientific literature on CO_2-EOR in the North Sea and Norway, with a focus on system synergies and contradictions in relation to climate change mitigation. The main themes in the scientific literature on CO_2-EOR in the North Sea are climate change, economics, and geological feasibility. Monitoring, safety, and leakage in addition to transportation of CO_2 are less salient. The results show that there are contrasting framings in the literature. One framing is that CO_2-EOR is a gateway to large-scale storage which maintains, or even expands, the extraction of fossil fuels and contributes to a sustainable transition in the long run through knowledge building and shared infrastructure. In contrast, another framing is that CO_2-EOR combined with CCS have goal conflicts and are therefore not compatible, illustrating complexities with geological storage. Finally, this study reflects on how techno-economic research on CO_2 storage in the North Sea and Norway is furthered through critical social science perspectives.

KEYWORDS

enhanced oil recovery (EOR), carbon capture and storage (CCS), Norway, North Sea, carbon dioxide storage, sustainability transition, bioenergy with carbon capture and storage (BECCS), carbon dioxide removal (CDR)

1. Introduction

In the context of rising climate change, there are different pathways to limit the temperature increase to 1.5°C as set out in the Paris Agreement, including various methods to store carbon dioxide (CO_2) to reduce emissions in the atmosphere (IPCC, 2023). The Intergovernmental Panel on Climate Change's (IPCC) sixth assessment report includes carbon dioxide enhanced oil recovery (CO_2-EOR) as a method that may store CO_2 permanently and describes CO_2-EOR as a possible bridge to a transition including carbon capture and storage (CCS) (IPCC, 2022). CO_2-EOR is an industrial process to extract fossil fuels by injecting CO_2 into oil fields, and some of this injected CO_2 is stored in geological formations after the industrial process which is why it is characterized as a CO_2 storage method (Núñez-López and Moskal, 2019). In fact, the Global CCS Institute (2022) states that 22 of 29 commercial CCS projects currently in operation apply CO_2-EOR, which can also be considered carbon capture utilization and storage (CCUS) initiatives, where CO_2 is first used in an industrial process before some of this CO_2 is subsequently stored (Muffett and Feit, 2019). Meanwhile, other applications of EOR inject different gases and fluids and are therefore not methods for storing CO_2. Besides the method of CO_2-EOR for storing CO_2, some projects store CO_2 in dedicated geological storage facilities for the sole benefit of climate change mitigation, such as in Norway, but there are challenges in financing new transport and storage sites (Geske et al., 2015a) and acquiring knowledge on geological characteristics (Mathisen and Skagestad, 2017). Akerboom et al. (2021) acknowledge that new storage sites can take a long time to materialize due to social, technical, legal, and economic challenges. Even though there are several places for potential CO_2 storage in Europe (Lux et al., 2023), there is a bottleneck in storage capacity due to a shortage of operating storage facilities and a lack of open-access knowledge on regional geological storage capacities (Fajardy et al., 2019). This lack of storage facilities, knowledge gaps, and challenges with CO_2 storage have implications for carbon dioxide removal (CDR) approaches including direct air carbon capture and storage (DACCS) and bioenergy with carbon capture and storage (BECCS), which can be illustrated by the case of Norway and the North Sea.

In Europe, the North Sea is home to most of the projects developing CO_2 storage, but Norway is the only country currently storing CO_2 at its storage site called Sleipner (Global CCS Institute, 2022). Norway has the highest potential for CO_2 storage volume in a European context (Lux et al., 2023). Fossil fuel companies that are involved in CCS projects in Norway are conducting research and development on EOR due to maturing oil fields in the North Sea region (Roefs et al., 2019), although CO_2-EOR is not implemented on a commercial scale in Europe (e.g., Kemp and Kasim, 2013; Mathisen and Skagestad, 2017; Bergmo et al., 2018). Norway is the only country in the world with operational commercial-scale CCS projects driven by CO_2 tax, and a Norwegian offshore CO_2 tax introduced in 1991 contributed to economically viable offshore CO_2 storage at Sleipner (North Sea) and Snøhvit (Barents Sea) which began storing CO_2 for the natural gas processing industry in 1996 and 2008, respectively. EOR is not applied at either of these storage sites. In 2024, the Norwegian Government will initiate the first open-source cross-border CO_2 storage project called Northern Lights which is part of the Longship CCS project, with the purpose of storing CO_2 from Europe (Northern Lights, 2023). Some of the CO_2 will be of biogenic origin such as from a waste-to-energy facility, so this can in part be characterized as a BECCS initiative (Schenuit et al., 2021). Since Norway has come the furthest of any country in Europe when it comes to CO_2 storage in addition to having knowledge on prospective future locations for both CO_2 storage and EOR (Norwegian Petroleum Directorate, 2011), this study focuses on Norway and its context in the North Sea region. Theoretically, Norway has the largest potential for both oil recovery from CO_2-EOR and CO_2 storage compared with neighbors in the North Sea region, followed by potentials in the UK section of the North Sea (Tzimas et al., 2005). Existing CO_2-EOR projects in North America, China, Saudi Arabia, and the United Arab Emirates are onshore (Elmabrouk et al., 2017), while the only large-scale offshore CO_2-EOR project in operation is in Brazil (Eide et al., 2019). Therefore, the North Sea region and Norway with its offshore CO_2 storage sites and possible offshore applications of CO_2-EOR stand out from most existing CO_2-EOR projects onshore.

According to the European Commission, the Northern Lights project will connect CO_2 capture initiatives in the United Kingdom (UK), Ireland, Belgium, the Netherlands, France, and Sweden (EC, 2023). Within the Nordic context, Sweden is increasingly investing in research and development on BECCS, and the Swedish Government and industry actors foresee the possibility of storing CO_2 in Norway as a starting point (SOU, 2020; Rodriguez et al., 2021; Lefvert et al., 2022). However, out of the 1.5 million tons per annum (Mtpa) of CO_2 capacity at Northern Lights starting in 2025, 0.8 Mtpa CO_2 is earmarked for two Norwegian facilities: Norcem cement at Brevik and Hafslund Oslo Celsio waste-to-energy (Northern Lights, 2023). In addition, Yara Sluiskil, a Dutch fertilizer facility will export 0.8 Mtpa CO_2 from the Netherlands to Norway (Yara, 2022). Even though there is additional demand, CO_2 from these Norwegian and Dutch companies means that the Northern Lights project will initially be at full storage capacity, until Northern Lights increases storage capacity to 5 Mtpa in the longer term (Northern Lights, 2023).

The relationship between CCS and CO_2-EOR is not new, and the shared history of CO_2-EOR and CCS in the 1970s in Texas illustrates overlaps between these technologies which can be integrated in systems (Loria and Bright, 2021). This is problematic since CO_2-EOR and CCS have fundamentally different purposes: CO_2-EOR is driven by the economic benefit of extracting additional oil and gas from nearly depleted fields, while CCS projects have the goal of mitigating climate change by permanent disposal of CO_2. As both technological systems evolve, it is important to distinguish them due to goal conflicts, but also to understand the relationship between CO_2-EOR and CCS since CO_2-EOR could be a catalyst for the development of CCS. Furthermore, CO_2-EOR and CCS could have systemic overlaps such as shared infrastructures, common actors, and synergies in industrial applications. Social science can provide insights by studying the framing of CO_2-EOR in the literature. Framing refers to a situated position on a topic which is relevant for policymaking (Waller et al., 2020). Framing illustrates perceptions from a certain viewpoint including its salient aspects which define problems and possible solutions (Megura and Gunderson, 2022). How an issue such as CCS and BECCS is framed can impact its deployment landscape (Gough and Mander, 2019). Studying the framing of the relationship between CO_2-EOR and CCS in the literature contributes to understanding themes and complexities in climate change mitigation.

Taking into consideration the demands for CO_2 storage and ongoing research and development linking CCS with CO_2-EOR, this review article aims to explore how CCS is represented in the scientific literature on CO_2-EOR in the North Sea and Norway, with a focus on system synergies and contradictions in relation to climate change mitigation. The research questions are: What are the main themes discussed in the scientific literature on EOR concerning the intersection of CO_2-EOR and CCS? How is the relationship between CO_2-EOR and CCS framed with the imperatives of climate change mitigation? The review article is divided into two parts: a descriptive thematic mapping of the literature followed by an analysis of the framings on the relationship between CO_2-EOR and CCS which also incorporates social science literature on CDR.

This study on CO_2-EOR has implications for CO_2 storage, which is part of the value chain in CCS, CCUS, BECCS, and DACCS initiatives. Through a focus on the geographical region of the North Sea, this study contributes to social science literature on CDR (e.g., Carton et al., 2020; Stuart et al., 2020; Asayama, 2021; McLaren et al., 2021; Hansson et al., 2022) and adds a contrasting and broadened perspective to the existing CO_2-EOR literature which, as will be illustrated in the review, is mostly treated in isolation from other branches of literature. This study also contributes focus on the North Sea empirical case to critical social sciences including literature on sustainability transitions which studies social, economic, and environmental aspects of systemic changes (Markard et al., 2012; Grubler et al., 2016) in addition to literature on carbon lock-in which refers to risks with prolonging an energy system based on fossil fuels in society (Unruh, 2000; Unruh and Carrillo-Hermosilla, 2006). According to Smith et al. (2023), there is a research gap on CDR studies in specific geographies, Markusson et al. (2020) suggest that more studies in specific geographies are needed to study the impacts of CDR, and Carton et al. (2023) state that empirically grounded studies on CDR could contribute to emissions reductions. By studying CO_2-EOR in the North Sea and Norway, this study highlights how CDR social science studies could add to techno-economic literature with implications for storing CO_2 as part of systems like BECCS, CCS, CCUS, and DACCS.

Section 2 describes the materials and methods for this study. Section 3 discusses themes in CO_2-EOR research and modeling studies in the North Sea based on a semi-systematic literature review with a focus on the last 17 years. Section 4 presents two framings on the relationship between CO_2-EOR and CCS, with support from perspectives in social science literature. Section 5 reflects on the literature review and discusses how critical social sciences could contribute to a deeper understanding of the socio-political context on CO_2 storage in the North Sea region.

2. Materials and methods

This study is divided into two parts: (1) a literature review on CO_2-EOR and CCS in the North Sea and (2) a critical analysis based on the results of the literature review in the light of social science literature to illustrate the framings on CO_2-EOR and CCS.

2.1. Literature review

The first part of this study (Section 3) is a qualitative semi-systematic literature review. According to Snyder (2019), a semi-systematic literature review is a narrative approach to studying a topic that has been researched from different disciplines using various methods, and it can be used to map themes to synthesize the knowledge on a certain topic. The material for this study was gathered in January 2023 from both Scopus and Web of Science which are recognized databases in engineering, environmental and social sciences. Scopus is a database that searches article titles, abstracts, and keywords of peer-reviewed publications, and the Web of Science search including title, abstract, and author keywords was used for consistency. Several search word combinations were tried, and the search combination of: *"CO_2" and "EOR" and ("North Sea" or "Norway")* was used to identify articles for this literature review. The search with Norway was meant to include the fields in all seas in Norway such as the Norwegian Sea and Barents Sea, while the search for the North Sea is inclusive of fields in the UK and Denmark. Norway is in focus since it is the only country in Europe with ongoing geological storage of CO_2, even though there are planned projects in the North Sea in Denmark, the UK, and the Netherlands (Global CCS Institute, 2022). There is extensive knowledge and mapping of prospective storage sites in Norway (Norwegian Petroleum Directorate, 2011). CO_2-EOR is not conducted or developed on a large scale anywhere in Europe (Thorne et al., 2020; Global CCS Institute, 2022).

The timeframe 2006 to 2022 was used to include research in the leadup to the United Nations Framework Convention on Climate Change (UNFCCC) conference in Copenhagen in 2009 up to the research published through the end of 2022. In Scopus, this search combination led to 104 items, and in the Web of Science, a search in "all databases" led to 48 items. Next, the result list was refined by conducting an additional search "within result search" for: *"CCS" or "CCUS"* in both databases. Scientific literature was considered relevant for this study if it included a focus on the North Sea or Norwegian context, leading to a total of 35 articles from peer-reviewed journals and conference papers in this study. This literature review has implications for other European countries that are interested in storage in the North Sea, including the UK, the Netherlands, Sweden, Denmark, Ireland, France, and Belgium (Global CCS Institute, 2022). The articles include a combination of open access articles and articles behind paywalls accessed via the Linköping University library. Figure 1 lists these articles by publication year.

Next, patterns were identified in the articles based on an inductive thematic analysis (Saldaña, 2013). These themes (Section 3) were selected based on their inclusion in the articles from different perspectives on the relationship between CO_2-EOR and CCS. These themes were identified by inductively mapping the content in the articles and then clustering the content into thematic areas. These themes are somewhat overlapping, but the purpose of the themes is to understand the common threads that link CO_2-EOR and CCS in the literature. To minimize repetition in the results narrative, specific examples are only described under the most prominent theme. In addition, the quotations and references in the results section show examples from scientific literature in this review to highlight key points within each theme, but this study does not provide a conclusive overview of all articles. This means that some of the inferences from the scientific literature may in fact be included in a broader set of articles than indicated in the citations.

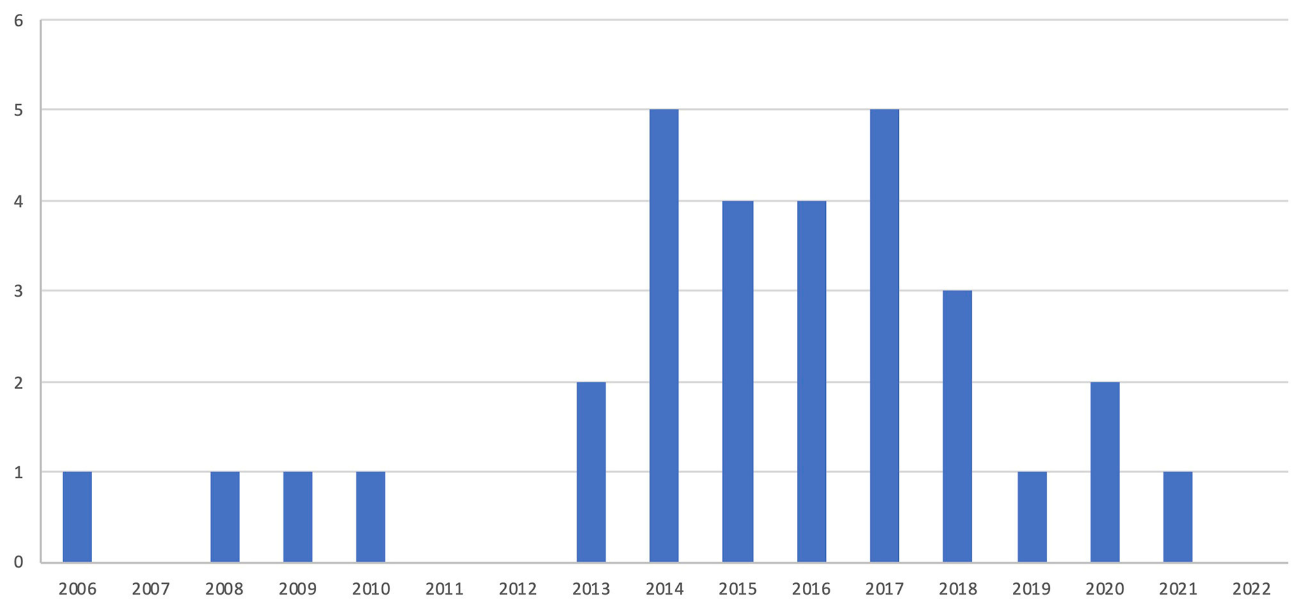

FIGURE 1
Number of articles in this literature review by year.

2.2. Framings

The second part of this study (Section 4) is largely based on the literature review and themes which served as the premise for identifying and discussing framings on CO_2-EOR and CCS. According to Entman (1993), frames show what matters most and serve different functions such as a way of defining problems, identifying causes, making moral judgments, and offering solutions. Frames reflect underlying perceptions and epistemologies (Hulme, 2009), and it is possible to have different frames within a particular text as exemplified by Waller et al. (2020). The purpose of analyzing and discussing framings on the relationship between CO_2-EOR and CCS is to understand the most salient aspects underpinning different perspectives on these technologies.

The use of frames in previous research on technological innovations, CDR, and CCS show that framings are a way to study salient aspects in perceptions on technologies related to climate change mitigation. In technological innovations research, framings of innovations can be portrayed in positive or negative ways (Magnusson et al., 2021). Frames are useful when studying CDR technologies to understand how they can be perceived as part of a climate change mitigation strategy (Gough and Mander, 2019). Due to uncertainties with innovations such as CCS, there are also different interpretations and perceptions that can be illustrated through frames (Hansson and Bryngelsson, 2009). Gunderson et al. (2020) apply frames in their research with fossil fuel companies to understand framings on CCS including what is absent from these framings. Framings can impact future solutions for climate change, and therefore studying framings contributes to future energy transitions.

In this study, the identified themes in the literature review are the starting point for identifying frames which illustrate perspectives on the relationship between CO_2-EOR and CCS with the imperative of climate change. The themes include contrasting perspectives on the compatibility between CO_2-EOR and CCS which are further discussed in the framings. While the themes are descriptive in nature, the framings illustrate polarized perspectives in how CO_2-EOR and CCS are linked. Through a qualitative discussion, this article presents two contrasting framings to illustrate synergies and goal conflicts between CO_2-EOR and CCS in this North Sea literature and within the broader context of critical social sciences literature on CO_2 storage. Additional social sciences literature is discussed to highlight the paradox of the two emerging framings in this study, particularly literature on carbon lock-in and sustainability transitions. Social science literature contributes to understanding technical studies through analytical reflections on system boundaries and possible paradoxes impacting climate change mitigation.

3. Themes at the crossroads of CO_2-EOR and CCS

This section describes each theme based on the literature review, with quotations and references that show examples from scientific literature. Many of the articles in this study are techno-economic studies, with development-oriented ambitions, written or funded by the fossil fuel industry. Based on a review of the scientific literature selected, various patterns emerged and were clustered into five broad themes which are: (1) climate change; (2) economics; (3) monitoring, safety, and leakage; (4) geology; and (5) transportation. This section highlights the perspectives of the authors in the 35 articles in this literature review, in addition to a few clarifying

TABLE 1 The level of inclusion of the different themes in each of the 35 articles included in this study, listed by year of publication from 2006 to 2022.

References	Climate change	Economics	Monitoring, safety, and leakage	Geology	Transportation
Steeneveldt et al. (2006)	Medium	High	High	Medium	Medium
Negrescu (2008)	High	High	Low	Low	Low
Wright et al. (2009)	Low	Medium	High	High	None
Kapteijn (2010)	High	High	Low	Low	Medium
Harrison and Falcone (2013)	Medium	High	High	High	None
Kemp and Kasim (2013)	Medium	High	Low	Low	Medium
Carpenter and Koperna (2014)	Medium	High	Medium	Medium	Medium
Cavanagh and Ringrose (2014)	High	High	Medium	Low	Medium
Mazzetti et al. (2014)	Medium	High	None	Low	Low
Mendelevitch (2014)	High	High	Medium	High	High
Neele et al. (2014)	Low	Medium	Low	Low	High
Shogenova et al. (2014)	Medium	High	Medium	Low	Low
Welkenhuysen et al. (2014)	Low	Medium	None	Medium	Medium
Geske et al. (2015a)	Low	High	Low	None	High
Geske et al. (2015b)	Low	High	Low	Low	High
Gruson et al. (2015)	Low	High	High	Medium	Low
Stewart and Haszeldine (2015)	High	Medium	Low	Low	Low
Ghanbari et al. (2016)	Medium	Medium	None	High	None
Mabon and Littlecott (2016)	High	Medium	None	None	Medium
Oei and Mendelevitch (2016)	High	High	Low	Low	High
Ward et al. (2016)	None	Low	Medium	High	None
Compernolle et al. (2017)	High	High	None	Low	Medium
Jakobsen et al. (2017)	High	High	Medium	Low	High
Karimaie et al. (2017)	Medium	Medium	Low	High	None
Mathisen and Skagestad (2017)	Medium	High	Low	Medium	Medium
Pham and Halland (2017)	None	Low	Low	High	Low
Welkenhuysen et al. (2017a)	Low	High	None	Medium	Low
Welkenhuysen et al. (2017b)	Medium	High	Low	High	Medium
Al-Masri et al. (2018)	High	High	None	High	None
Bergmo et al. (2018)	Low	None	Low	High	None
Welkenhuysen et al. (2018)	Low	High	Medium	High	Medium
Suicmez (2019)	Medium	High	Low	Medium	Medium
Roussanaly et al. (2020)	High	High	None	Low	High
Thorne et al. (2020)	High	Low	Medium	Low	Medium
Bonto et al. (2021)	Medium	Medium	High	High	Low

The gradient of green shading indicates the level of inclusion of the theme from mentioning it (light green/low), to discussing it (medium green/medium) or highlighting this theme in depth (dark green/high), such as including it in a modeling study. The blank spaces (none) indicate that the theme is not included in the study.

references that complement some of the information in the articles.

Table 1 shows the list of articles included in this literature review with a column for each theme showing the level of inclusion based on four gradients from not including it at all in a study (white color) to including the theme in depth (dark green). This shows which themes are in focus in each article, illustrating research priorities in studies on CO_2-EOR in the North Sea. The dark green gradient indicates that a theme is included in depth, while medium green indicates that a theme is discussed. When a theme is merely

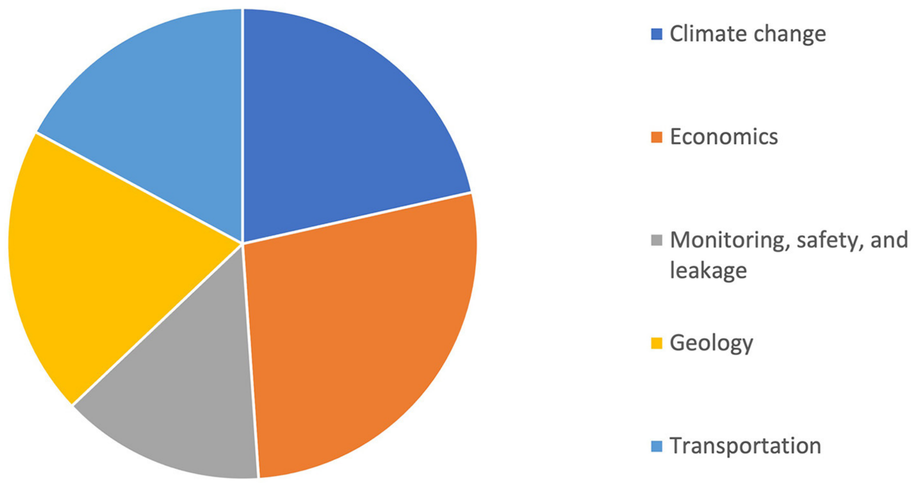

FIGURE 2
Pie chart showing the prevalence of each of the five themes in the reviewed articles.

mentioned, it is shown in light green. Taking the article by Gruson et al. (2015) as an example, here is an overview of how the themes were identified in an individual article: climate is only mentioned in the framing of the abstract (climate = light green), transportation pipelines are mentioned in one sentence (transportation = light green), injection wells and site-specific geologic conditions are discussed on several occasions (geology = medium green), and economic issues and monitoring are included in depth (economics = dark green; monitoring = dark green). Figure 2 also illustrates the prevalence of each of these themes in the review article. As depicted in the pie chart, economics was the most common theme, followed by climate change and then geology. Transportation and monitoring, safety, and leakage were the least recurring themes. This pie chart was designed by creating a numbering system for the themes based on the level of inclusion of each theme in each article as shown in Table 1: none (0), low (1), medium (2), and high (3) to create a sum for each of the themes in the reviewed articles.

3.1. Climate change

The first theme is climate change, which is discussed in about two-thirds of the articles. Although many of the articles in this literature review mention climate change or international climate agreements to reduce greenhouse gas emissions (GHG), only about half of the articles identify climate change as a key driver to store anthropogenic CO_2 emissions, which are from human activities such as the use of fossil fuels. Several articles include climate change framing in the abstract or introduction with no other mention of climate change (Geske et al., 2015b; Gruson et al., 2015; Welkenhuysen et al., 2018). Other articles frame the issue of climate change at the beginning and end of an article, without discussing climate change in the content of the article (Karimaie et al., 2017; Welkenhuysen et al., 2017b; Suicmez, 2019; Bonto et al., 2021). Meanwhile, some articles do not mention climate explicitly but discuss environmental aspects, CCS and/or a reduction of industrial CO_2 emissions (Negrescu, 2008; Mazzetti et al., 2014; Neele et al., 2014). Still, other articles do not include climate change or related concepts at all (Ward et al., 2016; Pham and Halland, 2017).

Several authors state that CO_2-EOR could contribute to the commercial development of CCS infrastructure and the start of the carbon storage industry in the North Sea and Norway. This could include the sharing of infrastructure (Mazzetti et al., 2014), development of a market for CO_2 (Pham and Halland, 2017), and initiation of large-scale storage (Neele et al., 2014). According to some authors, a benefit of CO_2-EOR is that the fossil fuel industry's infrastructure and geological knowledge could set the groundwork for offshore CO_2 storage via CCS in the North Sea. For example, Welkenhuysen et al. (2017a) state that CO_2-EOR infrastructure could be used for CO_2 storage after oil production. According to Mazzetti et al. (2014), there could be an economic motivation to store CO_2 from natural gas streams in EOR projects in the North Sea, and they state that "… the combination of CO_2-EOR with permanent CO_2 storage in oil reservoirs may be a critical, near-term solution for creating economically viable CCS projects, facilitating early CCS infrastructure—and kick-starting deployment of CCS." (p. 7289). This view shows that CO_2-EOR could contribute to the near-term application of CCS with the necessary infrastructure for CO_2 storage. Carpenter and Koperna (2014) discuss that there could even be a symbiotic relationship, "… not only does CCS need CO_2-EOR to help promote economic viability for CCS, but CO_2-EOR needs CCS to ensure adequate CO_2 supplies to facilitate growth in oil production from CO_2-EOR projects." (p. 6718). This forwards a view that CO_2-EOR and CCS could develop together and lead to integrated infrastructure for CO_2 storage in the North Sea region.

Another perspective in the scientific literature is that CO_2-EOR and CCS are incompatible with one another in creating a low-carbon future. According to some authors, this is because there is a goal conflict between these two applications, since CO_2-EOR supports the fossil fuel industry which makes it even more challenging to mitigate climate change. For example, Mendelevitch (2014) states, "There is high regulatory uncertainty on the acceptance of CO_2 abatement credentials generated from CO_2-EOR." (p. 151). This view questions if CO_2-EOR is abated emissions since oil is produced. In addition, Cavanagh and Ringrose (2014) state that a CO_2-EOR project would need to have significant CO_2 storage to have a net zero GHG impact. Harrison and Falcone (2013) are also critical of the possible climate change benefit of CO_2-EOR since this process produces oil while only displacing some oil produced from other sources, leading to a net increase in oil consumption. According to this view, oil production leads to goal conflicts when it comes to reducing GHG emissions since continued oil production both perpetuates the fossil fuel industry and makes it harder to reduce GHG emissions in the long term. Compernolle et al. (2017) also take the perspective that CO_2-EOR would increase net oil extraction, negatively impacting efforts toward decarbonization. At the same time, another view is that there could be an opportunity to implement CO_2-EOR in the near term as part of a sustainability transition. This is illustrated by focus groups with stakeholders in the UK conducted by Mabon and Littlecott (2016) that show some support to temporarily deploy CO_2-EOR in the North Sea which could financially contribute to infrastructure for CCS, but this would only be favorable if it were part of a transition toward decarbonization and low-carbon technologies.

3.2. Economics

Some of the main patterns clustered within the theme of economics discussed in the articles in this review include oil price, CO_2 price, the role of government, and legal and policy issues. CO_2-EOR is an industrial application to extract fossil fuels, and Mathisen and Skagestad (2017) state that CO_2-EOR is financially viable only if it leads to an increase in oil production. Oil price is named in several articles as a factor of the economic viability of CO_2-EOR in the North Sea even though there are no commercial CO_2-EOR projects in Europe (Geske et al., 2015b). Harrison and Falcone (2013) argue that 100 USD per barrel of oil would be needed to offset financial risks of CO_2-EOR. Welkenhuysen et al. (2017a) state: "CO_2-EOR is at this moment not applied in the North Sea oil fields, and especially with the current low oil prices, the profitability of such projects is questioned." (p. 7068). This shows that oil price is a key aspect in the economic profitability of EOR, and a low oil price could be a barrier for the initiation of commercial scale projects according to this view. Welkenhuysen et al. (2014) also argue that oil price is the most sensitive parameter when assessing the profitability of CO_2-EOR. Therefore, a low enough oil price contributes to an absence of the industrial application of offshore CO_2-EOR in the North Sea.

CO_2 tax is an example of an instrument that could stimulate CCS in either onshore or offshore projects according to several authors. Mendelevitch (2014) state that unless the CO_2 price is high enough, CCS will not takeoff in the coming decade. Meanwhile, in the USA, tax incentives and tax breaks have supported the development of onshore CO_2-EOR projects. In their financial models for CO_2-EOR in the North Sea in the UK, Kemp and Kasim (2013) discuss how current tax rates on oil fields in the UK are too high to make EOR a viable business case, since these taxes include corporation tax (30%), Supplementary Charge (32%), and Petroleum Revenue Tax (50%) on fields older than March 1993. The UK's Carbon Price Floor to encourage low carbon investments could lead to more carbon capture projects if there is a high enough CO_2 price (Kemp and Kasim, 2013). Therefore, they conclude that more research is needed on CO_2 prices and tax incentives to determine the economic viability of CO_2-EOR in the UK (Kemp and Kasim, 2013). Similarly, Compernolle et al. (2017) state that CO_2 price is not enough to lead to investment in offshore CO_2-EOR and CO_2 storage in the North Sea, and that combined policy measures are needed.

Several authors highlight uncertainty around legal and policy issues as a key factor in making CO_2 storage economically viable. According to Steeneveldt et al. (2006), "Apart from technical advance, legislation and regulatory changes will be the stronger drivers for closing the knowing-doing gap for CO_2 capture and storage." (p. 759). Geske et al. (2015b) state that CO_2 is characterized as waste, and it is therefore governed under the London Convention which regulates marine dumping. The London Protocol to the London Convention was brought up by some authors as a barrier to CO_2 transport and storage across national borders (Steeneveldt et al., 2006; Harrison and Falcone, 2013). According to the IMO (2019), a resolution in 2019 enables the provisional application of the 2009 amendment to Article 6 of the London Protocol enabling the export of CO_2 across country borders for sub-seabed storage. Since the 2009 amendment is not in force, this resolution alleviates the legal barrier addressed in the scientific literature, which could lead to opportunities for CO_2 export, if there is agreement between the countries involved.

In addition, there are other relevant global and European frameworks that impact the economic prospect of implementing CO_2 storage including the EU CCS Directive and the EU Emissions Trading System (ETS). The EU CCS Directive provides a framework for safe geological storage of CO_2 (EU, 2009b), and CCS is explicitly named as an activity in Annex I of the EU ETS (EU, 2009a), although the EU ETS does not currently include emissions from biomass, therefore there is no incentive for BECCS (EC, 2020; Rickels et al., 2021). The EU ETS is a cap-and-trade system to reduce GHG emissions in the European Economic Area which includes Norway (EC, 2021). Some authors argue that the low price of the carbon credits in the EU ETS, the European Union Allowance (EUA), has been a barrier for CCS (Cavanagh and Ringrose, 2014). Oei and Mendelevitch (2016) also share this view that the CO_2 price in the EU ETS is not significant enough to motivate investment in CCS. Although the price has risen from a high of 6 EUR in 2016 to 97 EUR at the end of January 2023 (Trading Economics, 2023), the price remains insufficient, so other economic instruments could be necessary to incentivize a reduction of CO_2 emissions according to this perspective.

3.3. Monitoring, safety, and leakage

This theme comprises the cluster of monitoring, safety, and leakage which are related issues addressed in the articles in this review. Although more than three-quarters of the articles mention monitoring, safety, or leakage, this theme is underdeveloped compared with the other themes. Some articles list monitoring, reporting, and verification (MRV) as a step in the CO_2 storage process, such as framing it as a key part of the CCS value chain (Jakobsen et al., 2017). This is because MRV creates economic value in CCS when facilities emitting CO_2 must comply with the EU MRV Regulation (EU, 2015) and EU CCS Directive (EU, 2009b) which are relevant in the North Sea region. CCUS such as CO_2-EOR has economic value in the utilization of CO_2 in an industrial process, while CCS without utilization relies on the CCS Directive and the price of EUAs under the EU ETS for monetary value. According to Mendelevitch (2014), "Permanent storage can only be credited if a monitoring scheme is in place that includes baseline monitoring and demonstrates and measures effective storage." (p. 135). Therefore, many authors view monitoring as a key aspect of CO_2 storage, especially if it were to contribute to climate change mitigation.

The scientific literature shows that there could be overlaps between monitoring at both CO_2-EOR and dedicated CO_2 storage sites. At the Sleipner CO_2 storage facility in Norway, monitoring has been conducted since its inception in 1996, but long-term monitoring issues over a 100-year timeframe are unknown, such as impacts of CO_2 on geological formations over time (Wright et al., 2009). This is because monitoring of offshore storage has only taken place over a few decades but monitoring over a longer timeframe could reduce uncertainties. According to Kapteijn (2010), surveillance infrastructure for EOR management could also be applied to survey dedicated CO_2 storage. Cavanagh and Ringrose (2014) agree that there are benefits of having CO_2 storage in gas fields which are already monitored. Furthermore, Steeneveldt et al. (2006) suggest that monitoring for CCS can learn from CO_2-EOR, "… monitoring techniques and safe practice encompassing proper operator training, maintenance procedures, pressure monitoring, reliable gas detection systems, emergency shut-down procedures and other safety systems relevant for EOR can be adapted for CO_2 storage" (p. 757-758). This perspective shows that monitoring CO_2 storage for climate change mitigation purposes could benefit from knowledge from CO_2-EOR monitoring programs (Steeneveldt et al., 2006). According to a study in the Danish North Sea, another aspect is the possibility of applying machine learning in monitoring approaches which could lower the costs of monitoring storage sites (Bonto et al., 2021).

The safety of CO_2-EOR and CO_2 storage is another issue addressed in the scientific literature. Some authors mention the importance of safe, long-term storage (Steeneveldt et al., 2006; Mendelevitch, 2014; Pham and Halland, 2017). According to Negrescu (2008) and Harrison and Falcone (2013), safety of storage sites is a reason monitoring is necessary. There are other concerns about safety when considering the long distance transport of CO_2 from mainland Europe to a storage site in the North Sea, including the use of temporary storage for CO_2 that is moved from one transport vessel to another (Geske et al., 2015a). Intermediate storage with additional safety measures could also increase the cost of transporting and storing CO_2 (Geske et al., 2015a). In addition, other monitoring variables described in the scientific literature include the type of monitoring, its frequency, and duration over time. According to Shogenova et al. (2014) and Gruson et al. (2015), state level regulations impact the length of monitoring periods for CCS projects which can vary between EU Member States. This shows that in the EU, there are different standards and procedures in each country, even though there are IPCC standards for monitoring stored CO_2 emissions, e.g., 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston, 2006).

Leakage from storage sites is an aspect of monitoring that is included in some articles (Steeneveldt et al., 2006; Harrison and Falcone, 2013; Mathisen and Skagestad, 2017; Thorne et al., 2020). Leakage of CO_2 could have a negative impact on climate change mitigation measures. According to Thorne et al. (2020), the amount of leakage in CO_2-EOR processes is uncertain, but in their model of the Norwegian Continental Shelf, they show that even with 10% leakage in CO_2-EOR due to transport and injection, there are less CO_2-equivalent emissions per kilogram of oil resulting from CO_2-EOR than from conventional oil extraction. Here, the reference case of what CO_2-EOR is compared with is critical in identifying the hypothetical cost or benefit in terms of CO_2 emissions. Another concern is CO_2 leakage from power outages at CO_2-EOR sites (Mathisen and Skagestad, 2017; Thorne et al., 2020).

3.4. Geology

Geological characteristics determine the feasibility of CO_2-EOR and CO_2 storage, but there are many uncertainties and knowledge gaps identified by the scientific literature. This includes a lack of detailed knowledge about geological formations which can be a barrier for CO_2 storage (Mathisen and Skagestad, 2017; Al-Masri et al., 2018). According to Harrison and Falcone (2013), there is potential for CO_2 storage in the North Sea, but it would require assessments which are already available for oil and gas fields. Therefore, taking advantage of existing sites and knowledge held by oil and gas companies could be more economical than assessing additional sites. Even though there could be potential to store CO_2 in other geological formations, depleted oil and gas fields are currently the cheaper alternative since the cost to evaluate these new storage sites make it too expensive (Harrison and Falcone, 2013). Based on a literature review on the Danish North Sea by Bonto et al. (2021), there could also be potential to store CO_2 in other types of rock such as offshore chalk formations in the North Sea, although more research would be needed to explore this possibility. This differs from the experience of storage in sandstone formations at Sleipner and Snøhvit, and planned at the Aurora storage site as part of the Northern Lights project.

Interest in CO_2-EOR is rising in the North Sea partly due to declining oil fields. Studies show different potentials for storing CO_2. Geske et al. (2015b) state that there could be potential for 1.4–4.0 Gigatonne (Gt) of CO_2 storage per year when applying CO_2-EOR over 40 years in the British and Norwegian oil fields in the North Sea. Mendelevitch (2014) published a review article showing that there are inconsistencies when compiling data on CO_2-EOR potential in different countries in the North Sea, so even though they state that there is substantial oil recovery potential in the North Sea, equating to 1.2 Gt CO_2 storage per year, these amounts are based on different calculation methods in the UK, Norway, and Denmark. These different calculation methods make it difficult to compare the possible amount of oil recovery and the possible CO_2 storage capacity across geographies. This shows that there are uncertainties and inconsistent ways of measuring storage potential in the North Sea.

Another aspect discussed in several articles is onshore vs. offshore storage. Commercial scale CO_2-EOR projects to date are onshore, and the models for offshore storage show that it could be more expensive partly due to higher compression costs offshore (Ghanbari et al., 2016). Geske et al. (2015a) suggest that offshore storage could lead to a higher rate of public acceptance. Conducting commercial scale CO_2-EOR would be new in the North Sea, but it could be driven by climate change and economic variables according to the literature. To this end, Al-Masri et al. (2018) state that CO_2-EOR using CO_2 from anthropogenic sources could provide a significant environmental benefit and therefore motivate an investment in new storage sites, since this would decrease the net emissions in the atmosphere.

3.5. Transportation

Infrastructure for CO_2 transport is discussed in depth in about one-fifth of the articles. According to Kemp and Kasim (2013), there could be economic benefits of a networked pipeline in the Central North Sea in the UK, using a combination of new and existing pipelines. Two associated transport studies show that there could be possibilities to optimize the vessel and pipeline transportation part of CCS infrastructure, but authors suggest that more studies are needed (Geske et al., 2015a,b). Oei and Mendelevitch (2016) state that the most likely storage option in a European context is a regional network of collaborations to store CO_2 in the North Sea. This vision would necessitate regional cooperation to address the geographical difference between where CO_2 is emitted and where it could potentially be stored. In their study on the EU CCS Directive (EU, 2009b), Shogenova et al. (2014) state that only three European countries have developed shared principles for managing transboundary cooperation on transporting, injecting, and storing CO_2 in the North Sea—Germany, the Netherlands, and the UK—but they suggest that there could be more transboundary cooperation in the future. Despite these principles, investment costs, political support, and public acceptance remain challenges for CCS in Europe.

CO_2 can be transported via pipelines and/or vessels, and most studies discuss having vessels which makes sense with offshore storage projects in the North Sea when industries applying carbon capture are near coastlines. In studies on transportation options for CO_2 storage, several authors conclude that marine transport by vessel is more cost effective (Kapteijn, 2010; Geske et al., 2015a; Jakobsen et al., 2017). Furthermore, Neele et al. (2014) state that vessels could benefit both CO_2-EOR and CCS at early projects instead of constructing pipeline networks. This is because vessels are more flexible, offering a timelier option with a lower investment cost than pipelines (Neele et al., 2014; Welkenhuysen et al., 2014; Geske et al., 2015b). Meanwhile, other authors focus on transportation pipelines in the North Sea region (Oei and Mendelevitch, 2016; Compernolle et al., 2017). Oei and Mendelevitch (2016) discuss the need for extensive pipelines for implementing CCS across Europe which would be very expensive, stating that sites with proximity to offshore storage in the North Sea have the highest possibility of being realized. Mazzetti et al. (2014) reiterate the concern that expensive transportation pipelines for CO_2 are a barrier for CO_2 storage. Therefore, the articles show that vessels and proximity to CO_2 storage sites in the North Sea contribute favorable conditions for implementing CCS in a European context.

CO_2-EOR could potentially finance infrastructure used by CCS projects such as transportation networks in the North Sea. It could thereby contribute to shared infrastructure for CCS and CO_2-EOR according to some authors (Cavanagh and Ringrose, 2014; Mendelevitch, 2014; Mabon and Littlecott, 2016) and cover the costs of a European CO_2 transportation and storage network (Geske et al., 2015b). At the same time, infrastructure development requires public acceptance and long-term planning such as having a "North Sea transition plan" (Mabon and Littlecott, 2016, p. 135). This means that developing CCS in the North Sea region is a long-term commitment including several actors and cross-border collaborations. Furthermore, according to Kapteijn (2010), combining CCS and CO_2-EOR could lead to an integrated system which contributes to financing CCS infrastructure for industries to reduce CO_2 emissions. An integrated system with shared infrastructure could enable CO_2 storage. Nevertheless, there are contradictions in the literature regarding the optimal type of transportation network, and there are additional complexities to consider with offshore storage within Europe than with transport to onshore storage sites in North America (e.g., Kapteijn, 2010; Compernolle et al., 2017).

4. Framings of CO_2-EOR and CCS

This section discusses framings of CO_2-EOR and CCS, with the themes resulting from the literature review described in Section 3 as a starting point, in addition to incorporating social sciences literature to further illustrate the relationship between CO_2-EOR and CCS with the imperatives of climate change mitigation. This literature review shows that there are different perspectives on CO_2-EOR in the North Sea, including conflicting views on its relationship with CCS. Based on the themes in this study, there are two main framings of climate change in the North Sea in the CO_2-EOR literature. The first framing is that CO_2-EOR is a gateway to other types of large-scale storage with the sole purpose of storing CO_2 for climate change mitigation purposes. In contrast, the second framing is that CO_2-EOR and CCS are incompatible with one another due to goal conflicts. These framings show that there are complexities for future geological storage, yet a critical social science perspective is absent in the articles in this review, and such a perspective could contribute context regarding the realizability of future socio-technical transitions. Markusson et al. (2011) states that framings of CCS demonstration projects matter because framings impact project designs, even if framings can change over time. Cox et al. (2018) describe how framing of a problem and technology impacts governance and policy decisions. Therefore, framings on technologies in research shapes both future technology design and its implementation in society. Expanding on the literature review selection for this article, this section incorporates both literature from this review and additional related scientific literature to further contextualize the framings.

4.1. CO_2-EOR as a gateway to storage for climate change mitigation

According to the first framing, which is the dominant framing in this literature review, CO_2-EOR creates an opportunity for large-scale CO_2 storage in the North Sea. This framing is also supported by the IPCC (2022) report which states that while EOR potential is a small fraction of the need for CCS, EOR is a gateway to CCS pilot and demonstration projects. Fossil fuel companies have geological knowledge due to decades of exploitation of oil and gas fields which could help identify potential CO_2 storage sites for CCS (Mathisen and Skagestad, 2017; Al-Masri et al., 2018). Godec et al. (2013) show the economic advantages for fossil fuel companies and tax-collecting states in addition to CO_2 storage benefits when merging CO_2-EOR with CCS. Even though there are no concrete plans for commercial-level CO_2-EOR projects in the North Sea, most of the literature in this review suggests that there could be benefits of linking CO_2-EOR with CCS in at least an early stage toward decarbonization (e.g., Carpenter and Koperna, 2014; Cavanagh and Ringrose, 2014; Mazzetti et al., 2014). This is similar to the findings by Núñez-López and Moskal (2019) whose literature review highlights the potential of CO_2-EOR to contribute to decarbonization in the short term when coupling it with CCS. This is because CO_2-EOR is a commercially established process, and it could be combined with capture of anthropogenic CO_2 emissions such as from large point sources at industrial facilities (Núñez-López and Moskal, 2019). Adding to the perspectives of many of the authors in this literature review, Raffa (2021) suggests that there are opportunities to combine old and new EOR technologies with CO_2 storage as one of many solutions to reduce emissions to mitigate climate change.

Most articles in this literature review suggest that there is an opportunity for CO_2-EOR and CCS projects to collaborate. Cavanagh and Ringrose (2014) state that CO_2-EOR contributes to the development of CO_2 transport and storage infrastructure in the European context, which could contribute to reducing costs for future CCS projects. There is a trend in Norway where different actors are responsible for parts of the CCS value chain, such as for capture vs. transport and storage (Chailleux, 2019). This could create opportunities for shared infrastructure for transport and storage for both CO_2-EOR and CCS. Furthermore, until the global demand for fossil fuels starts decreasing, there could be an opportunity for CO_2-EOR to contribute to the energy system (Raffa, 2021). Several authors argue that capturing and storing CO_2 emissions from anthropogenic activities, opposed to using CO_2 occurring in natural underground sources which would not otherwise end up in the atmosphere, is relevant to maximize the climate benefit of CO_2-EOR (Mendelevitch, 2014; Karimaie et al., 2017; Al-Masri et al., 2018).

A tension is that CO_2-EOR is only conducted when it is economically profitable for the extraction of fossil fuels, so it is a shift to consider maximizing CO_2 storage instead. At the same time, Edwards and Celia (2018) state that it is most economical to use captured CO_2 in EOR rather than in dedicated geological storage sites, unless there are economic instruments for climate change mitigation activities. Based on economic arguments, utilizing CO_2 that is captured from anthropogenic CO_2 sources for EOR is expensive, so most current CO_2-EOR projects utilize CO_2 from natural geological sources (Hill et al., 2013; Cooney et al., 2015). Based on their scenario study in the North Sea, Roefs et al. (2019) show that there could be economic and environmental benefits of combining CO_2-EOR and CCS, but it depends on CO_2 price and oil price, which is an argument that is consistent with several authors in the reviewed literature. According to some authors, CCS could benefit from the experiences of CO_2-EOR in monitoring, and the two could work together in monitoring efforts (Steeneveldt et al., 2006), but there are different views on the compatibility of monitoring schemes for offshore storage in the North Sea region (Mendelevitch, 2014).

4.2. Incompatibilities between CO_2-EOR and CCS

A second framing is that coupling CO_2-EOR and CCS is not compatible with climate change mitigation measures since it perpetuates a cycle of GHG emissions, regardless of if CO_2 comes from natural underground geological sources or from anthropogenic sources such as industries. Some authors are critical of the climate change mitigation benefit of storing CO_2 via EOR due to goal conflicts since oil is produced (Harrison and Falcone, 2013; Mendelevitch, 2014; Compernolle et al., 2017). Stewart and Haszeldine (2015) suggest that CO_2 utilized by EOR could otherwise be permanently stored in geological formations in the North Sea without supporting the fossil fuel industry. According to this perspective, using dedicated geological storage for CO_2 is better than applying CO_2-EOR in the North Sea region. Meanwhile, when using CO_2 from natural underground geological sources vs. from anthropogenic sources, only the latter leads to less CO_2 in the atmosphere. Even though there are tradeoffs depending on the alternatives being compared, CCS and CO_2-EOR are incompatible with one another according to this framing.

System boundaries are relevant when estimating emission levels and considering the impact of CO_2 storage on climate change mitigation. When expanding their system boundaries to include refining, transport, and combustion of oil during the project's lifetime, their model shows that CO_2-EOR ranges from carbon negative to net positive emissions in the North Sea (Stewart and Haszeldine, 2015). According to Oei and Mendelevitch (2016), even though CO_2-EOR could drive CCS projects, subsidizing the fossil fuel industry to advance CCS technology is problematic for emissions reductions. Based on this framing, using captured CO_2 in CO_2-EOR projects contradicts the climate change mitigation purpose of CCS projects. Therefore, this framing shows that there is some skepticism whether CO_2-EOR could contribute to decarbonization. Another concern is uncertainties, and according to Thorne et al. (2020), addressing uncertainties in CO_2-EOR processes such as minimizing the amount of leaking CO_2 is relevant from a climate change mitigation perspective.

Although this framing is not as strong in the literature review as the first framing, it is more prevalent in social science literature addressing CCS in the context of climate change mitigation more generally without a specific focus on the North Sea region or Norway. Social science literature on CDR outside of the scope of this review emphasize this framing. Carton et al. (2020) show that investing in technologies such as CCS supports the continuation of fossil fuel industries and thereby counters a sustainability transition. McLaren et al. (2021) state that utilizing CO_2 such as through EOR could be more economically viable than dedicated geological storage, but EOR is problematic since it contributes to the fossil fuel industry. Furthermore, Asayama (2021) state that carbon capture in CCS projects is often associated with retrofitting power plants or industries using fossil fuels and thereby prolongs carbon lock-in and the fossil fuel regime. In addition, Buck (2018) points out that the main market for captured CO_2 is EOR which perpetuates dependence on fossil fuels. At the same time, 80% of global energy supply is from fossil fuels, a level that has been consistent during the past few decades, despite an increase in the renewable energy supply (Ritchie and Roser, 2020). Since there is still an upwards trend in primary energy consumption (apart from 2020 during the COVID pandemic), there is a strong reliance on fossil fuels, even while there is a shift toward more renewable energy. Despite these energy trends, Markard et al. (2021) state that technologies like EOR and CCS could lead to further sustainability challenges by perpetuating unsustainable systems reliant on fossil fuels.

5. Discussion

This section reflects on the scientific literature in this review and discusses how critical social sciences could contribute to a deeper understanding of the socio-political context of CO_2 storage in the North Sea region and its impact on climate change mitigation. In their study in Sweden, Nurdiawati and Urban (2022) show that refining companies are the strongest proponents of CCS followed by industries and researchers, while NGOs and politicians are more skeptical. The dominant perspective in this literature review is from the fossil fuel industry, which have a stake in the implementation of CO_2-EOR since it is an industrial application that extends fossil fuel extraction.

About one third of the articles in the review merely mention climate change or emissions reductions without any discussion (e.g., Neele et al., 2014; Gruson et al., 2015) or do not mention climate change at all (Ward et al., 2016; Pham and Halland, 2017). These articles instead focus on the economic advantage of implementing CO_2-EOR for oil extraction purposes as a motivation for CO_2-EOR in geological and engineering feasibility studies that investigate the possibilities for CO_2-EOR in the North Sea region. Given the possibilities to position CO_2-EOR positively for the fossil fuel industry, it is somewhat surprising that some articles do not mention climate change, but it shows that there are strong economic motivations for CO_2-EOR that legitimate such studies. The goal conflicts between CO_2-EOR and CCS depend on how the technologies are implemented such as how much CO_2 is stored and if negative emissions are also feasible in the CO_2 accounting. In addition, even if there are goal conflicts in the short term, there could be synergies in the long term if CO_2-EOR contributes to reduced emissions through a faster transition to CCS toward a lower-carbon society.

This literature review shows a lack of literature on social science perspectives when considering the key words used in this study focusing on CO_2-EOR in Norway and the North Sea. Only one of the articles is from social sciences, by Mabon and Littlecott (2016) which discusses a "transition" in the North Sea with CO_2-EOR as a bridge toward CCS and other climate change mitigation measures. Additional social sciences literature could add new perspectives on the context in which CO_2-EOR and CCS technologies are embedded. This study's focus on CO_2-EOR in the North Sea region and Norway highlights the relationship between CO_2-EOR and CCS in addition to illustrating a social sciences research gap in this area, which has implications for storing CO_2 from CDR projects since CO_2-EOR can be seen as part of the transition to CCS and dedicated geological storage.

When it comes to studies on BECCS and CDR research more broadly, this social science research gap is also evident. A new report, The State of Carbon Dioxide Removal by Smith et al. (2023) illustrates a research gap in social science studies including empirical studies in a specific geography. Markusson et al. (2020) emphasize the importance of such geographical studies to understand impacts of CDR in different places in addition to aspects of politics and justice. Similarly, in their review article, Carton et al. (2023) state that more empirically focused cases are relevant to prevent mitigation deterrence, which refers to substituting short-term mitigation measures with CDR, but empirical cases could contribute to reducing any delays in mitigating climate change. Besides a lack of empirical studies with a focus on a particular geography in CDR research which often addresses overarching questions, there also seems to be a lack of media coverage and scientific debate on the storage of CO_2 (Hansson et al., 2022). An analysis by Hansson et al. (2022) shows that there is less critique in the public debate on geological storage after 2014, and the authors conclude that critical social sciences could contribute new insights on environmental challenges such as CO_2 storage.

In addition to the lack of empirical case studies and media coverage related to CO_2 storage, half of the literature in this review is concentrated in two journals: *Energy Procedia* (10 articles) and the *International Journal of Greenhouse Gas Control* (7 articles). This shows that the topic of CO_2-EOR in the North Sea region and Norway is not widespread outside of certain disciplines that are most apt to publish in these two journals.

Even though the articles in this study focus on conventional CCS, it is surprising that most articles do not mention BECCS since they are usually discussed in tandem in the literature. Only one article in this review mentions conducting CCS on biogenic sources in a study on a waste-to-energy plant that would include both fossil and biogenic emissions (Roussanaly et al., 2020). This could partly be since the research community and IPCC scientists' focus on BECCS is new in recent years, as shown by the IPCC (2018) special report on 1.5°C. In addition, the large point sources of biogenic CO_2 emissions do not occur in the North Sea countries but rather take place in Sweden and Finland in the Nordic context

(Rodriguez et al., 2021) which is outside of the geographical region of this literature review. At the same time, Norway has some point sources of biogenic emissions from waste incineration just like Sweden, and there are ongoing projects to implement BECCS in both countries. Although the CO_2-EOR literature in the North Sea and Norway do show that it could contribute as a gateway to CCS, the CO_2-EOR literature do not mention acting as a bridge to BECCS. Another possible reason that literature on CO_2-EOR focus on CCS but not BECCS is that the EU ETS considers emissions from fossil sources but not from biogenic sources (EC, 2020; Rickels et al., 2021). Even though the literature on CO_2-EOR in the North Sea and Norway usually does not include BECCS, there could be overlaps in actors and infrastructures such as for transporting CO_2, so there could be a benefit to including BECCS in the narrative of CO_2-EOR research to understand the broader context and possible carbon lock-in.

The literature on CDR and net emissions is separate from the body of literature on EOR and CCS studied in this literature review, even though these two bodies of literature have complementary analyses and deal with infrastructures that may be integrated. The literature in this review and the CDR literature show that there are economic barriers to scaling up these technologies for climate change mitigation, in addition to different ways of accounting for emissions. For example, Carton et al. (2020) state that net emissions accounting is socially constructed and politically designed by the UNFCCC, and there are inconsistencies in how emissions are counted. Therefore, they argue that alternative ways of understanding emissions are needed. Stuart et al. (2020) state that when accounting for CO_2 emissions, CO_2-EOR does not consider the additional CO_2 emissions in the lifecycle of the extracted fossil fuels. Brauers et al. (2021) suggest accounting for lock-in when taking decisions in the context of energy transitions to balance climate goals with energy security in the long term. Another issue is double counting the CO_2 emissions reduced in both CCS and CO_2-EOR systems (Muffett and Feit, 2019). Even though there are challenges regarding policies and emissions calculations when integrating carbon capture and EOR systems, Cooney et al. (2015) show that using CO_2 from anthropogenic sources in EOR could contribute to emissions reductions in comparison with using CO_2 from natural geological sources. Therefore, whether CO_2-EOR reduces emissions depends on the source of CO_2 utilized and system boundaries (Cooney et al., 2015).

Storing CO_2 via EOR could lead to less urgency for the fossil fuel industry to decrease its operations, thereby strengthening the fossil fuel regime despite climate change concerns. Within the Nordic context, the Swedish Government, which is one of very few that explicitly addresses this concern, has stated that it is against contributing to EOR and perpetuating the fossil fuel industry (SOU, 2020). This shows that there are political preferences against EOR, even if CO_2 is eventually stored. Endres et al. (2016) describe the framing shift from CCS to CCUS and its implications for climate change when CO_2 is viewed as a commodity for industrial processes such as EOR. This framing legitimates the future existence of fossil fuel companies, even though there are inconsistencies in how the terms CCUS and CCS are used which causes ambiguity (Olfe-Kräutlein et al., 2022). Palm and Nikoleris (2020) show that there are contrasting expectations on CO_2-EOR depending on if fossil fuels are framed as the problem or if GHG emissions are considered the main concern. There seems to be a preference for the latter framing in CCS projects. In fact, most countries with CCS projects are also major fossil fuel producers, including Canada, USA, and Norway (Reiner, 2016), and at least 85% of CCS projects involve fossil fuel companies as an affiliate or funder (Chalmin, 2021). Rauter (2022) points to the paradox that Norway is both an exporter of fossil fuels and a progressive climate change leader at the same time with a national electricity mix which relies on hydropower. This means that Norway economically benefits from the fossil fuel industry and may also gain financially when CO_2 is returned for storage.

Social acceptance is discussed in the social sciences literature on CCS. Stakeholders often have concerns about the feasibility of large-scale technologies such as CCS (Bellamy et al., 2022). Yet, public or social acceptance is only discussed in two of the articles in this review (Geske et al., 2015a; Mabon and Littlecott, 2016). Hansson et al. (2022) hypothesize that there could be less focus on the question of storage when it is offshore, such as in the North Sea context, rather than onshore where there have historically been more public concerns, but the climate aspect of storage is still relevant. Furthermore, this lack of public concern or engagement in the question of offshore storage could lead to less public pressure on actors to handle storage in a way that is safe and prioritizes the climate change benefit of long-term CO_2 storage (Hansson et al., 2022). Although there may be less public concern about offshore storage, there could be concerns that are specific to the North Sea regional context. For example, Merk et al. (2022) studies the social acceptability of CCS in Europe and finds that there could be acceptance challenges regarding the storage of imported CO_2 in the Norwegian North Sea. This shows that perspectives from stakeholders are relevant to understand the feasibility of storing CO_2 in a European context, especially in the case of international collaborations and transport across country borders.

6. Conclusions

Growing interest in CO_2 storage in Europe, including in the Nordics warrants suitable and economically feasible storage facilities that could contribute to decreasing GHG in the atmosphere. This study focuses on how CCS is represented in the scientific literature on CO_2-EOR in the North Sea and Norway. This is a specific case to study possible overlaps between these two technologies since CO_2-EOR does not take place on a large scale anywhere in Europe, and there are few storage sites for CCS in Europe, with Norway taking the lead with two storage sites in operation and new sites developing through the Northern Lights project. There are five emerging themes in the literature which are: climate change; economics; monitoring, safety, and leakage; geology; and transportation. Two polarized framings on the relationship between CO_2-EOR and CCS are illustrated in the results. The first framing focuses on synergies between CO_2-EOR and CCS whereby CO_2-EOR is framed as a gateway to storing CO_2. This is due to economics and financial arguments such as opportunities to share and scale up infrastructure to transport and store CO_2, knowledge sharing about geology and monitoring practices, and possibilities to store CO_2 in geological formations. The second framing, however not as prevalent in the review, is that there are incompatibilities between CO_2-EOR and CCS including goal conflicts between the two technologies. This includes that EOR and CCS have different underlying main purposes, EOR perpetuates the fossil fuel infrastructure which counteracts societal and industrial transitions and possibly also climate change mitigation. Although the two framings identified in this study serve as a starting point to discuss the possible role of CO_2-EOR and CCS in the context of sustainability transitions and carbon lock-in, this literature review also shows that there are several research gaps that could be addressed to create a deeper understanding of the socio-political context and how it relates to the relationship between these two technologies.

This literature review highlights several tensions and areas where critical social sciences research could contribute to understanding, or at least initiate more critical discussions, of potential future pathways for CO_2 storage as a climate change mitigation measure. First, this literature review shows that knowledge on CO_2-EOR in the North Sea is driven by fossil fuel industry research, with a techno-economic focus. Second, most of this body of research on CO_2-EOR is not critical toward the phenomenon of EOR that perpetuates the production and consumption of fossil fuels or draw narrow system boundaries when analyzing the phenomenon. Third, most EOR research in the North Sea focuses on reducing emissions while considering fossil fuels as part of a sustainability transition, without taking the starting point that fossil fuels are the underlying problem causing climate change. Fourth, the body of research on EOR in the North Sea is separate from the literature on CDR which includes research on CCS and BECCS from critical social science perspectives, and Hansson et al. (2022) also highlight that the BECCS literature with few exceptions omits analysis of geological storage. This means that there are more opportunities for critical social science research on geological storage, including analytical integration of different research disciplines. Furthermore, an understanding of the impact of CCS and BECCS on climate and energy presupposes that research on EOR and CDR communicate with each other, such as by publishing in the same journals and by initiating critical social sciences research at the crossroads between CO_2-EOR and CCS.

This article shows that the current system where EOR is cheaper for storing and handling CO_2 than having dedicated storage is highly complex and that changing tax rates is not enough to change how the system works to benefit climate change mitigation. Even though EOR is driven by an economic incentive for the fossil fuel industry in a society that perpetuates the fossil fuel regime, the framings in this review highlight different viewpoints on how compatible EOR is in a future sustainability transition in Norway, which also has implications for other countries that are interested in storage options in the North Sea region, including the UK, the Netherlands, Sweden, Denmark, Ireland, France, and Belgium (Global CCS Institute, 2022). Social science research on geological storage could also benefit CCS, BECCS, DACCS, and CCUS initiatives in Europe, including opportunities for scaling up storage. For example, there is proposed geological storage in the North Sea off the coast of the UK totaling up to 26 Mtpa through Humber Zero and Zero Carbon Humber (Global CCS Institute, 2022). In Denmark, Project Greensand plans to store CO_2 in the North Sea through a state-supported initiative with the capacity of 8 Mtpa by 2030 (Project Greensand, 2023). In the Netherlands, there are a few ongoing CCS projects including Aramis, @Antwerp, and Porthos with at least one of these projects planning to ship CO_2 for storage in Norway via Northern Lights while domestic storage opportunities in the Dutch North Sea are explored (CCUS Hub, 2023).

The absence of social science literature on geological storage in the North Sea point to opportunities for new research perspectives on CO_2-EOR and CCS, e.g., to challenge or empirically validate key concepts like carbon lock-in by testing or operationalizing them in concrete geographical contexts. This could contribute to navigating future pathways for the geological storage in more sustainable directions. Demand for CO_2 storage capacity demands more social science research to ensure that CO_2 storage from CCS and BECCS initiatives is deployed in a way that is sustainable from long-term societal and environmental perspectives and contributes to net CDR to meet climate change mitigation goals. In addition, techno-economic studies can be furthered by including qualitative social science perspectives to understand embedded socio-political aspects, expand system boundaries, and contribute to social acceptance. Therefore, there are opportunities for both techno-economic studies and critical social sciences to expand their research areas within CDR to impact future sustainability transitions.

When considering the urgency to mitigate climate change in society by reducing GHG emissions, CCS could reduce the fossil fuel industry's impact on the atmosphere, although there are different perspectives on how this benefit is perceived and under what conditions CCS supports a sustainable transition. CCS is often considered as an add-on technology for the capture part of the value chain when applied to an existing industrial facility or power plant, while the transport, injection, and storage aspects of the value chain are new, and there could be synergies for industrial integration with CO_2-EOR, both in the North Sea region and in other geographies. Most of the literature in this review show that CO_2-EOR and CCS are handled as two operational processes that can be integrated side-by-side with some regulatory and tax adjustments, without highlighting scientific literature that challenges these arguments. Therefore, an integrated systems perspective could contribute by critically challenging the feasibility of these systems, such as addressing a shortcoming that synergies between CO_2-EOR and CCS are viewed from an idealized market perspective without prioritizing climate change mitigation. Future pathways that implement CO_2 storage will contribute to CDR methods, and the type of CO_2 storage method applied may lead to different levels of CO_2 reduction and impacts on climate change mitigation.

Author contributions

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

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Conflict of interest

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

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Communicating carbon removal

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Removing carbon dioxide from the atmosphere is "unavoidable" if net zero emissions are to be achieved, and is fast rising up the climate policy agenda. Research, development, demonstration, and deployment of various methods has begun, but technical advances alone will not guarantee a role for them in tackling climate change. For those engrossed in carbon removal debates, it is easy to forget that most people have never heard of these strategies. Public perception of carbon removal is therefore particularly sensitive to framings—the ways in which scientists, entrepreneurs, activists, politicians, the media, and others choose to organize and communicate it. In this perspective, we highlight four aspects of carbon removal for which their framing will play a decisive role in whether—and how—different methods are taken forward. First, the use of analogies can be helpful in guiding mental models, but can also inadvertently imply processes or outcomes that do not apply in the new example. Second, a taxonomic split between "nature-based" and "technological" methods threatens to divert attention from the actual qualities of different methods and constrain our policy options. Third, people are likely to overestimate the emissions-reduction potential of carbon removal, but this misperception can be corrected. Fourth, communications overlook the social arrangements for carbon removal and the alternative trajectories that implementation may take. We end by offering key recommendations for how we can communicate carbon removal more responsibly.

KEYWORDS

carbon removal, communication, responsible innovation, public perception, framing

Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change shows that the remaining carbon budget—the amount of carbon dioxide that can still be emitted while keeping global warming below 1.5 degrees—is almost gone (IPCC, 2021). Removing carbon dioxide that is already in the atmosphere is "unavoidable" if net zero emissions are to be achieved, through accelerating near-term mitigation, counterbalancing residual emissions from hard-to-abate sectors in the mid-term, and achieving net negative emissions in the long term (IPCC, 2022). There are different methods of carbon removal, including those that capture carbon through photosynthesis, such as forestation, biochar, and bioenergy with carbon capture and storage (BECCS); and those that capture carbon through chemical processes, such as direct air carbon capture and storage (DACCS), enhanced weathering, and ocean alkalinity enhancement (Minx et al., 2018). Depending on the capture method, the carbon can then be stored in above ground biomass, soils, geological reservoirs, minerals, or marine sediment and calcifiers.

With research, development, demonstration, and deployment (RDD&D) of various methods having begun in earnest, carbon removal is fast rising up the climate policy agenda. Yet, technical advances alone will not guarantee a role for any given carbon removal method in tackling climate change. They must also have the support of the public. For those engrossed in carbon removal debates, it is easy to forget that most people have never heard of these strategies (Smith et al., 2023). For example, across several countries, fewer than 20% of survey respondents report any prior awareness of carbon removal (Carlisle et al., 2020). This means that unlike concepts (like climate change) for which people already have clear mental models and opinions, carbon removal is still a blank slate.

Public perception of carbon removal is therefore particularly sensitive to framings—the ways in which scientists, entrepreneurs, activists, politicians, the media, and others choose to organize and communicate information about it. Responsible communication of carbon removal requires an awareness of and attention to such framings and the contending interests and uncertainties that underpin them (Bellamy, 2018). It requires that we "unframe" carbon removal by placing it within broader discursive fields to facilitate a robust societal debate about where public support does—and does not—lie (Bellamy and Lezaun, 2017). In this perspective, we highlight four aspects of carbon removal for which their framing will play a decisive role in whether—and how—different methods are ultimately taken forward.

Framing by analogy

One way of helping people make sense of carbon removal is by using analogies or metaphors to create guiding mental models to understand new concepts (Castree, 2020). In lieu of other information, analogies and metaphors can shape public perceptions of how carbon removal methods work, as well as their benefits, risks, and trade-offs. While analogies are vital education tools, they can also inadvertently imply processes or outcomes that do not apply in the new example (Raimi et al., 2017).

For example, describing DACCS as like "giant fans" may convey some aspects of the process and energy required for this technology, but does not convey the need to transport captured carbon. On the other hand, describing DACCS as working like "artificial trees" may convey the idea of storing carbon through this process, but doesn't instill understanding of the energy required. Thus, communicators must carefully employ analogies and metaphors that accurately convey key processes of carbon removal, avoid those that could create misunderstandings, and clearly delineate how carbon removal both is and is not like these example phenomena.

The nature framing

There is a taxonomic split in some carbon removal communications between "natural" or "nature-based" and "technological" methods. This has significant implications for public acceptance, as people are well known to prefer natural-seeming actions over unnatural ones (Sjöberg, 2000). Contrary to widely held assumptions, however, what constitutes a "natural" method of carbon removal is not self-evident, but is selected by people acting in social groups (Bellamy and Osaka, 2020). Nature is universal, encapsulating the physical world in its entirety, including untouched nature, nature modified by humans, and humans themselves. Thus, any efforts to establish some subset of nature as the "one true nature" are unavoidably exclusionary. Such exclusions are apparent in some carbon removal communications, where things manufactured from nature (e.g., DACCS) are typically excluded from the "natural" category, as are enhancements of relatively untouched natures, such as the oceans (e.g., ocean alkalinity enhancement), and enhancements of nature modified by humans, such as agriculture (e.g., enhanced weathering). In one particularly inconsistent example, BECCS and biochar both involve enhancing an existing natural process (biomass growth) and things manufactured from nature (power stations and pyrolysis plants, respectively), but only the latter is deemed "natural."

Armed with this knowledge, carbon removal communicators have two choices. One choice is to (cynically) capitalize on the power of the nature framing and give a significant boost to perceptions of their preferred methods. The danger here is twofold. First, attention may be diverted from the actual qualities of a method and substituted with a general sense of "goodness," subjecting the methods to lower standards of approval (Osaka et al., 2021). Second, the appeal of nature, combined with a restricted set of methods, constrains what are considered desirable, fundable, and implementable policy options. The other choice would be to acknowledge the politics and dangers of the nature framing and either stress the "nature" in all carbon removal methods (Bellamy and Osaka, 2020); stress the "technology" in so-called "natural" carbon removal methods (Markusson, 2022); or better still, avoid the label altogether and instead refer to specific methods and/or use scientific terminology (Osaka et al., 2021). Either way, all carbon removal methods would be evaluated on an equal footing, rather than some benefiting from the label and others not.

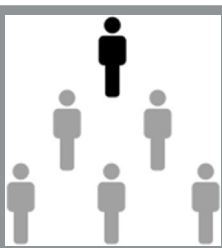
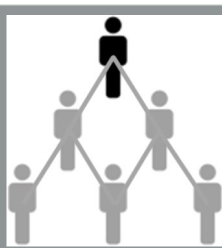
The moral hazard framing

Climate advocates often fear that discussion of carbon removal will deter from the need for emissions reductions in general (Lenzi et al., 2018), or specifically for fossil fuel emissions through offsetting[1] or residual emissions that are deemed too costly or hard-to-abate.[2] This could happen either at the level of individual people's judgements or at the institutional or societal level (Jebari et al., 2021). Some empirical evidence suggest that this "moral hazard" effect can occur at the individual level for some forms of carbon removal (Hart et al., 2022); however, these effects are small and do not emerge for all forms of carbon removal (i.e., reforestation). Experiments find that information about carbon

1 Carbon removal could be used for offsetting but is not the same as offsetting (see Allen et al., 2020).

2 Typically cited hard-to-abate sectors include aviation, shipping, concrete production and agriculture, but there is significant ambiguity around the meaning of residual emissions and what should and should not count as such (see Lund et al., 2023).

TABLE 1 Four ideal-typical implementation contexts for carbon removal (after Rayner, 1991; Bellamy, 2018; Halik et al., 2018).

	 Entrepreneurial carbon removal	 Opportunistic carbon removal	 Governmental carbon removal	 Community carbon removal
Value of carbon removal	A means to generate equal opportunities for wealth and prosperity	A means to enhance personal financial and social power	A means to maintain stability for the governing system	A means to secure equal social outcomes for group members
Regime of carbon removal	A bottom-up regime of private organizations or individuals employing a laissez-faire style	A personalized, top-down regime employing an intimidating style	A centralized, top-down regime employing a regulatory style	A bottom-up, community-based regime employing a preventative style
Policies of carbon removal	Fiscal incentives and RDD&D support to facilitate individual decisions	Personal, idiosyncratic rules derived from strongman rule	Command and control and incentive regulation from government	Command and control regulation and information derived from consensus
Evaluation of carbon removal	Focussed on economic growth and individual liberty, with compliance through the market system	Focussed on maintenance or expansion of power, with compliance forced on rivals	Focussed on functional standards, with compliance imposed by 'best available science'	Focussed on equality of outcomes and ecological condition, with self-compliance by community members

removal and solar geoengineering can variously reduce emissions-reductions support, increase it, or have no effect either way (Raimi, 2021).

Furthermore, there is reason to think that this too is the result of framing. People are notoriously bad at estimating the effects of emissions-reducing activities (Larrick et al., 2015), and thus likely to overestimate the emissions-reduction potential of carbon removal. But these misperceptions can be corrected. For solar geoengineering, moral hazard effects disappear when people are correctly told that these technologies are not a silver bullet (Raimi et al., 2019). Parallel research finds that interventions promoting individual-level climate behaviors can crowd out policy support when people overestimate their emission-reducing potential, but this effect disappears when these misperceptions are corrected (Hagmann et al., 2019).

Thus, policymakers need not avoid carbon removal because of a fear that it will inevitably crowd out public support for emission reductions. Instead, communicators must clearly explain to the public that while carbon removal may help reach climate goals, it can only do so on the margins of substantial emissions reductions. When possible, putting the extent of the carbon removal potential in comparison to the potential for emissions reductions from actions like shifting to renewable energy may help keep people from falling prey to moral hazard effects.

Framing implementation

Communications on carbon removal—and indeed research on public perceptions of carbon removal—overwhelmingly focus on the technical characteristics (and societal responses to those characteristics) of carbon removal: the trees of forestation, the "giant fans" of DACCS, or the fine-grained rock of enhanced weathering, and so on. But carbon removal methods are not simply technical objects, they are combinations of technical objects and social arrangements that work together as a single system. Carbon removal methods simply will not work without an implementation context: purposes, people, institutions, policies, politics, procedures, and so on. In other words, the implementation of carbon removal is only being half-framed. And early empirical work shows that the missing half of carbon removal communications can make all the difference in terms of public support. The policy instruments chosen to incentivize BECCS, for example, can significantly change the way people perceive the technology itself (Bellamy et al., 2019).

Crucially, the implementation contexts for carbon removal are not yet written. "Upstream" of significant RDD&D we can—and should—explicate the alternative trajectories that the implementation of carbon removal methods may take. To illustrate, Table 1 describes four very different possible implementation contexts derived from cultural theory. For example, the value of carbon removal does not lie only in its capacity to help stabilize climate and society; it is also an opportunity to generate prosperity, personal power, or more equal outcomes. Carbon removal need not be implemented in a centralized, regulatory regime; it could instead be private and laissez-faire, idiosyncratic and intimidating, or community-based and preventative. The policies of carbon removal need not be driven by government; they could facilitate individual decisions, or be derived through strongman rule, or group consensus. The evaluation of carbon removal does not only concern functional standards; it also concerns liberty and economic growth, the maintenance or expansion of power, and social equality and ecological condition.

The task for carbon removal communicators then is to not presume a particular implementation context, but to articulate such alternative pathways. Who does the communicating is also important: messengers should be those with identities or styles of argumentation that do not imbue communications with a meaning of conflict between identifiable social groups (Kahan, 2012). In this way, people of different social groups are more likely to view information in an open-minded way.

Conclusion and recommendations

The public's lack of knowledge makes them beholden to the agenda of their communicators, whether that is to fund carbon removal RDD&D, to fight against its inclusion in portfolios of climate action, or to use carbon removal to justify lackluster emissions-reductions. With this great power of persuasion comes great responsibility; communicators must consider how their attempts to inform may be biased by their own opinion, as well as how other communicators may be building the case for alternative frames of carbon removal.

Public support for carbon removal will hinge on responsible explanations by communicators who are aware of and attend to different framings. In particular, there must be reflection on the analogies and examples chosen to make sense of carbon removal methods which remain unfamiliar to a great many people. There must be reflection on whether to invoke nature to describe particular methods. There must be reflection on how to situate carbon removal methods in relation to emissions reductions. And there must be reflection on the different possible implementation contexts for carbon removal. To help engender more responsible communications around carbon removal, we offer four recommendations to scientists, entrepreneurs, activists, politicians, the media, and others:

1. Inform the public about carbon removal using clear language and analogies but make clear how it differs from these existing processes.
2. Avoid framing carbon removal methods as "nature-based" or "natural" and instead refer to specific methods and/or use scientific terminology.
3. Stress that carbon removal is not a substitute for necessary and urgent emissions reductions: reductions first, removals second.
4. Communicate the social arrangements of carbon removal as well as the technical objects; articulating the alternative trajectories that carbon removal implementation could take.

Data availability statement

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

Author contributions

RB and KR contributed equally to the conception and writing of the article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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

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Disentangling the "net" from the "offset": learning for net-zero climate policy from an analysis of "no-net-loss" in biodiversity

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Net-zero has proved a rapid and powerful convening concept for climate policy. Rather than treating it as a novel development from the perspective of climate policy, we examine net-zero in the context of the longer history and experience of the "no-net-loss" framing from biodiversity policy. Drawing on material from scholarly, policy and activist literature and cultural political economy theory, we interpret the turn to "net" policies and practices as part of the political economy of neoliberalism, in which the quantification and commodification of the environment, and in particular—trading through an offset market, enable continued ideological dominance of economic freedoms. This analysis highlights the ways in which the adoption of a "net" framing reconstructs the goals, processes and mechanisms involved. It is the neoliberal commitment to markets that drives the adoption of net framings for the very purpose of validating offsetting markets. Understanding the making of "net" measures in this way highlights the potential to disentangle the "net" from the "offset", and we discuss the various obfuscations and perversities this entanglement affords. We argue that the delivery of net outcomes might be separated from the mechanism of offsetting, and the marketization of compensation it is typically presumed to involve, but may yet remain entangled in neoliberal political ideology. In conclusion we suggest some conditions for more effective, fair and sustainable delivery of "net-zero" climate policy.

KEYWORDS

net-zero, climate policies, biodiversity policies, offsetting, neoliberalism

1. Introduction

In recent years, climate policy has seemingly coalesced around the goal of net-zero, the achievement of a global carbon-neutral situation in which any residual emissions of carbon are counterbalanced by additional anthropogenic removals, thus stabilizing the rise in global temperatures. In politics and scholarship, the emergence of net-zero as a central frame for climate policy has typically been treated as a *sui generis* event, a result of the convergence of increasing climate impacts, depleting carbon budget, and political demands for a "bottom-up" regime in which nationally determined contributions (NDCs) replaced the mandatory emissions cuts anticipated under the Kyoto Protocol. As a policy framing, net-zero has achieved a remarkable degree of convening power within international climate negotiations.[1] At last count 148 countries have adopted it as a goal, albeit in diverse formulations.[2]

1 See for example UK Government assessment of the outcomes of COP26. Available online at: https://ukcop26.org/wp-content/uploads/2021/11/COP26-Presidency-Outcomes-The-Climate-Pact.pdf.

2 From the "Net-Zero Tracker" Available online at: https://zerotracker.net/ (accessed June 12, 2023).

A mythic narrative of the origins of net-zero has emerged, attributing its emergence to backroom political pressure exerted by leading campaigners working with the UNFCCC's Christina Figures in 2013–15 to convince actors such as German Chancellor Merkel and World Bank President Jim Kim to support the goal of carbon neutrality at the Paris summit (Darby, 2019).[3] The net-zero framing drew much increased attention to techniques that would remove carbon dioxide from the atmosphere as a means to counter-balance residual, "hard-to-abate" emissions. Climate scientists have since highlighted the substantial requirement for development and deployment of such techniques in almost all pathways that meet the 1.5°C temperature target also adopted at Paris (Kriegler et al., 2018; Luderer et al., 2018).[4] Many entrepreneurs have entered this space typically seeking to raise finance for proposed carbon removal efforts against the promise of expanding carbon markets. While the bare facts of such an account are not in question, in explaining its emergence, more attention should be paid to the political economy of net-zero and its components. In particular, as we demonstrate here, net zero and its use of offsetting along with the wide promotion of policies and practices defined in net terms are a product of the neoliberal policy context. Scholars have explored the historical emergence of carbon removal approaches (Carton et al., 2020; Schenuit et al., 2021). But in the context of climate policy, there has been little attention given to the longer history of "net" framings and mechanisms in policy elsewhere. Tracing the origins of older net mechanisms, their operations, drivers and outcomes in different spheres can shed light on present questions around net-zero in climate policy. In this paper, by examining the history of a parallel neoliberal environmental policy instrument for the natural environment; "no-net-loss" (NNL) in biodiversity and its entanglement with biodiversity offsetting (BDO), we suggest that there are critical lessons that must be learned in climate policy if net-zero is to deliver on the expectations of the Paris Agreement.

1.1. The landscape of "net" policy

Although less widespread than net-zero today, with policies adopted in around 100 countries (and mandatory in 34) (zu Ermgassen et al., 2019), BDO and NNL have a significantly longer history. Biodiversity offsetting and no-net-loss policies are the mechanisms by which nature conservation governance seeks to compensate for development related impacts on wildlife habitats by quantifying and then delivering "equivalent" and sometimes additional biodiversity "values" or "units" elsewhere or in the future. While the terminology of "biodiversity offsetting" did not emerge until the early 2000s, offset mechanisms for habitats or species date to the 1970s, and "no-net-loss" as a goal to the late 1980s, preceding the adoption even of the first emissions reduction goals in climate negotiations (although contemporaneous with experimentation with "bubble policy" for some air pollutants under the US Clean Air Act). Subsequently NNL and BDO ideas were popularized by market-oriented think-tanks, notably the Washington DC-based Forest Trends and their subsidiary the Business and Biodiversity Offset Network (BBOP) as well as international institutions including multilateral development banks and the International Finance Corporation, which promoted them in the development projects they underwrote. Such proponents of offsetting promoted it alongside a "mitigation hierarchy" which suggests that projects should first avoid impacts, second minimize them in practice, third restore damage if possible, and only finally "offset" for any remaining impacts (Business and Biodiversity Offset Programme, (n.d.), 2009, 2012; International Finance Corporation, 2012).[5] For a brief overview of the policy landscape and extent of avoidance offsetting for both biodiversity and climate, see Table 1.

No-net-loss and biodiversity offsetting were controversial and contested from the start, and remain so (Sullivan and Hannis, 2015), with at best mixed evidence of effectiveness, and a range of problems arising in implementation (zu Ermgassen et al., 2019). As we will see in Section 2, problems and controversies arise at technical, political and philosophical levels. Many of these revolve around the concepts and practices of habitat creation or restoration. In a break with previous practice focused on preventing harm by protecting habitat, the NNL framing requires, and emphasizes the possibility of habitat *creation* or biodiversity *restoration*. On a technical level, besides a host of issues around measurement, maintenance, monitoring and more, this raises questions about the scientific validity of such promises (Maron et al., 2012). At the political level it opens debate about the appropriate policy mechanisms and in particular the role of offsetting (Benabou, 2014; Carver, 2021). And at the philosophical level it raises concerns about the ethics of putting a price on nature (McAfee, 1999) and the risk that the promise of restoration functions as a justification for further destruction (Katz, 2000).

The continued spread and adoption of BDO, NNL and more recently "net-gain" policies reflects a picture that looks familiar in climate circles. At a global level the loss of biodiversity continues, with well-grounded fears that critical thresholds of damage may already be passed (Rockström et al., 2009; IPBES, 2019). The drivers of biodiversity loss (in land-use change, agriculture, fisheries etc.) are seen as difficult to reverse, closely coupled to economic growth, and otherwise supportive of sustainable development in the global South (IPBES, 2019; Hahn et al., 2022). Finance for biodiversity protection or restoration is scarce (Waldron et al., 2013), and both states and voluntary organizations are grateful for the prospects of funding from offset schemes as sources of new and

3 The Paris Agreement wording does not include the explicit term net-zero, but the aim of achieving: "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty." (PA, 4.1)

4 Whilst holding temperature rises to no more than 1.5C requires (at least) net-zero emissions globally, achieving net-zero does not itself imply any particular temperature outcome, but would prevent any further rise above the level determined by extant atmospheric concentrations of greenhouse gases.

5 The high-profile adoption of the mitigation hierarchy by the IFC should not be understood purely as a progressive initiative, but also as an effort to defuse intensifying campaigns by both environment and development NGOs for stricter and more transparent standards for project finance in commercial and public banking (Wright, 2007).

supposedly additional investment into biodiversity programmes, even if the outcomes are patchy (Githiru et al., 2015). Promises of technological advances to enable future habitat restoration (in biotechnology, gene science and AI, for example) circulate in scientific and political settings (see e.g., Corlett, 2017).

These dynamics closely parallel the contemporary circumstances of climate politics: the carbon budget for 1.5°C is nearly, if not already exhausted (Peters, 2018; IPCC, 2021), yet emissions remain strongly linked to economic development, growth (and in some regions, poverty alleviation). Funding for mitigation, adaptation, and carbon removal remains insufficient despite shifts in public and private finance. Promises abound of carbon removal through novel technologies and techniques, including a range of "nature-based solutions" (Temple, 2021). Voluntary and commercial organizations supporting mitigation and removal techniques are grateful for offset funding (even though it is inadequate to deliver high quality removals). Reflecting the shift from no-net-loss to net-gain in biodiversity, climate advocates increasingly suggest future "net-negative" approaches that enable some form of overall "climate restoration" or repair are likely to be needed, beyond "net-zero" and the stabilization of temperatures. In both cases the shift moves from simply maintaining the contemporary baseline to account for prior historical environmental harms, in effect accepting that the current baseline is normatively too low.

1.2. Distinguishing policies and mechanisms

In this paper, we reflect particularly on the contiguity between NNL as a policy frame, and BDO as an implementation mechanism, noting they have generally functioned as interchangeable in practice (Carver, 2021) but need not necessarily be the same thing. They are tightly intertwined in the literature, as are net-zero, and carbon offsetting. But here we conclude that not only are extant "net" policies deeply imbricated with neoliberalism, but that *the net* (as an aggregate outcome), and *the offset* (as a mechanism) need not be inevitably linked. We argue that offsetting, as the direct one-to-one matching of harms and benefits within or outside of trading markets, is not a *necessary* tool to deliver a "net" outcome (a desired aggregate state), and that the two should not be conflated. We recognize that in common parlance, the balancing of harms and benefits in net policies could be termed an "offset". Others have already highlighted the distinction between such high-level balancing, and marketized offsetting (e.g., Asayama et al., 2021). Here we reserve the term "offsetting" for a process of one-to-one matching of units of harm and benefit in sequence, whether within a market or not (see Table 1). Understood in these terms, a net outcome can be delivered without an offsetting mechanism, and moreover an offsetting mechanism can exist without marketization and trading. For instance, a mandate for compensatory habitat creation can be established without creating tradable habitat destruction credits: this would be offsetting without marketization. And the balancing of the "net" might be achieved through state-level planning for aggregate environmental benefits and restoration, and not delegated to the corporate actors involved in polluting or habitat destruction: this would be "netting" without offsetting.[6] In contrast bringing netting and offsetting together requires a series of "makings" to construct targets, metrics, and commodities in particular ways, involving actors conceived in specific forms. The choices involved here are not a necessary consequence of a "net" policy goal, but of the political economy within which it is established and pursued.

That the obsession with offsetting, despite its patent shortcomings, is a product of the neoliberal policy context, in which the "potency and mobility of conceptual technologies and the [imbricated] logic of balance-sheet accounting" (Carver, 2021, p. 1) gain additional traction, is not a new insight. For example Dunlap and Sullivan (2019) describe both carbon and biodiversity offsetting as neoliberal policies, an aspect of "accumulation by alienation". Even if net outcomes could be delivered without offsetting, here we focus on the ways in which the popularity of "netting"—the promotion of policies and practices defined in "net" terms—also embodies the neoliberal turn. Contemporary net policies commodify and marketize environmental entities to manage the side-effects of contemporary capitalism. In the case of climate, net policies construct globalized corporate operations (offsetting practices) on a foundation of nationalistic sovereignty in the form of nationally determined contributions—the key innovation of the Paris climate accord of 2015. Whilst the market mechanism of offsetting is not a necessary consequence of a net framing, to the contrary there are good reasons to understand the choice of a "net" goal as—at least in part—an outcome of the extant market-based political economy, and thus to see the intertwining of "the net", the market and offsetting as a predictable, if problematic, configuration under neoliberal capitalism.

The paper continues with a brief review of NNL literature to highlight the concerns and issues arising in biodiversity "net/offsetting" policy (Section 2). It then examines and unpacks the steps in which the net and offsets are co-constructed (Section 3). In Section 4 it explores the parallels with climate policy and discusses implications for carbon removal practices, especially "nature-based solutions" (as the climate analog of habitat recreation). Finally in Section 5 conclusions are drawn and recommendations offered for future policy.[7]

2. The experience of no net loss

In contrast with net-zero as climate policy, no net loss (NNL) has a longer and richer experience. Wetland offsetting first emerged under the 1977 US Clean Water Act, with the approach developing iteratively in the late 1970s with the US

6 James Murray, of Business Green, suggests something similar—the creation of a publicly managed funding pool for carbon removals, paid into by corporations Available online at: https://twitter.com/james_bg/status/1616718977673138176?s=51&t=Fyjh_7NMnf45VrA4cttHcw.

7 Materials and methods: The paper analyses material derived from an online literature search for "no-net-loss of biodiversity" and cognate terms. It examines this literature to identify the key steps involved in the development of this policy approach, and to summarize philosophical, political and practical critiques found in the literature. The paper then utilizes the perspective of cultural political economy to unpack the processes involved in policy formation and the co-production of goals, measurability, equivalences, incentives, actors and expectations.

Environmental Protection Agency's experimental "bubble policy" local emissions trading schemes for particulates, sulfur dioxide and hydrocarbons under the Clean Air Act (Lane, 2012; Halvorson, 2019; Carver, 2021). The latter largely fell into disuse in the 1980s (Halvorson, 2019), but forms of habitat and wetland offsetting expanded, with no-net-loss entering the lexicon in the late 1980s when it was adopted in US wetlands policy in the GW Bush presidency. Subsequently, and particularly in the first decade of this century, NNL and BDO spread widely in international settings, in both the global North and South. Governments had (in the context of the UN Convention on Biological Diversity), committed to achieve, by 2010, "a significant reduction of the current rate of biodiversity loss at the global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on Earth". Netting and offsetting were heavily promoted to, and by, financial institutions in this period (Pricewaterhouse Coopers, 2010). This framing translated the policy goal of reducing biodiversity loss into both an intelligible risk management mechanism and an emerging market for financiers. As Benabou (2014, p. 110) notes, "The growing interest of corporate actors for biodiversity offsetting as a risk management strategy [was] largely fueled by its uptake by major financial institutions." Here we summarize literature that assesses and evaluates NNL and BDO policy, before interpreting the experience in the light of political economy (Section 3) and exploring its applicability to net-zero (Section 4). Before embarking on that process, we note that to illustrate, compare and contrast the construction of NNL and net-zero requires some consistent terminology. In Box 1 we translate the jargon used in climate and biodiversity policies into abstract terms that can be applied in either case, and more generally in cases of "netting" and "offsetting".

The NNL/BDO approach began with an aim of broadly halting biodiversity loss. It now typically imposes duties on project developers whose activities may cause harm to follow a "mitigation hierarchy" so as to minimize damage, and to compensate for any residual harm by preventing damage, or supporting equivalent habitat restoration elsewhere. In addition to such mandatory approaches, various actors and states have experimented with voluntary schemes in which those causing harms can pay other actors to protect or restore biodiversity elsewhere. Such activities can also generate credits which can be traded or banked for future use. The assumed equivalence of "avoided" loss (preventing harm) and new habitat creation is noteworthy. With limited technical possibilities to create new habitat, the prevention of loss (regardless of location) is indeed important. But the net result of such compensation is only to "stabilize the rate of loss", not to stabilize the total biodiversity resource at an ecosystem or territorial scale. As a result the counterfactual or baseline scenario has been one of the most debated issues in the biodiversity management literature (Bull and Brownlie, 2017; Maron et al., 2018; zu Ermgassen et al., 2019). In recognition that merely stabilizing the rate of loss against an already depleted resource level was inadequate (on top of the uncertainties around the policy actually stemming loss at all), some new policies aim to deliver "net gain" through additional habitat creation or restoration activities.

However, whether assessed against a goal of stemming the loss of biodiversity, or merely stabilizing the rate of loss to within a particular baseline or counterfactual, most evaluations of NNL reveal underperformance. Shortfalls against objectives have been recorded or projected in evaluations in multiple countries, including Indonesia, Brazil & Mozambique (Sonter et al., 2020), Australia (May et al., 2017; Sonter et al., 2020), France (Quétier et al., 2014), and Canada (Clare and Krogman, 2013). A recent global assessment (zu Ermgassen et al., 2019, p. 1) found that only about "one-third of NNL policies and individual biodiversity offsets reported achieving NNL." The best success rates were found for wetlands, whereas none of the two-thirds of all BDOs applied to forested habitats or species demonstrated successful NNL outcomes, and there was also zero success found where "avoided loss" offsets were used. Focusing on regional scale outcomes, Sonter et al. (2020, p. 1) found that "no policy achieves NNL of biodiversity in any case study", primarily due to practical limitations in the availability of suitable land. Such evaluations of NNL point to a range of serious problems. Here we summarize these at three broad levels: the philosophical, the practical and the political.[8]

TABLE 1 The broad landscape of NNL and NZ policies.

No-Net Loss of biodiversity goal	Net-Zero emissions climate goal
101 Countries that have NNL policies with established mechanisms	148 Countries that have policies or goals for *future* achievement of net zero
37 Countries that have mandatory NNL requirements, typically in environmental impacts assessment laws	34 Countries that have formal sectoral or regional compliance emissions trading schemes (27 are in the EU ETS)
\$2.6–7.3 bn Estimated financial cost of biodiversity offsetting in 2016	\$911 bn Estimated value of emissions trading (\$909bn) and voluntary carbon market (VCM) trading (\$2bn) in 2022
10 Countries that impose the mitigation hierarchy firmly, with effective guidance	22 Countries that met the UN "Race to Zero" procedural starting line standards in 2022 (Pledge, plan, act and monitor)
150,000 square kilometers Aggregate coverage of the total 12,983 completed or ongoing offsetting projects documented by GIBOP (in 37 countries). For comparison, global loss of forests alone since 2001 stands at 4.73 million km^2	2 giga-tons-CO_2 pa Estimated current removals (99.9% from land management). For comparison, marketed offsets total around 13 Gt, and annual emissions total almost 37 Gt.

Sources: Global Inventory of Biodiversity Offset Policies (GIBOP) 2019: https://portals.iucn.og/offsetpolicy/; State of Biodiversity Mitigation 2017: http://www.forest-trends.org/wp-content/uploads/2018/01/doc_5707.pdf; Net-Zero Stocktake, 2022: https://zerotracker.net/analysis/net-zero-stocktake-2022; 2023 data: https://zerotracker.net/; Reuters, 2023: https://www.reuters.com/business/sustainable-business/global-carbon-markets-value-hit-record-909-bln-last-year-2023-02-07/; Global Forest Watch, https://www.globalforestwatch.org/dashboards/global/; and State of CDR report, 2023: https://www.stateofcdr.org/.

8 Maron et al. (2018) suggest a four-fold categorisation of contestation over offsetting "ethical, social, technical, or governance challenges". Our three level categorisation divides social questions into philosophical (more than just ethical) and political issues, and splits governance questions into technical or political issues. In part our aim is to deliberately problematize the political dimension, in contrast with concepts of governance that can be technocratic and depoliticizing.

BOX 1 Terminology[a].

Additionality: a measure of whether a benefit has arisen as a direct consequence of a policy intervention and consists only of gains that would not otherwise have occurred (requires a counterfactual assessment).
Banking: the accumulation of a reserve of benefits (typically in the form of credits) that can be deployed to provide offsets for future harms. Breaks a temporal link between harm and benefit.
Baseline: a historic (or projected) state against which the level of the resource might be measured—(e.g., emissions in comparison to 1990 levels or biodiversity at site pre-impact level) c.f. reference scenario *qv*.
Benefit: the thing or activity that compensates, offsets or repairs harm.
Compliance market: a market for credits *qv* established by public authorities with mandatory participation. Typically relevant actors are required to procure permits equivalent to the harms they cause.
Commodification: making units of a thing uniform and consistent, and thus exchangeable for money based on a standard rate of exchange.
Desired state: the optimum absolute level of the resource (maybe termed as return to a particular historic level). Unlikely to be the same as stabilization *qv*.
Fungibility: describing equivalence and commensurability of units to enable exchange (e.g., the use of global warming potential (GWP) to make GHGs commensurable).
Harm: the thing or activity that is to be reduced, offset or compensated for.
Leakage: a harm arising outside of a regulated system, caused by an actor notionally included in that system (e.g., by relocation of a harmful development to an unregulated location).
Like for like: Harms and benefits that fall within comparable classes and are measured using the same metric (see fungibility *qv*).
Mitigation hierarchy: The operating rule by which, first, harms are avoided, then unavoidable impacts minimized, and only then are residual impacts offset.
No net loss: An outcome in which the total amount of some resource does not decline below the level expected under some counterfactual scenario (thus no-net-loss may not mean stabilization *qv*).
Offsetting: a one-to-one matching process, providing a benefit elsewhere to notionally balance a specific harm, typically financed by the entity causing the harm.
Permanence: a measure of how long a benefit is sustained over time.
Permit/credit: the authority to generate a specific amount of harm arising from the actual or notional creation of an equivalent benefit. Can be traded on markets for credits, but may also be auctioned or issued without payment by relevant authorities.
Quantification: establishing a numerical metric or units to make things comparable, and enable measurement of the quantity of harms and benefits.
Reference scenario: (sometimes "counterfactual" or "business as usual" scenario, c.f. "baseline" *qv*) the projected future state in the absence of intervention, also sometimes used for purposes of target-setting (e.g., "reduce harm by a certain level in comparison to business as usual").
Residual harm: a harm that cannot be practically eliminated, and thus to achieve a net balance, must be offset (c.f. mitigation hierarchy).
Resource: the underlying public good (hospitable climate, flourishing ecology) that is protected or sustained by the policy. In practice, typically a commons-based resource.
Restoration: providing a benefit to compensate for a historic/past harm (includes direct repair of past harms arising from a specific activity or project).
Stabilization: where the aggregate level of ongoing harm is fully balanced by aggregate additional benefits.
Voluntary market: a market for credits established by non-statutory actors to trade in credits generated outside of compliance markets.

[a]This glossary of terms derives in part from Maron et al. (2016). In offering this terminology we aim to enable comparison, not to establish "correct" definitions. As the paper reveals, the situated meanings of these terms are ideologically constructed in ways that may obscure the underlying processes they involve.

2.1. Criticisms of NNL

At the philosophical level we include questions of principle and of ethics. Concerns have been raised not only regarding the extent of equivalence and fungibility between different expressions of biodiversity, but also regarding the moral basis and unjust consequences of commodification of biodiversity in the first place. McAfee (1999, p. 133) argues that: "by valuing local nature in relation to international markets, denominating diversity in dollars, euros, or yen," such approaches abstract "nature from its spatial and social contexts" and reinforce "the claims of global elites to the greatest share of the earth's biomass and all it contains." Ives and Bekessy (2015, p. 568) argue that the utilitarian ethics of offsetting overlook multiple values of nature, and conclude that: "offsetting may exacerbate environmental harm because it erodes ethical barriers based on moral objections to the destruction of biodiversity." Spash (2015) similarly argues that offsetting erodes moral protections for nature and acts to help define nature in purely economic terms. This reinforces the risk of utilitarian justifications for continued damage, which as noted by Katz (2000) are enabled by (typically exaggerated) promises regarding the viability of later restoration, providing a "license to trash" (Koh et al., 2017, p. 186).

Practical challenges arise in the basic requirements of quantification and measurement to enable like-for-like compensation or comparison. They appear also in difficulties in ensuring additionality or permanence, avoiding leakage, and in basic physical challenges such as site availability. Even similar habitats may have divergent ecological values in different locations, or as they change over time. Newly created habitats can rarely substitute directly for established ones. In other words there is typically poor equivalence in the units of biodiversity involved in NNL practices (Lindenmayer et al., 2017). As a result, "many of the expectations set by current offset policy for ecological restoration … [are] unsupported by evidence" (Maron et al., 2012, p. 141) with notable technical limitations arising from time lags, uncertainty and problems with measurability of the value being offset. Creating credible metrics to make biodiversity fungible is therefore problematic (zu Ermgassen et al., 2019; Sonter et al., 2020). Over-simplified metrics in offsets miss "significant environmental and social welfare values across space, type and time" (Brownlie et al., 2013, p. 27). As Parson and Kravitz (2013) note for market-based instruments more generally, this spatial non-equivalence can have serious implications for environmental justice. And even if common metrics can be agreed that have sufficient scientific integrity, practical fungibility depends also on consistent monitoring, certification and transparency: all of which have been identified as inadequate (Bull et al., 2018; Kujala et al., 2022).

Concerns over additionality (whether the offset site would have been protected/restored regardless of the program) intersect with those of permanence (whether the offset site remains of equivalent biodiversity value into the long term). Additionality problems seem common amongst avoided loss offsets, where there may have been little risk to the specific site "protected" in the exchange (Thorn et al., 2018; Damiens et al., 2021). They also arise more generally where the long-term maintenance of the offset site is dependent on the diversion of conservation resources already allocated in the public or voluntary sector (Thorn et al., 2018; Damiens et al., 2021). While the use of already allocated public resources promotes permanence it undermines additionality. More generally there are widespread issues of leakage, from damage outside the NNL policy coverage, and practical limits to land availability for compensation. Sonter et al. (2020, p. 1) conclude that NNL "fails to slow regional biodiversity declines because policies regulate only a subset of sectors, and expanding policy scope requires more land than is available for compensation activities."

The political dimensions of NNL are equally diverse and problematic. Effective mechanisms and institutions for planning and implementation are often lacking, weak or captured. Decisions on baselines and counterfactuals have impacts at multiple scales, including serious implications for the distribution of costs and benefits. And short-termism is endemic. May et al. (2017) highlight a lack of long-term and contingency planning, while Quétier et al. (2014) point at a broad lack of institutional mechanisms and science context. Offsets are deployed as a temporary fix by "institutions [that are] structurally blind to long-term concerns" Damiens et al. (2021, p. 60). All these concerns are exacerbated by agency capture (Clare and Krogman, 2013). For example, in Alberta, in part as a product of goal ambiguity, agency capture led to a bias toward compensatory payments, rather than avoidance of damage; with compensation sites inappropriately located (Clare and Krogman, 2013). More generally, voluntary offsetting is widely promoted by private enterprises as a mechanism to frame or even deter future regulatory intervention (Benabou, 2014). The politics of capture mean that evidence of low success rates is widely ignored (Lindenmayer et al., 2017; May et al., 2017; zu Ermgassen et al., 2019), and without major governance shifts NNL cannot be expected to deliver (Damiens et al., 2021).

Amongst the most politicized decisions are those regarding baselines and counterfactuals. In many cases these accept a continued long-term decline of biodiversity as a product of continuing economic development. This fundamentally undermines the goal of NNL, while exacerbating the likelihood of non-additionality at a project level (Maron et al., 2018; Sonter et al., 2020). And at a grand-scale, governments often divert offset payments into meeting biodiversity targets to which they were already committed, rather than treating offsets as necessarily additional (Maron et al., 2015). Moreover, offset systems tend to conceal the extent of transfers between different interests, even as they alter the pattern of such transfers (Parson and Kravitz, 2013). For instance, "Project-based offset programs can transfer huge rents to project developers, depending on how baselines are defined" (Parson and Kravitz, 2013, p. 429). The interpretation, application and enforcement of metrics—which affect overall compensation costs for the developer—are also prone to politicization. What is sometimes called "moral hazard" in climate policy is found also in biodiversity NNL where the economic contexts or the interests of actors involved, including ecological consultants working for developers, can affect the calculations of proposed loss and biodiversity gain in ways that will ameliorate costs for the developer (Carver and Sullivan, 2017).

2.2. Improving NNL?

While the broad picture painted by the literature is negative, many scholars are concerned to suggest possibilities for improvement, and identify conditions under which BDOs can contribute to NNL or even net gain. The central condition appears to be that NNL and BDO should be placed within a national and regional regulatory framework for constraining and avoiding biodiversity loss (Simmonds et al., 2020). In this respect BDOs resemble other tradable permit policies, in which a binding overall cap is critical to effectiveness (Parson and Kravitz, 2013). The specifics of the policy also matter, and arguably the (relatively few) successes identified often occur *despite*, rather than *because of*, the existing framework of policy. BDOs are more often stimulated through a regulatory framework than by financial market trading (Bull and Strange, 2018), and the most commonly cited reason for success was where high offset multipliers were required, with large offset areas designated, relative to the impacted area (zu Ermgassen et al., 2019). According to Gibbons and Lindenmayer (2007) success is more likely where the habitats involved are relatively simple and common and offsets are well managed with high compliance rates. Koh et al. (2017) highlight the importance of clearly separating decision phases so that the initial acceptability of the development is decided without consideration of the possible or appropriate scope of compensation, so as to avoid the "license to trash" effect, understood as a moral hazard or mitigation deterrence risk in net-zero literature (McLaren et al., 2019). Koh et al. (2017) also recommend use of both quantitative and qualitative ecological valuation methods and social safeguards to prevent environmental injustice.

Despite the lack of evidence for NNL and BDOs, there are still many efforts in the literature to justify offsetting. These typically begin from a premise that offsets are necessary because of the lack of other incentives and values for biodiversity protection (e.g., Gibbons et al., 2016; Koh et al., 2019). We suggest that such discursive battles may not be a product of objective assessment, but of political presumptions (about baselines, feasible scenarios, effective incentives etc.) and cultural political economy more broadly. They reflect a world in which continued harm to biodiversity is seen as inevitable, with a baseline of decline in the absence of intervention, and despite the incommensurability of different forms of biodiversity, offsets are seen as a least-worst option, especially if used to promote net-gain, rather than merely NNL. Nonetheless, the literature is crystal clear that NNL/BDOs/ecological compensation cannot fulfill the central role in biodiversity policy, but rather, at best, could complement a strong legal framework, and territorial targets and measures. But the limitations of NNL are more often treated as reason to call for "net gain" outcomes rather than to revisit the choice of policy mechanisms. "Net-gain" (delivering more restoration benefits than harms), however, not only intensifies the existing challenges of NNL, but also involves new complexities especially regarding frames of reference, such as the state to be restored (Bull and Brownlie, 2017). Nonetheless, mainstream politics still persists in pursuing netting and offsetting. In the next section we explore some possible reasons why.

3. The neoliberal "makings" of net policy

Our literature-based review of NNL policy effectiveness in Section 2 not only reveals its very limited success, but highlights obstacles arising in the processes whereby a specific object or resource is made manipulable through policy intervention. In a Foucaldian tradition, Scott (1998) centers the concept of legibility, materialized in monitoring, measurement and standardization processes that allow a state to govern territory and resources. Yet what we see in the construction of "biodiversity" as a resource goes beyond seeing like a state, to "seeing like a market" such that the biodiversity resource, as constructed or made in NNL and BDO policy becomes a tradeable commodity. In this section we unpack the multiple makings of net policy, demonstrating the depth of the co-productive or co-evolutionary processes (McLaren and Markusson, 2020) that develop between policy goals, framings, tools and actors, and highlight relationships with tenets of neoliberal ideology. To do so we draw on cultural political economy (Sum and Jessop, 2013) as an analytic approach which recognizes both the materiality of resources, and simultaneously, the potential for objects of policy to be culturally constructed and reconstructed.

As an ideology neoliberalism centers economic growth as the mechanism to deliver human progress, resisting state intervention in economic and social affairs, and promoting free markets, free trade and capital mobility on utilitarian efficiency grounds. The contemporary era of neoliberalism has been particularly marked by the growing role and power of finance (Kotz, 2010; Fine and Saad-Filho, 2016). So when it comes to "externalities" such as biodiversity loss and climate change, neoliberal policy aims to avoid any brake on growth (and entirely eschews the possibility of changing economic system), rejects regulatory constraints on individuals or corporations, instead developing complex systems of interventions to create new markets in novel commodities (and derivatives thereof), not only commodifying, but marketizing and even financializing the underlying resource (Fletcher, 2010; Pawliczek and Sullivan, 2011). In the case of BDOs this means "constructing [development-related] harm as a result of market failures, which [it is presumed] can be resolved through market solutions" (Sullivan and Hannis, 2015, p. 162).

These market solutions for NNL promise a new "restoration economy" in the form of habitat (re)creation as opposed to preventive constraints on harm to biodiversity. This too is rooted in neoliberal ideology about innovation, markets and growth, and in practice, in new alliances between financial capital, corporate governments, and cash-strapped conservation organizations (Fairhead et al., 2012). For Huff and Brock (2017) such alliances represent "a Faustian bargain" ridden with "precarious and crisis-laden … compromises." While appearing the only way to fund conservation, these alliances around NNL underwrite narratives of "green growth" (Carver, 2021) capital "accumulation by environmental restoration" (Huff and Brock, 2017) and "green capitalism" (Buller, 2022). Yet the model relies on the availability of conservation-ready land for investment, thus normalizing past degradation and justifying continuing unsustainable land use and development. Thus, alongside activities such as bioprospecting and ecotourism, BDOs enable the extraction of profits from nature. Huff and Brock (2017) argue that this sustains—or amplifies—a longer term "exclusionary, racist, and violent trajectory" in neoliberal conservation, or as Buller (2022, p. 87) puts it offsetting is "at its core a neo-colonial effort".

Biodiversity markets have been extended beyond offsetting, with the creation of financial derivatives based on the values attributed to biodiversity. Swiss Re, for example has established a "biodiversity index" to underpin insurance products- which as Buller (Buller, 2022, p. 248) recounts, required "several transformations, novel methodologies and conceptual shifts" to segment the natural world into "units whose value can be appraised and exchanged" in a new arena for profit accumulation. Financialization underpins neoliberal accumulation "articulated through the power of the state to impose, drive, underwrite and manage the internationalization of production and finance in each territory, often under the perverse ideological veil of promoting non-interventionism" (Fine and Saad-Filho, 2016, p. 688). BDO exhibits a similar apparent perversity, where complex interventions are required to enable an ideologically abstracted "non-interventionist, free market" approach to the management of externalities. The paradox is discursively resolved through the state intervening at an abstract level to establish the conditions for neo-liberal market competition, which while clearly reflecting the interests of a class or even sector of financial capital, does not (apparently) pick winners between the competing capitalist enterprises involved.[9]

It might seem ironic that the application of neoliberal ideology—which seeks to minimize and even deny the case for government intervention—by its rejection thereof, demands intervention to construct the very markets it wishes to keep free of interference. The BDO case makes the foundational role of the state in developing and defending markets excruciatingly clear. As Koh et al. (2019, p. 679) emphasize, "the government, contrary to received wisdom, plays a key role not just in enforcing mandatory policies but also in determining the supply and demand of biodiversity units, supervising the transaction or granting legitimacy to the compensation site."

3.1. Six dimensions of the "makings" of net policies

The BDO case also demonstrates the coproduction of particular forms of goals and particular forms of actors as a result of the integration of neoliberal ideology. Here we briefly describe six different dimensions which are remade in NNL that are resonant more broadly with other net policies, such as net-zero. Uncovering these dimensions of the "makings" of net policies is essential if we are to evaluate their effectiveness fully.

- **Making goals:** "net" policies or practices necessarily reshape our understanding of the goal or target involved. Rather than being framed in terms of reducing or eliminating harms, or rates of loss and damage, it is instead constituted as a "stabilization" of harm. In a net goal the overall quantity of damage is irrelevant, as long as it is balanced by an equivalent gain (Armstrong and McLaren, 2022). The move to net goals theoretically separates the "net" harm from the absolute number of potentially damaging activities or transactions: this facilitates not only a compensatory and often market-based response, but also the financial neoliberal desire to maximize the number of trades of the commodity

9 Maybe worth a footnote here on carbon prices, vs renewables (ROCs, FITs, etc) for a salutary lesson on how such abstraction runs counter to environmental needs.

or derivatives involved. From the neoliberal perspective, therefore, an outcome with many harms counterbalanced by many benefits is preferable to one with few harms and few benefits. Net goals defined in terms of stabilization require not just measurement, but quantification, baselines or counterfactuals, and in practice become "accounting" goals rather than "material" goals. Moreover, net goals, even "net-gain" goals, naturalize continuing incidents of harm (as the very mechanism to trigger gain or restoration activities), and more broadly therefore institutionalize the inevitability of development or economic activity and the harms arising from it, even if the net effect is—assuming successful implementation of the policy—a stabilization or overall improvement in the net state.

- **Making measurable:** "net" policies or practices demand that interventions produce measurable and quantifiable outcomes, because otherwise they can't be compared with one another. This is a break with qualitative assessment of biodiversity value. In modernism, quantification is a central feature of business and bureaucratic cultures that "manage only what is measured" (Ridgway, 1956). Under neoliberalism, measurability is an essential precursor to commodification and exchange. But the demand for measurability also creates pressures for simplification or abstraction, measuring only certain dimensions of the resource (such as the land area of habitat involved). This reframes nature as disaggregated and distinct units that can be exchanged across time and space to balance between ecological losses and gains, stripping away any value that cannot be so quantified, and abstracting nature "from location, ignoring broader dimensions of place and deepening a nature–culture divide" (Apostolopoulou and Adams, 2017, p. 23). Moreover, incentives are diverted to interventions that can be precisely measured and verified, as opposed to those with merely qualitative benefits.
- **Making equivalences:** net policies and practices demand not only measurability but equivalences, making possible fungibility between different things (e.g., wetlands and forests, lions, and butterflies) and different locations, quantities and timings. Buller (2022) highlights the adoption of habitat banking processes as a particular driver of constructions of equivalence, insofar as it broke any remaining link with early efforts to match compensatory sites on a "like-for-like" basis in a material or temporal way. Composite measures like "units of biodiversity" have been developed to enable comparison, and trading, bypassing philosophical questions about what a unit of biodiversity means and how it can be consistently measured. The quest for fungibility lies at the heart of economists' approaches to sustainability (Pearce and Turner, 1989) and simultaneously at the heart of neoliberal capitalism which seeks to reduce policy issues to choices in markets denominated in money and efficiency. The practical and philosophical challenges of making equivalences feature strongly in literature on NNL and BDO policy. Quétier and Lavorel (2011) for example, highlight that genuine equivalence requires attention not just to areas and species involved but also the time dimension. While "restoration science is representing entire ecosystems as abstract, mobile, and fungible entities" (Robertson, 2000, p. 463) the process of commodification of nature remains necessarily incomplete as a result of the complexity of these technical challenges, politicizing "crucial steps of abstraction and valuation … [as] negotiations between and within differentiated segments of the state and civil society" (Robertson, 2000, p. 463). Koh et al. (2019) suggest that there is only limited commodification because the value of offsets reflects the costs of restoration or management, not some measure of the intrinsic value of the biodiversity. Yet the stripping away of aspects of value in the process of commodification is one reason why it is problematic in such contexts.
- **Making incentives:** net policies and practices also construct and validate particular forms of incentive for action, especially through the link with offsetting mechanisms. The necessary incentive is generally presumed to be pecuniary, rather than legal (regulatory) or normative, even though such alternatives might be equally conceivable as a means to deliver net outcomes. Neoliberal principles of both deregulatory politics and private property rights are implemented in the move embedded in NNL and BDO: from a social or public obligation to protect the natural interest, toward a private right to development, which cannot be suspended, only made conditional upon the purchase of a compensatory offset. More specifically the standard model goes beyond mandating the protection or creation of compensatory habitat for a specific development, to the development of trading or offsetting markets in biodiversity credits, which in turn establish the commodity "price" and direct new (theoretically additional) flows of investment to the purpose of biodiversity protection. Yet in the exchange of credits, the value of non-human nature is made equivalent to its financial cost (an abstracted exchange value, rather than a use, or even production value), further abstracting it from other sources of value (Apostolopoulou and Adams, 2017).
- **Making actors:** net policies and practices also have implications for who is considered to have agency, and what sort of agency they enjoy (i.e., what sort of subjectivity is created or reinforced). It is inevitable in constructing incentives, that particular forms of actors are presumed. Consider the difference between policy goals that "protect and enhance biodiversity" through strict regulation of damaging activity even on private land, and those that seek NNL or net gain. The latter enables the marketization of biodiversity, and constitutes the actors involved as consumers and producers, rather than as citizens with rights and responsibilities. This is not to claim that the ultimate outcomes for biodiversity are necessarily worse in the latter framing, but to highlight that it not only presumes certain ideological preconditions, but also that it constitutes actors in distinctive ways. However, Parson and Kravitz (2013, p. 431) note that in environmental policy more widely, "either framing the decision situation as a market or increasing market-like attributes (e.g., anonymity, transience, social distance) induces more rent-seeking and other self-interested behavior than under alternative framings"—at both individual and community levels. Attaching NNL of biodiversity to

the development project, rather than a territorial scale, ignores diffuse harms to biodiversity (such as from pervasive chemical pollution), permits huge "leakage" by relocation of projects, and/or makes avoidance of damage by the foregoing of development that much less likely. But critically, with respect to the participants, it also reinforces the constitution of the corporate developer as the key actor and arbiter of conservation harm, rather than the community, the citizen or the regulator. This is the case, even as within offsetting schemes agency is transferred from the site managers at the practical ground-level to the traders and market managers who are also, in some case also the regulators. Moreover, NNL and BDO schemes have also re-positioned environmental NGOs: as participants or intermediates in such schemes, sometimes even providers or manager of offsets, they have been distanced from their conventional role in resisting ecologically harmful economic activity.

- **Making expectations:** net practices and policies (re)shape expectations at several levels. In particular they presume the existence, or creation, of restorative technologies (e.g., habitat recreation, de-extinction), and thus bear a particular relationship to the inevitability and desirability of innovation. More broadly they presume the continuation of development and growth (not only as a product of a continued innovation process, but as an inevitable source of demand for land-use change and offsets). Net approaches therefore defend the underlying model of economic growth through continued development, framing the cessation of biodiversity damage as implausible utopian thinking, not to be seriously entertained. But as Apostolopoulou and Adams (2017) suggest, by linking conservation to ongoing development and growth, and presenting offsetting as a technical issue, the problem of biodiversity loss due to development is depoliticized. The expectation that market-led innovation will provide solutions is another neoliberal article of faith reinforced by the net/offset combination. It is no surprise that entrepreneurs aim to apply in-vogue technologies (gene-tech, drones, and blockchain) to the emerging biodiversity markets: the model of seeking diverse applications for novel technologies is well established in neoliberal innovation financing (Goldstein, 2018). However, the introduction of such technologies in efforts as diverse as drone and blockchain tracking of wildlife to reduce poaching (Mitra et al., 2021)[10] and gene-manipulation for de-extinction (Adams, 2016) all contribute to ethical concerns that commodification is "de-naturing" biodiversity.

Across these six dimensions we see a consistent fingerprint of neoliberal ideology, both on what is made by the interventions, and in turn in how what is made reproduces or reinforces those ideologies, constituting a model in which abstract commodities are traded between private entities in line with profit motives, portrayed as success regardless of the empirical outcomes on the ground in the longer term. This helps keep the whole system unchallengeable in any substantive way. In other words, neoliberal policy options are not just adopted, but made. Their dominance reflects not an objective assessment of what might be effective at delivering goals, but a process of remaking of goals, metrics, equivalences, actors, incentives, and expectations recursively in line with ideological presumptions. In the neoliberal context then, net policies do not merely enable offsetting mechanisms, nor is it that the policies actually demand such measures; it is the neoliberal commitment to economic growth, markets and financialization that drives the adoption of net framings for the very purpose of validating offsetting markets. In the next section we consider whether we should expect the same in the introduction of net-zero to the climate policy arena.

4. Is climate policy different?

Here we summarize how net-zero reflects these six "makings", highlighting some critical themes for the future of climate policy, and discussing some key points where nature and climate "netting" intersect.

In respect of *goals,* the adoption of net-zero is a deliberate reframing of the climate target. It might appear that the novelty in net-zero resides with the "zero" rather than the "net". After all natural sinks have been a (controversial) part of climate policy since Kyoto, and emissions trading long established in several countries and regions. But at least until the Copenhagen COP failure in 2009, removals were treated as a relative minor issue—mainly one of accounting, rather than a manipulable component of the climate goal. And emissions trading was focused on shuffling the responsibilities to cut emissions between different actors. It is only in the Paris era, that the net—as an aggregate outcome achieved through balancing of sources and sinks—has moved to the center of policy. In part this is a product of the understanding that the carbon budget is on the brink of exhaustion, and thus "zero" is critical, but understanding the move to *net-zero* as simply about the rational tightening of the (net) emissions target to zero would be to miss the processes through which and the interests by which contemporary climate policy has been shaped.

Above we noted the use of the net-zero framing as a means of convening support for new action and elevating aspirations in the face of depleting carbon budgets and growing climate risks. This process paralleled a shift from top-down political targets under Kyoto to "nationally determined contributions", a growing role for non-state actors, and a revival of offsetting approaches (notably through the Taskforce for Scaling Voluntary Carbon Markets).[11] The consequence of such a neo-liberalization of environmental policy is not necessarily a weakening, but as with NNL, the reframing places the material outcomes of policy on a lower level of priority than the deployment of mechanisms that resonate with neoliberal ideology. And it combines more flexibility with a greater risk of overshoot. In particular the huge uncertainties associated with high dependence on speculative carbon removal (Anderson and Peters, 2016)—like those associated with habitat

10 Also see Available online at: https://cryptobriefing.com/blockchain-save-endangered-species/.

11 See: Available online at: https://www.iif.com/tsvcm.

recreation—are largely overlooked in the efforts to get corporate and financial actors involved. Critically however, in bringing fungibility and flexibility to the center of climate policy, the net-zero framing enables continued postponement of action, and risks further buck passing through offsetting.[12] Like NNL, the net-zero goal is an accounting goal. It promises expanding, perhaps even unlimited, markets for removal, and has reinvigorated offsetting claims, and the creation of voluntary carbon markets. Reinforcing the argument that neoliberal ideologies underpin net-zero, rather than the reframing as net-zero unintentionally enabling neoliberal measures, McLaren and Markusson (2020) identify the emergence of net and neutrality concepts enabled by hypothetical removal technology and a presumption of fungibility and trading (in models and politics) which *preceded* net-zero rhetoric by some years. Similarly, Schenuit et al. (2021) trace constructions of fungibility for nature-based carbon removals in countries like Australia back before Paris.

As with no-net-loss of biodiversity, climate net-zero has also shifted presumptions about the *baseline* for policy goals. In this case the move is to reorient the baseline entirely: targeting stabilization at a future date (typically 2050), rather than measuring emissions reductions against a specific past state (such as 1990 or 2005).[13] This might reduce confusion and contestation over different historic baselines for emissions, focusing attention instead on the degree and rate of future action. But whether considering the past, or the future, "global net-zero" (the implicit outcome of the "balance of sources and sinks" mandated by the Paris accord) thereby tends to erase questions of justice (Mohan et al., 2021). Differential responsibility for past emissions is swept away, while a common net-zero goal is treated too often as meaning every country (and indeed every corporate entity) should meet the same target over the same timescale: ignoring both differential responsibilities and differential capabilities to contribute. And whilst the commonly presumed baseline of net-zero by 2050 might seem clear about eliminating net emissions to the atmosphere, in a further echo of NNL challenges, the counterfactual projections of economic growth which feature in modeling pathways to net-zero strongly structure the scale of any requirement for carbon removal, much of which effectively is "needed" to compensate for residual emissions or emissions overshoot resulting from continued growth. The goals made in net-zero policy thus accommodate neoliberal expectations of continued economic growth, while also disavowing the additional responsibilities than might accrue to the states, institutions and companies driving neoliberalism for their historic climate liabilities.

In terms of *measurability* the adoption of net-zero does not require the same degree of change in measurement that was demanded by NNL (novel quantitative measures for qualitative concerns like situated and socially valued habitat features and ecosystems). However, "measuring" greenhouse gases remains complex, especially when seeking to account at the enterprise or national level (as opposed to simply recording global atmospheric concentrations). So while measuring the outcome might seem fairly easy, measuring the different components of emissions and sinks so as to implement net-zero policy is harder at this differential scale. Measurement is particularly difficult for natural sinks where uptake of carbon might be accelerated by enhanced weathering, ocean fertilization or alkalinisation, or soil carbon management for example. Assessments of such approaches" carbon uptake are already more model than measure, with, for example, measures of uptake in soil complicated by variability in baseline carbon content, seasonal variability in uptake, and losses in soil erosion events, amongst other factors. Measuring enhanced sink uptake typically relies on "accounting" for net effects. This holds also for other carbon removal techniques: while measuring the CO_2 piped into a store from direct air capture (DAC) or bioenergy with carbon capture and storage (BECCS) may be technically quite simple, accounting for all the consequential emissions and leakage from energy requirements, or in the material inputs is much more challenging. Yet precise measurement is presumed when carbon removal techniques are incorporated into neoliberal carbon markets and offsetting schemes.

In terms of *equivalence* and *fungibility*, again the transition to net-zero is not as radical a shift as that in NNL (where at an extreme, completely different species or habitats were made fungible). Yet again it would also be unhelpful to ignore the degree to which non-fungible aspects of GHG emissions are further collapsed in making them compatible with net-zero visions, or to disguise the political choices in making different sinks equivalent and fungible as technical accounting challenges (Carton et al., 2020). Where a purely scientific perspective might see carbon as fungible (arguing that a ton is a ton: no matter where or when emitted, or from what process, it will have the same impact on the climate), this is false. First, timing does matter with respect to the overall climatic impact, especially when considering techniques where removed carbon is not permanently stored and might be released by wildfires, for example. More broadly it is inappropriate to treat carbon in biological cycles as *fungible* with carbon in geological cycles (Carton et al., 2021). Efforts to construct equivalence for carbon removals began in the 2000s (e.g., Grönkvist et al., 2006), but have massively intensified in recent years. The European Union is seeking to agree a framework for carbon removal certification which enables fungibility between biological removals and geological (fossil) emissions. And the Article 6 Supervisory Body is working on accounting rules for removals under the UNFCCC. Such procedures have paid growing attention to questions of permanence but even that issue remains unresolved and contentious. Second, the assumption of perfect fungibility draws too tight a boundary around the carbon unit—different gases in different locations serve different social purposes and face different risks (Carton et al., 2021). Yet metrics for comparing emissions of different gases typically

12 See CSSN Net-zero working group paper. Available online at: https://cssn.org/wp-content/uploads/2022/06/Net-Zero-and-Carbon-Offsetting-Position-Paper.pdf.

13 This is not to say that countries have abandoned emissions reductions targets measured against historic baselines, but that such targets have largely become subsidiary to the future-oriented net-zero goal. In the UK for example, the Government maintains that it is on track to achieve net-zero, even as emissions increasingly exceed the budgets previously established in law to drive emissions reductions.

only consider physical and chemical characteristics.[14] And such questions are invisible at the enterprise accounting level, where the International Standards Organization (ISO) is working on a dedicated carbon neutrality standard, based on a British PAS standard devised in 2010. ISO already adopted emissions measurement and inventory standards. All these means of establishing fungibility rest on neoliberal preferences for market-based approaches and incentives.

Climate policy already involves neo-liberal *actors*, including technological entrepreneurs, industrial corporations and financial institutions. Yet net-zero has attracted new entrants especially in the entrepreneurial spaces around nascent carbon removal technologies, and in the associated and challenging spaces of measurement and tracking of emissions, with particular efforts to deploy blockchain solutions. It has also seen intensified financial sector interest. While multilateral bodies such as the IFC and World Bank have been long involved, the Glasgow Finance Alliance for Net-Zero now boasts "more than 450 member firms from across the global financial sector, representing more than $130 trillion in assets under management and advice",[15] including banks, asset managers, investment managers, insurers, financial services companies and financial consultants. In 2022 UN's "race to zero" campaign included over 5,000 businesses (alongside other institutional members, accounting for over 50% of global GDP),[16] and many businesses are now making their own net-zero declarations (even though net-zero makes sense theoretically only as a global goal, implemented by states).[17] This turn toward *privatization* of climate action might accelerate both emissions cuts and deployment of carbon removal, but it emphasizes an offsetting model of delivery, and also raises questions of distributive justice, especially where companies effectively stake a claim to limited carbon removal capacities (Armstrong and McLaren, 2022).

Similarly, the financialization of *incentives* involved in net-zero policies is not new (the EU emissions trading system was established in 2005), yet under net-zero there seems to be intensified interest in market making, including demands for either new markets for carbon removal, or efforts to incorporate them in existing trading mechanisms such as voluntary carbon markets, compliance market trading in the EU and New Zealand, or the emissions intensity calculations of the California Air Resources Board.[18] We are also seeing novel private sector "advance market commitments" for carbon removal orchestrated by entities such as digital payments company Stripe. And even if such measures were pursued only by states[19] this would not indicate a rejection of neoliberal ideology. State military procurement is an archetypical neoliberal model—maintaining private, "competitive", profit maximizing business as the productive actor, in contrast with models such as the "Green New Deal" (Galvin and Healy, 2020) which would revive Keynesian economic principles of state spending targeted at climate and broader environmental and social goals.

Specific *expectations* have also been established or solidified in the construction of net-zero. A fundamental presumption that some continuing harm is inevitable or necessary underlies the recognition of residuals that will have to be counterbalanced (as opposed to eventually eliminated) (Buck et al., 2023). Similarly as with the shift from NNL to Net Gain, the climate literature and commentary sphere is filled with debate over the need for a move to "net-negative" (beyond the accounting baseline) a global state in which atmospheric carbon dioxide levels are drawn down to some safe level, a form of climate repair or restoration[20], triggering contestation over what historic state to aim at (McLaren, 2018). But the most rapid and novel shifts in expectations have emerged around innovation and carbon removal, with not only anticipation of proliferation of carbon removal techniques through venture-capital driven innovation, but also a distinctive phenomenon in which technologies have been reframed or even evoked—*de novo*—through modeling. Carbon capture technologies such as mineralization and Carbon Capture and Storage (CCS), earlier treated as ways to abate fossil carbon flows in flue gases from combustion have transmuted into carbon removal technologies applied in the outside world, including enhanced weathering and ocean alkalinisation (in which carbon-absorbent minerals are spread in the environment, rather than reacted with flue-gas CO_2 in a pressure vessel) and Direct Air Capture (DAC) in which ambient air rather than flue gas is directed over reactive chemicals to strip out CO_2. The most extreme case is that of bioenergy with carbon capture and storage (BECCS), in which existing and emerging technologies of biomass combustion and carbon capture and storage were first combined as imaginaries in climate models, and still lack large-scale commercial demonstration in practice (Low and Schäfer, 2020). The net-zero imaginary follows neoliberal presumptions of inevitable growth, and associated harms being mitigated through market-led innovation.

4.1. More than parallels?

Overall there are clear parallels between the makings of NNL and those of net-zero. In many respects the neoliberal making of

14 The most widely used metric [Global Warming Potential (GWP)] dates back to 1990—but the net-zero era has spurred new efforts to incorporate short-lived gases in a GWP* (and criticism that this combines stock and flow pollutants inappropriately). These take into account the lifespan of the gases in the atmosphere, but not whether the original source is biological or geological.

15 See Available online at: https://www.gfanzero.com/about/.

16 From Available online at: https://unfccc.int/climate-action/race-to-zero-campaign (accessed March 22, 2022).

17 Partial adoption of net-zero cannot deliver the global goals set by Paris, and in practice if global net zero is achieved it will involve some sectors and some states still being net emitters and others being net removers. The drive to spread net-zero targets to as many countries and businesses as possible is only ever a proxy for the global net-zero goal.

18 See Available online at: https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program.

19 For example in Sweden, the state has allocated €3.8bn to procure BECCS removals to offset emissions in hard-to-abate sectors such as agriculture (Lundberg and Fridahl, 2022).

20 See, for example, Available online at: https://www.climaterepair.cam.ac.uk/.

net-zero began well before the policy discourse even emerged, but the processes have continued, intensified and solidified in ways that reflect neoliberal ideology. Yet in some spaces NNL and net-zero are not simply parallels, but are different attempts at commodifying the same natural resources: many carbon removal techniques have biological underpinnings and rely on the exploitation of biomass. There is a double intertwining of offsetting and "netting" then in the potential deployment of nature-based, or bio-based carbon removal to contribute to net-zero (Griscom et al., 2017). Here the driving forces of neoliberal environmentality (Fletcher, 2010) risk conflict between biodiversity and climate goals specifically because the complex and multi-faceted values of biodiversity and climate have been flattened and simplified into tradeable commodities. Exaggerated promises notwithstanding (Bastin et al., 2019; Lewis et al., 2019), interventions in ecosystems would appear to have more potential to support both net-zero and biodiversity goals if directed to integrated biodiversity ends, but as potentially creating conflict between the goals if driven by carbon metrics (Smith et al., 2022). The optimum policy approach to achieve this seems unlikely to involve offsetting mechanisms, yet proponents of carbon markets and nature-based solutions alike tend to present offsetting—and particularly carbon offsetting, because of the growing quantities of climate finance anticipated—as the only (or at least an essential) way to direct substantial funding into the development and deployment of such techniques. However, biological carbon removal techniques such as afforestation, BECCS, or kelp farming maximize carbon by maximizing *productivity*, which tends to undermine biodiversity. By contrast natural ecosystems tend to accumulate larger carbon pools (but at less rapid rates), but carbon removal techniques tend to suspend ecosystems in a particular productive state, rather than allowing for the evolution and development necessary both for biodiversity to adapt to climate change and to accumulate carbon in mature systems.

5. Conclusions

We have shown that both NNL and net-zero (and their mutual obsessions with offsetting as the central mechanism to implement these policies) are expressions of similar neoliberal presumptions and prescriptions about fungibility, financialization, economic growth and efficient markets. In turn both rely on a series of interventions or makings, in which policy goals, measurement and metrics, equivalences, incentives, actors and expectations are all (re)constructed in line with neoliberal ideologies. And, perhaps unsurprisingly, both areas experience similar problems and critique. Philosophical critique highlights the conversion of commons-based resources into forms of enclosed and commodified natural capital, and emphasizes ethical and justice implications of such a transformation. Politically they share concerns about the power of vested interests and the politicization of baselines and counterfactuals in line with ideological commitments to economic growth. And practically they raise similar concerns about the additionality, permanence and leakage of offsetting benefits, and about the expectations for greater availability of offsetting benefits than is socially or environmentally sustainable.

By surfacing and unpacking the neoliberal foundations of these policy models we can see ways in which weaknesses are magnified and possible reforms or alternative approaches are overlooked by the neoliberal gaze. Moreover, the principles inherent to net policies are built on accounting logics and "trust in numbers" that, although predicated on an established drive for objectivity shared in science and bureaucratic cultures, still often distort and pervert what is being measured for the sake of management (Porter, 1996). To make net policies effective in social and environmental terms begins with understanding their multiple entanglements with neoliberal presumptions, and specifically demands separating them from the mechanism of offsetting. We close with five principles for more effective net policy.

First to minimize the *need* for benefit restoration by prioritizing measures to minimize residual harms. This means adopting and firmly enforcing the mitigation hierarchy. This radically shifts *expectations* away from presumptions of inevitable continued development and damage, removing the perceived need for marketisation and offsetting mechanisms. Second establish clear, and accountable *separate* targets for harm minimization and benefit restoration to avoid a tendency toward moral hazards (c.f., McLaren et al., 2019). This not only begins to remake targets, but disrupts assumptions of equivalence, enshrining awareness of the difference and incommensurability of different benefits. Third, to establish and implement *targets at global or ecologically relevant territorial levels* through coordinated planning rather than attaching them to specific projects or businesses. This not only contributes to remaking the targets, attaching them primarily to the stability of the climate or biodiversity, rather than to the interests of the economy, but more importantly, remakes the actors, constituting them as collective, regional or global, rather than private and corporate. Fourth, to provide *direct funding support or mandates* for the provision of benefits to alleviate the demand for marketized offsetting as a source of finance. This remakes the incentives involved, and disconnects action from the neoliberal presumption that markets are best. Fifth, to construct policies and set targets with *attention to the multiple values associated* with the benefits concerned, particularly with respect to social justice. This is not just about remaking targets, but more importantly about disrupting equivalence, by attaching multiple variable values to the benefits and harms involved, and respecting the unmeasurable elements that are present, rather than narrowing everything down to those aspects that can be measured. Collectively, through the application of these principles the needs for long-term restoration could be detached from balancing residual harms; and the potential benefits of net policy making might be disentangled from the neoliberal mechanisms of offsetting.

Data availability statement

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

Author contributions

DM and LC jointly conceived, investigated, wrote and edited the work, and approved it for publication. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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

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Ecologies of integrated modeling: configuring policy-relevance in Swedish climate governance

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Due to the long timescales and deep uncertainties involved, comprehensive model-building has played a pivotal role in creating shared expectations about future trajectories for addressing climate change processes, mobilizing a network of knowledge-based experts who assist in defining common problems, identifying policy solutions, and assessing the policy outcomes. At the intersection between climate change science and climate governance, where wholly empirical methods are infeasible, numerical simulations have become the central practice for evaluating truth claims, and the key medium for the transport and translation of data, methods, and guiding principles among the actors involved. What makes integrated assessment unique as a comprehensive modeling-effort is that it is explicitly policy-oriented, justified by its policy-relevance. Although recognized by the Intergovernmental Panel on Climate Change as invaluable to their review assessments, the role of integrated modeling in implementations of the Paris Agreement, such as in impact assessments of climate legislation on the national level, is far less known. Taking as its starting-point the boundary-work carried out in public administration, this paper examines how foresight knowledge produced with the help of model-based scenario analysis has been made relevant in Swedish climate policymaking, focusing on the processes by which key indicators for political action become institutionalized through the choice and use of model parameters. It concludes by arguing for an expanded understanding of policy-relevance, beyond institutional approaches and toward a process-based point of view, treating relevance as something in-the-making.

KEYWORDS

climate mitigation, integrated assessment, model-based forecast, scenario analysis, science-policy interface, policy-relevance

1. Introduction: model-based forecasts of climate change mitigation pathways

When it comes to the role of scientific research in informing public policy about wicked problems, like that of climate change, integrated assessment processes with the aim of organizing, evaluating, and presenting the latest scientific findings to inform political decision-making have become increasingly important (Funtowicz and Ravetz, 1993). Climate change mitigation, for instance, involves the simultaneous transition of industry, transport, agriculture, and energy systems on national, regional, as well as international levels, comprising a wide range of stakeholders. Such problems are wicked because they affect multiple temporal and spatial scales at the same time; they are also transboundary, as they stretch across several governance levels, involving many different policy fields, and requiring expert input from a plethora of disciplines (Ravetz, 1987). Since the anticipation of climate impacts is neither routine nor short-term, with a scarcity of objective data, these are problems that involve scientific knowledge and its present limits, encouraging assessments that are built on highly uncertain findings of the best available research "[…] at a particular time, given the information currently available, even if those judgments involve a considerable degree of subjectivity" (Moss and Schneider, 2000, p. 36).

Because of the transboundary nature of the problem, coordinated responses to climate change have relied upon unusually sophisticated information systems. It has spurred the development of new institutions and organizations for compiling a whole swath of individual measurements across the globe into a coherent assortment of commensurable and in effect useful numbers. First, by recording the variables measured, then by connecting the data within any one system, as well as between systems, before linking and sharing it across various scales to enable the production of synoptical forecasts through computer simulation (Miller and Edwards, 2001; Edwards, 2010). Due to the long timescales and deep uncertainties involved, numerical simulation modeling has played a pivotal role in creating shared expectations about future trajectories for addressing climate change processes, mobilizing a network of knowledge-based experts who assist in defining common problems, identifying policy solutions, and assessing the policy outcomes (Borie et al., 2021). At the intersection between climate change science and climate governance, where wholly empirical methods are infeasible, numerical simulations have become the central practice for evaluating truth claims (Edwards, 1996), and the key medium for the transport and translation of data, methods, and guiding principles among the actors involved (Shackley and Wynne, 1995a).

The Intergovernmental Panel on Climate Change's (IPCC) exploration of climate change mitigation pathways compatible with the temperature goals of the Paris Agreement is a case in point (Intergovernmental Panel on Climate Change, 2014). Some of the most prominent and influential tools to help us explore low-carbon futures are integrated assessment models (IAMs), which is a family of numerical simulation models that seek to capture the societal dynamics between energy use choices, land use changes, and its consequences for various sectors of the economy. Unlike modeling the convection of heat through the atmosphere, or the way it absorbs solar radiation, however, the same regularities of nature do not apply to the economic demand and supply of different fuels or the behavioral relationships between income, diets, and transport use (Dessai and Hulme, 2004). Relying for the natural-systems side on outputs from other efforts based primarily in the climate sciences (Edwards, 1996, p. 51), model-building for the sake of integrated assessments puts its focus on the economic, technological, and political elements of anthropogenic forcing, with ambitions much more modest than prediction at statistically significant levels (Ackerman et al., 2009).

Instead of predicting the future then, exploratory techniques of model-based forecast are employed as a means of providing policymakers with a map to navigate the trade-offs and consequences of various so-called emissions scenarios. Simulating scenarios of interacting environmental, financial, and technological change (Intergovernmental Panel on Climate Change, 2000), mitigation pathways are mapped out by combining and mutually revising scientific evidence in concert with various policy means, objectives, and value judgments into potential policy solutions. Once policies are implemented, their consequences can be carefully monitored, and the cartography of pathways reapplied, based on the analysis of those consequences (Edenhofer and Kowarsch, 2015, p. 60–63). By identifying poorly understood or previously unanticipated consequences, such as co-benefits, policy synergies, and cascading effects, model-based scenario analysis has been widely adopted as a strategy for deciding what mitigation policies to implement and when.

What makes integrated assessment unique as a comprehensive modeling-effort is that it is explicitly policy-oriented, justified by its policy-relevance (Cointe et al., 2019). Although recognized by the Intergovernmental Panel on Climate Change (2014, p. 51) as invaluable to their review assessments, the role of integrated modeling in implementations of the Paris Agreement, such as in impact assessments of climate legislation on the national level, is far less known. This is no trivial oversight, because the incentives that influence policymakers most in political decision-making tend to reward projects that are nicely bounded, enjoy a tangible and easily perceived connection between action and outcome, and can produce a steady series of short-term payoffs (Brunner, 1996, p. 129–130, 142–144; Edwards, 1996, p. 156). Yet, scenario analyzes would at best be able to assign highly subjective estimates to the costs and benefits associated with various mitigation pathways [Intergovernmental Panel on Climate Change, 2014, p. 40], whose outcomes would take decades to materialize, with few milestones to mark the path of progress.

In such cases, when "[…] uncertainty is high, and actors, unsure of what outcomes are possible, are unable to specify reliably their own interest, nor understand with precision the interests of others" (Sabel and Victor, 2017, p. 16), integrated bargaining around top-down treaties become very demanding and other strategies may have to be more widely employed as a fallback position. With the adoption of the Paris Agreement, scholars have identified a general shift away from the top-down model of the Kyoto Protocol and toward a bottom-up policy regime with voluntary pledges in its place (Falkner, 2016; Guillemot, 2017; Jordan et al., 2018). Often described in terms of a transition toward a solution-oriented mode (Jabbour and Flachsland, 2017), this change in the structure of the international climate policy regime has reinforced the importance of scenarios to serve as a basis also for the efforts undertaken by each country to reduce national emissions (Hermansen et al., 2021; Hermansen and Sundqvist, 2022).

However, given the centrality of their role in the implementation of the Paris Agreement, the scenario analyzes carried out in the administrative branch of governments have been poorly documented, and their influence on mitigation policy remains ill-understood. In the wake of the bottom-up structure of the Paris Agreement, as Hermansen et al. (2021, p. 3) point out, there is thus a need for empirical studies examining how the foresight knowledge produced with the help of model-based scenario analysis is made relevant at the national just as much as at global level, including the significance of actors other than modelers in contributing to these assessment processes.[1] By looking at the case of the Swedish climate policy framework in particular, the aim of the present study is to contribute to addressing this gap in the existing research literature.

2. Conceptual framework: emissions scenarios at the science-policy interface of integrated assessment

In a global world of complex interactions, there is a rising demand for accessible and comparable knowledge. Since numbers are said to possess many features that cater to this demand, quantification has been recognized as a pervasive feature of contemporary governance (Rottenburg et al., 2015). Politics in the 20th century created a whole array of indicators, such as gross domestic product (GDP), that became crucial for the structure of entire policy fields. Politics in the 21st century, inspired by New Public Management (NPM) discourse, deepened this trend both by developing more indicators (Bartl et al., 2019, p. 8) and by connecting the development and use of indicators to techniques of model-based forecast.

Indicators are a special form of quantification in that they emphasize the intentional use of numbers for the sake of political action (Espeland, 2015). They can be described as numbers that use a limited set of measurable parameters to make phenomena visible that cannot be observed directly (Porter, 2015). The otherwise intangible consequences of a changing climate can for instance be forecasted by simulating a number of interacting systems, under a given set of conditions, to explore the linkages and trade-offs between different policy options. An often-cited definition states that "[…] desirable indicators are those that summarize or otherwise simplify relevant information, make visible or perceptible phenomena of interest, and quantify, measure, and communicate relevant information" (Gallopín, 1996, p. 108). While this definition might not be entirely uncontroversial, it nevertheless highlights four key features that are typically associated with indicators of importance to processes of integrated assessment. First, as already mentioned, indicators are a form of quantification; second, the knowledge produced is the result of a reduction in complexity; third, indicators make phenomena visible that might not otherwise be directly observable; and fourth, since indicators are based on indirect measurement rather than direct observation, questions of validity become especially salient, and the relevance to policy of the knowledge produced tends to be a burning issue (Bartl et al., 2019, p. 9–13).

Since indicators simplify complex phenomena, their interpretation depends on mediums, such as numerical simulation models, that ensure their communicability (Lehtonen, 2015). Mediums aid interpretation by relating the phenomena of interest to a chosen measure. However, these mediums implicitly contain causal attributions and, hence, suggest scripts for political action. Whereas the specific conditions of a medium may be obvious in expert circles, this is not necessarily the case when they are transferred into the political sphere (Bartl et al., 2019). During the last two decades, research on the science-policy interface of integrated assessment has for instance concerned itself with questions of transparency and participation (Schneider, 1997; Van Der Sluijs, 2002). It has focused on efforts by modelers to make explicit the specifications underlying various emissions scenarios, and to facilitate policymakers with a better grasp of how to interpret the foresight knowledge produced (Kriegler et al., 2015; Harmsen et al., 2021). When it comes to fostering policy-relevant science, emphasis has been on how to improve the quality of communication between modelers and policymakers (Dilling and Lemos, 2011; Lemos et al., 2012; Kirchhoff et al., 2013). Combating the opaqueness of models has been recognized as one of the most decisive aspects of such an undertaking (Robertson, 2020). Without a sense of the uncertainties pertaining to model parameters and structure, scholars have cautioned that the numbers and figures produced may end up providing a distorted picture of the stakes involved in following specific mitigation pathways (Stirling, 2010; Rosen, 2015; Krey et al., 2019).

There has been a general concern that, due to the growing role of large-scale information systems in anticipating climate impacts, the technical performativity of valuation in integrated assessments of climate change has delegated the definition and measure of value to models (e.g., Scheinke et al., 2011; Frisch, 2013; Beck and Mahony, 2018; Hollneicher, 2022). Unsurprisingly so, because the power of indicators lies in their ability to reduce a plurality of meanings and valuations to a single number, and thereby to function successfully as objects of compromise between actors (Boltanski and Thévenot, 2006): it is precisely the polysemy of language that can be overcome by quantification. The relevance to policy of foresight knowledge emphasized by certain indicators, then, is not invariable. Rather, it may become relevant if indicators are used collectively, if they are attributed a relatively consensual meaning, and if their production, publication, and use have significant consequences for the constitution, reproduction, or transformation of a particular field of policymaking (Bartl et al., 2019, p. 13); or vice versa, to become irrelevant if their indicators fail to have these consequences.

This means that there is an inherently political dimension even to methodological issues in the quantification process (Saltelli et al., 2016, 2020; Havstad and Brown, 2017, p. 110–115).[2] As noted by Winsberg (2012, p. 130), "[…] climate

1 I borrow the term "foresight knowledge" from Von Schomberg et al. (2006, p. 149–151), for whom it denotes an action-oriented form of strategic knowledge used for agenda setting and problem-solving related to the anticipation of future threats, challenges, or opportunities, and whose quality, insofar as it is characterized by relatively high degrees of uncertainty, has to be evaluated on grounds of its plausibility rather than in terms how accurate it is in predicting events.

2 A much-debated indicator in integrated assessments of climate change is the social discount rate applied to climate impacts. Although some modelers stress that a concern for intergenerational justice must lie at its heart, others advocate the use of observed market interest rates to inform this choice. But even if we adopt a descriptive as opposed to a prescriptive approach to the choice of discount rate, it is unavoidably the product of a value judgment, namely, that governments ought to "[…] consider individuals' everyday decision-making to determine what consideration future generations receive

modeling involves literally thousands of unforced methodological choices," a result of the fact that such models are highly idealized representations of incredibly complex target systems, and doubly so when we consider that integrated assessments include energy, transport, and agricultural factors too. Such choices include decisions about possible parameterizations and model structures; parameter values; choices between different approximation methods; decisions about which climate forcings to include in the model, exclude as insignificant, or approximate with a simple parameter; choices of higher or lower model resolution; decisions about aggregating ensembles of models, and so on Beck and Krueger (2016). To the extent that such choices become embedded within models, the design of emissions scenarios allow for integrated assessments to rely on the quantification of numerical data, building expectations about the future to make plans and collectively binding decisions (Shackley and Wynne, 1995b; Turnhout, 2009). As Klenk and Meehan (2015, p. 162) have argued:

> In the context of climate change and transdisciplinary science, […] we should understand integration as an exclusionary practice, which establishes boundaries between what knowledge claims are internalized from what knowledge claims are externalized. Differentiated matters of concern become factual claims deliberately and carefully composed through practices of production, reduction, negotiation, translation, amplification, [and] circulation[.]

Boundary judgments involved in the design of scenarios thus influence the scope of future potential reflected in scenario outcomes, which is to say that the analytical distinction between value-neutral modeling and value-laden policymaking is unhelpful in the context of integrated assessments (Edenhofer and Kowarsch, 2015, p. 59; Kowarsch, 2016, p. 101–132), and that sociological attention ought to be paid to the processes by which key indicators for political action become institutionalized through the seemingly technical choice and use of model parameters and numerical inputs (Saltelli et al., 2020). If not, burying parameters within the structure of black-boxed models risks making modelers into technocrats that both identify and formulate the relevant problems, identify the relevant goals, and prescribe the means, all the while policymakers, at the end of the process, simply implement the recommended policies.[3]

In mapping out mitigation pathways then, assessments of scientific findings are in many ways entangled with the valuation of climate impacts (Stanton et al., 2009, p. 179; Pfenninger, 2017; Doukas et al., 2018, p. 4–6). Making use of scenarios to mobilize, shape, and hold together matters of political concern (Lidskog, 2014), integrated assessments involve a constant interaction between scientific and political processes. In situations like these, where weighing the social consequences of climate change is inseparable from evaluating the characterization of ambiguous data, the standards of evidence, or the adequacy of the chosen conceptual frameworks, integrated assessment processes "[…] determine which knowledge is relevant while at the same time being co-constituted by the same knowledge" (Hermansen et al., 2021, p. 5), establishing climate change as simultaneously knowable and governable (Miller, 2004). In this paper, integrated assessments will be examined as sites for the co-production of science and social order (Jasanoff, 2004; Lövbrand, 2011; Mahony, 2013). Such a co-productionist approach focuses on how the use of scientific instruments—such as parameters in numerical simulations models—bind our collective performance of matters of political concern—mitigating climate change—through the production of knowledge; and conversely, how the production of knowledge—in this case, about the feasibility of mitigation pathways—is shaped by the indicators that mediums like models give expression to (e.g., Sundberg, 2007).

Model-based scenario analysis thus makes for a paradigmatic focal point to understand how problems that have long-term but uncertain implications, and that must be addressed in a coordinated manner, are worked out. In such cases, where the linear model of interfacing science and policy—wherein science is understood to inform policy by producing objective, valid, and reliable knowledge, such that to develop a policy is seen as a matter of scientists delivering the facts and then, in a second step, policymakers sorting out diverse values and preferences (Funtowicz, 2006, p. 139)—fails to capture the nature of policy-relevance in post-normal science (Van Der Sluijs, 2010; Beck, 2011), it becomes necessary to study relevance in-the-making. As opposed to ex post evaluations of the foresight knowledge produced, policy-relevance within processes of integrated assessment is herein approached as relational achievements that are assembled in the boundary-work of delegation, argumentation, negotiation, and conclusion, and in effect something to be studied as provisional accomplishments (Sundqvist et al., 2015). Boundary-work is necessary to create common understanding, to ensure reliability across domains, and to gather information that can retain integrity across time, space, and local contingencies. It does not, however, presuppose consensus. Taking inspiration from Jasanoff (1987; 1990, p. 234–236), who uses "boundary-work" to denote "[…] contestations over scientific knowledge and its appropriate relationship to policy that reflect and reinforce different conceptions of social order" (Low and Schäfer, 2020, p. 2), this paper homes in on model-based scenario analysis as a set of practices for the configuration of policy-relevance, where such configurations can either be contested or entrenched.

Consequently, the conceptual framework of this paper qualifies the above-mentioned aim: to examine how the foresight knowledge produced with the help of model-based scenario analysis has been made relevant in Swedish climate policymaking, focusing on the processes by which key indicators for political action become institutionalized through the choice and use of model parameters.

in climate policymaking" (Beck and Krueger, 2016, p. 636. See also Broome, 2010).

3 It is worth pointing out that for some assumptions central to integrated assessments of climate change, the exercise of valuation tied to them have been widely recognized and explicitly addressed. Two examples well worth mentioning are the rate of pure time preference and the rate of risk aversion (Stern, 2007, p. 25–45).

3. Methodology: boundary-work in impact assessments of national climate legislation

Turning its attention to the administrative agencies of government, the analysis revolves around the boundary-work carried out by administrators assessing Swedish climate policy. Administrative agencies are government bodies that are authorized to manage aspects of law and regulation, and to develop more precise and technical rules than is possible in a legislative setting. Though a long-standing feature of governance arrangements, administrative agencies have come to prominence in the last three decades as a key part of neoliberal inspired NPM-reforms in the Anglosphere, across Europe, and beyond. These agencies typically have a restricted technocratic or advisory mission that is intentionally disconnected from partisan preferences or public opinion, with their operations detached from short-term political concerns and instead focused on rational execution of policy (Roberts, 2010, p. 6–13). The focus on administrative agencies and the relevance-making that emerges in and around their work is therefore instructive, because these bodies would seem to epitomize the technocratic nature of contemporary policymaking. However, they also embody informal webs of relationships within which administrators work to adapt to, make sense of, and enact new sociotechnical arrangements in practice. Administrative agencies do not just compile scientific evidence; they actively construct expertise, respond to it, interpret it within their context, incorporate it into their own models and reports (Bocking, 2004, p. 42), and fit all this together with their own bureaucratic cultures and agendas (Süsser et al., 2021; Hermansen and Sundqvist, 2022). In assessments of national climate legislation, understanding the dynamics between scenario analyzes of climate impacts on the one hand, and domestic climate policymaking on the other, requires treating policy-relevance itself as an active effort, pursued not just by modelers and policymakers, but at least as much by the administrators that mediate between the two.

In order to give empirical weight to this approach, the analysis is based on two main sources of data. First, a survey of white papers and reports produced as part of Sweden's climate policy framework. While white papers are produced by the government, setting out their proposals for future legislation, the reports are usually commissioned by ministries, sometimes with affiliated experts from academia and interest groups, though most often authored by administrators in various agencies of the executive branch. Secondly, textual analysis has been pursued in conjunction with semi-structured, in-depth interviews with informants working directly with policy assessment, specifically as it relates to climate mitigation. Conducted over the past 12 months with 12 informants working at the science-policy interface of the Swedish government, the interviews ranged from half an hour to 45 min in length. At the time of the interviews, the informants were affiliated with either the Swedish Environmental Protection Agency, the Swedish Energy Agency, the Swedish Climate Policy Council, or the Swedish Governments Offices Office for Administrative Affairs, serving as investigators coordinating and conducting the Swedish government's action on climate mitigation, expert advisors to the government on the progress of its climate goals, or specialists in public agency initiatives to strengthen the scientific basis of Swedish climate policy.

The use of interviews to study scientific practice has been criticized. According to the actor-network approach (e.g., Latour and Woolgar, 1986; Latour, 1987), actors' accounts should not be used as sources of information about what they are doing, only about how they do it. From this perspective, interviews are less suitable than observations, which are free from the actors' subjective understanding and interpretations of activities and events. Interviews are also at odds with the anthropological approach to science, in which aspects of scientific activity readily taken for granted should be apprehended as strange (Latour and Woolgar, 1986, p. 29). However, from a social constructivist approach concerned primarily with "how"-questions, interviews are less problematic, or even preferable (Sundberg, 2005, p. 51–54), especially so in this case, since they capture the hermeneutic dimension that is so central to the use of model-based scenario analysis in the production of foresight knowledge (Von Schomberg et al., 2006, p. 150).[4] Providing orientation in an otherwise uncharted territory (Edenhofer and Kowarsch, 2015), scenarios reflect different interpretations of the risks and uncertainties involved in traversing mitigation pathways. Selective compromises must therefore be made, making the translation of qualitative conceptions about net-zero transitions into quantifiable scenarios a fruitful site for the study of intersubjectivity. Considering the tension between the usefulness of scenarios in projecting the future and the significant uncertainties under which climate policymaking must be carried out, the central theme in the analysis is how relevance is configured through the reduction of complexity. An important element of this theme is the construction of a shared sense of plausibility when it comes to descriptions of how the future may develop. It is this intersubjective side to the boundary-work performed through model-based scenario analysis that the chosen methods seek to investigate. Relying on textual analysis and interviews, the methodological gambit of this paper is that sociological questions, theories, and approaches may recover features that are not acknowledged in the same way from the practitioners' own perspectives (cf. Lynch, 1985, p. 19).

4. Background: the Swedish climate policy framework

The Swedish government is beholden to the European Union's (EU) determined contribution under the Paris Agreement for a greenhouse gas (GHG) reduction of 40% by the year 2030. Just a few months before the meeting in Paris in 2015, however, the government began working on a national climate plan, setting down a goal in the statement of government policy that Sweden should become the world's first fossil-free welfare country [Swedish

4 Furthermore, all scientific practices are not equally suitable for observations. For instance, the practical work on the shop floor in an experimental laboratory is accessible in an entirely different manner than the model-based scenario analyzes of administrative agencies, whose structure of organization is dispersed between numerous sites and whose work is not so easily studied as an observer in a physical space (Sundberg, 2005, p. 53).

Government Bill (Prop.), 2017, p. 7–9]. Two years later, it decided on a climate policy framework [Swedish Government Bill (Prop.), 2017, p. 146], including climate goals and a climate act. The government's aim is to achieve net-zero emissions by 2045, which means an 85% reduction compared to the year 1990. The remaining part required to reach zero emissions is expected to take place through increased carbon dioxide absorption, bioenergy with carbon capture and storage (BECCS), and investments in emission-reducing measures outside of Sweden's borders [Swedish Government Bill (Prop.), 2017, p. 37; Swedish Government Official Report (SOU), 2021, p. 160–166].

In regard to climate policy impact assessment, the climate act [Swedish Laws and Regulations (SFS), 2017, p. 720] binds future governments to its targets through a requirement to present annual reports on measures decided and planned, to indicate the effects these have had and are expected to have on GHG emissions, and to indicate further measures required to reach the intended targets [Swedish Environmental Protection Agency, 2012, p. 40; Swedish Government Official Report (SOU), 2016, p. 76–77; Swedish Environmental Protection Agency, 2019a, p. 30–35]. In order to facilitate the impact assessment, long-term scenarios are updated every 2 years with recently passed policy measures and with new estimations by the Swedish Environmental Protection Agency (2021, p. 6) on the price development of coal, oil, natural gas, emission permits, and annual GDP growth. Reference scenarios about expected emissions until 2045 are developed and used as baselines against which alternative scenarios can be compared and the effects of policy options estimated (Swedish Environmental Protection Agency, 2012, p. 20–21). Once scenarios have been simulated, the results are used to describe indicative target paths from the actual emission level in 2015, over the milestones in 2030 and 2040, to net-zero emissions by the year 2045 [Swedish Government Bill (Prop.), 2017, p. 31–42].

Reporting takes place in connection with the submission of the budget bill, with the additional proviso that the government must put forward an updated action plan every 4 years. Additionally, the climate framework includes a Climate Policy Council, which is an independent body of expert advisors whose task it is to evaluate the government's climate report annually and its action plan quadrennially, and whose feedback must then be taken into consideration by the government in the following year's report. In this sense, the Swedish climate policy framework is similar to the Paris Agreement in that clear and ambitious goals are formulated—the most ambitious in the world—and that a continuous assessment is in place.

5. Analysis: navigating an information ecology of models

Outlining a national roadmap toward low-carbon futures, the chief indicators employed in Sweden's assessment work are those putting a monetary cost on the policy measures adopted to reach specified emissions targets. At the heart of the Swedish integrated modeling-effort is thus the ambition to estimate the socioeconomic consequences of various climate policy options, using emissions scenarios to explore how the transition toward net-zero can be achieved in the most cost-effective manner. Although administrators acknowledge that it is in principle impossible to predict in advance which mitigation pathways are most cost-effective in the long term,[5] scenarios analysis is nevertheless hailed as paramount to manage issues of uncertainty, scale, and delay between action and response, with an action plan that continually evolves as new forks in the road, alternative destinations, pitfalls, and uncharted territories turn up [Swedish Environmental Protection Agency, 2012, p. 32; Swedish Government Official Report (SOU), 2016, p. 38–39].

One of the most important instruments in the climate policy impact assessment is the computable general equilibrium (GCE) model used by the Swedish National Institute of Economic Research, called EMEC. CGE-models are a family of economic models used to estimate how an economy might react to changes in, for instance, policy. Production and utility functions are specified based on model assumptions about functional form and elasticities. It is then calibrated to be consistent with the Swedish Central Bureau of Statistics' national and environmental accounts for a chosen base year, which serves as a reference scenario. In the development of the reference scenario, account is taken, among other things, of current raw material price forecasts and existing and decided policy measures. Since EMEC is a so-called recursive-dynamic model, the economy can be projected into the future between equilibrium positions. At each point in time, the modeled actors choose optimal levels of production and consumption based on the given conditions. Economic growth in the model is driven by the growth of the labor force and of labor productivity. As the economy grows, investments in physical capital also increase, causing the capital stock to grow, which feeds positively back into economic growth again. When exogenous shocks, such as changes in world market prices, or various policy measures, like tax increases, are entered into the model, new equilibria are calculated, and the results are compared to the reference scenario. Just like other country-specific CGE-models, EMEC can primarily be used to assess the effects of non-marginal policy or environmental impacts. This model type is particularly useful for analysis of policy measures that can be expected to affect or have repercussions in large parts of the economy. It is thus employed to compare and rank different policy options on the basis of, for instance, the lowest overall welfare cost to reach an emissions target (Swedish Environmental Protection Agency, 2012, p. 34–35).

In order to estimate the impact of policy options aimed at specific markets or sectors of society, whose repercussions in the rest of the economy is likely negligible, the Swedish government complements their use of EMEC with partial equilibrium (PE) and sector specific models. Of particular importance to its climate policy impact assessment is the energy system model TIMES-Nordic, which, in contrast to the highly aggregated design of a CGE-model, can represent the technical details of energy production. Following the optimization criteria dictated by EMEC, TIMES-Nordic is used to calculate the combination of existing and

5 Echoing Working Group III of the Intergovernmental Panel on Climate Change (2014, p. 58), the Swedish Energy Agency (2021, p. 6) has been keen to emphasize that their scenario analyzes are not meant to be predictive, but that their simulations are dependent on the conditions that have been assumed for each scenario and thus rather explorative in nature.

new facilities and energy flows that meet the specified energy needs at the lowest possible discounted cost to 2050, estimating the price and available supply of different types of energy. It is a bottom-up model that contains detailed descriptions of facilities and flows in the energy system, such as different types of power plants and fuels. Being so detailed, however, the model requires a lot of input data on, among other things, energy prices, energy needs, fuel quantities, and investment costs (Swedish Energy Agency, 2021). Since the resulting GHG emissions depend on the types of energy that cover the energy needs at the lowest cost, model results are highly contingent on assumed future energy costs.

Indeed, many inputs—like the expected rate of electrification in society, the impact of stricter requirements in the GHG reduction mandate, technology diffusion rates in the transport sector, and changed production costs for wind power—relate to situations far into the future and are subject to significant uncertainty. Prices of energy types are good examples of parameters that are given as inputs in TIMES-Nordic yet whose uncertainty greatly affects the model result. In fact, as administrators are keen to emphasize, the real challenge consists in including as many conceivable energy types and facilities as possible since they could unexpectedly become part of the optimal pathway. If, for instance, some unconventional policy measure was to be proposed by policymakers, or if, say, there would be falling investment costs due to disruptive innovation, this could result in sudden changes in energy prices. Some of the most important parameters, such as the costs of renewable electricity production technologies, are therefore also some of the most uncertain ones. Being a sector specific model though, TIMES-Nordic does not consider any economic effects outside the energy system, which means that the data must be fed back into a CGE-model in order to estimate the impacts on the domestic economy as a whole—and this is where the epistemic uncertainties in the Swedish government's integrated modeling-effort start to have a significant impact on the model results.

In order to make their scenario analyzes more relevant to climate policy impact assessment, administrators overwhelmingly agree that there is a need for increased integration and interpretation of model results. As they reiterate, it is not enough that the models and their basic functioning and frameworks are transparent to the user, as in the case of EMEC and TIMES-Nordic, whose detailed model descriptions are openly available. On the contrary, administrators would like to see more resources being put into improving the agencies own experiences in developing or at least professionally using numerical simulation models, not the least so that they can have a more sophisticated understanding of the inferential risks of the model choices, so as to make them more qualified to interpret the data. One such suggestion, with reference to the British government's strategy, is to support greater capabilities for in-house modeling. In contrast to their British counterparts, the Swedish administrative agencies outsource most of the modeling to consulting companies. As a result, there are no established forms for ongoing collaboration and cooperation between the agencies regarding the actual modeling. Furthermore, since consultants take care of the modeling, the models are at best weakly coupled, and so assessments from each of the agencies are relatively compartmentalized, without a clear working method or framework for how to weigh together results that have been calculated in different types of models and for different sectors of society. The Swedish Environmental Protection Agency (2022b, p. 3), for instance, emphasizes that:

> [...] more comprehensive work is needed with both quantitative and qualitative analyzes in collaboration between the relevant authorities[.] [...] The authorities should contribute their competences with the aim of achieving a long-term and deeper collaboration that results in more useful analyzes and data. The objective [...] should be to develop joint scenario methods to produce data and assessments of socioeconomic consequences that are requested by the government. [My translation].

Although the use of emissions scenarios in Sweden's action plan is governed by the European Parliament (2013) regulation on a common mechanism for monitoring and reporting GHG emissions, the Swedish Climate Policy Council (2020, p. 7, 19) similarly criticizes its government for the lack of a national coordination of the impact assessment process. Estimated impacts of policy measures on future emissions have not only been processed through a variety of distinct models but also presented in different units and formats, which, as the Climate Policy Council points out, makes it difficult to compare and assess the results.[6] Similarly, the Swedish National Audit Office (2019) recently recommended that the government clarify which areas of responsibility for scenarios that the various agencies have, including how scenarios for economy, traffic, and energy should inform each other.

Whilst several widely shared scenario assumptions regarding energy prices, carbon prices, GDP growth, population forecasts, and technological development have been applied to the overall assessment work, scenario analyzes of how net-zero emissions can be reached in different sectors have involved a plethora of agencies acting individually [Swedish Government Official Report (SOU), 2016, p. 168], each with their own informal rules for doing things. The Swedish Environmental Protection Agency, the Swedish Energy Agency, the Swedish National Institute of Economic Research, the Swedish Transport Administration, and the Swedish Board of Agriculture all develop target scenarios for different sectors, each with their own brand of model, ranging from the EMEC CGE-model and the TIMES-Nordic energy systems model to other sector specific ones like the agricultural SASM model, the HBEFA road transport emissions model, and the Heureka RegWise forest management model (Swedish Environmental Protection Agency, 2022b, p. 10–21). In this sense, the Swedish case of climate policy impact assessment matches the observations made by Braunreiter et al. (2023) in their study of model-based scenario analysis in the Swiss energy industry, in which they note that scenario use is rarely part of a formalized process. Navigating the myriad areas of expertise that are involved in drafting,

6 Echoing WG3 of the Intergovernmental Panel on Climate Change (2014, p. 58), the Swedish Energy Agency (2021, p. 6) has been keen to emphasize that their scenario analyzes are not meant to be predictive, but that their simulations are dependent on the conditions that have been assumed for each scenario and thus rather explorative in nature.

reviewing, and assessing Sweden's action plan, these processes of relevance-making are better described as distributed and emergent across information systems than in any sense centralized and premeditated. Since the integrated modeling-effort of the Swedish climate policy framework is compartmentalized in an informal network of sociotechnical connections, the relationships between these agencies are at least as important for configuring relevance as the models themselves. For instance, at the request of the Environmental Protection Agency, TIMES-Nordic is employed to calculate prices for electricity, district heating, and solid biofuels, which is then used by the National Institute for Economic Research in EMEC. Based on the result of EMEC, the Energy Agency then receives data from the National Institute for Economic Research on the value added for various industries. This information provides a basis for the Energy Agency's assessment of how much energy will be demanded by various industrial sectors and by the vehicle fleet. The Energy Agency also takes part in the Transport Administration's scenarios but makes its own assessments of the energy needs of the transport system. These numbers are then delivered back to the Environmental Protection Agency, where it is compiled and reported to policymakers.

Regarding the way in which data is processed in the computer-based simulations of low-carbon futures employed by these administrative agencies, one could do worse than to paraphrase the famous expression about regress and note, as Oreskes (2011, p. 103) does, "[…] that it is models all the way down." What Oreskes' (2011, p. 105) expression aptly captures is how the data employed in assessing the Swedish action plan is not simply collected; it is checked, filtered, and interpreted by numerical simulation models. The growth in GDP and the added value of various industrial branches that the EMEC puts out are for instance used as input to assess the energy demands of the Swedish industry and transport sector, which means that it feeds into, and significantly affects, the results from TIMES-Nordic and HBEFA. Since assessments of future energy demands are highly contingent upon the numerical input, this introduces uncertainties in the calculation of the models further down the line, which can lead to incorrect estimates of future GHG emissions in the final report. While it is commonly understood that net-zero transitions involve complex relationships playing out over long terms, which obviously makes them difficult to assess, the Swedish Scientific Council for Sustainable Development (2018) warns that the current, sociotechnical organization of Sweden's climate policy impact assessment makes them even more so. In other words, the manner in which the Swedish government's integrated modeling-effort is organized—or, rather, its lack of organization—is believed by these experts to amplify epistemic uncertainties.

5.1. Between robust policy options…

On the one hand then, to produce foresight knowledge of relevance to the action plan, agencies must make their models communicate with each other in such a way that they may collectively contribute to manage all this uncertainty. At the information systems-level of Swedish climate policy impact assessment, where emissions scenarios are simulated, this is less of an intentional and pre-planned activity than one of navigating an information ecology, working within the already existing conditions without thereby being completely determined by them. The dominant criterion for relevance can of course shift: it is only as permanent as the sociotechnical network of administrators and experts involved in climate policy impact assessment agree about its undisputed status. But no single actor can accomplish such a herculean task all alone. In order to participate in the process by which climate mitigation is shaped into a shared matter of political concern, these actors have to adapt to the wider information ecology of the impact assessment process.

The current conditions enacting a selective pressure on the way in which these administrators pursue model-based scenario analysis is by encouraging the production of foresight knowledge that can be used not only to estimate the costs of mitigation pathways, but even more importantly, to indicate the risks that the outcome of a policy option will differ from what is expected. Since they are based on different assumptions regarding future development within various sectors of the economy, emissions scenarios can at best indicate probable socioeconomic consequences of policy options. But such model results need to be interpreted, contextualized, and made subject to sensitivity analysis and plausibility assessment, and should not, therefore, be treated as forecasts. Rather, model results can contribute information about the order of magnitude and direction of relationships between various factors, as well as assist with analytical perspectives regarding dynamic effects and connections in the domestic economy. Model results can thus add valuable insights into the complexity of the structure that policymakers seek to manage, but they are not intended or suitable to be used directly as a basis for policy design.

In many ways, this reasoning resembles Dryzek (1983, p. 360–361) recommended replacement of optimization as the primary criterion for the design of policies with a stronger focus on "robustness," since "[…] a robust policy alternative is one expected to perform tolerably well across the whole range of scenarios given any one of the pertinent theoretical perspectives. […] Its main virtue is its invulnerability to the weaknesses in our understanding, and to unexpected changes in the environment of policy" (see also Lempert and Schlesinger, 2000; Hallegatte, 2009, p. 241–243). If a steadfast course toward low-carbon futures is to be kept, the action plan needs to be somewhat predictable in function while at the same time mitigating as much as possible against known unknowns. In the Swedish case, the importance attributed to the sensitivity of energy price parameters has gone hand in hand with the relevance ascribed to indications of how robust the performance of various policy options is to quantifiable risks. Swedish administrators consistently stress the importance of designing an action plan that can maintain a stable and predictable level of performance even in face of the many challenges to anticipation that a long-term, nation-wide transition involves. Since changing environmental, social, technological, and economic conditions may suddenly alter the costs associated with emission reductions, and thereby the incentives that may need to be implemented and maintained, it is crucial to reduce the price risk of decarbonization. Designing for the ability of Sweden's net-zero transition to remain on course in a world that is rapidly changing, administrators are working within information ecosystems where they are encouraged to assist in identifying policy options whose performance is maximally robust to price risks.

Because of increased climate ambitions at the EU-level, however, administrators believe that the demand for sector-wide analyzes, with high levels of detail, will only grow. In the EU's new "Fit for 55"-package, land use in agriculture and forestry are important areas for domestic policy measures (Swedish Environmental Protection Agency, 2021). Due to the aggregated design of EMEC, price changes within these sectors are difficult to assess in a robust fashion. An acknowledgment of this can be found in the Swedish National Institute of Economic Research's (2021, p. 65) latest environmental economic report, where the authors note that:

> EMEC captures flows of forest biomass used in energy production, and the biogenic carbon dioxide emissions resulting from biomass combustion. Other than that, the carbon balances in the LULUCF-sector are not represented. Land is not represented as a finite resource in the model, and uptake and storage of carbon in living biomass is not accounted for. [...] It means that there is a strong limitation on the types of questions that can be answered by the model, which is especially problematic with regard to the need for assessments of how Sweden can fulfill its obligation in the LULUCF-sector. [My translation].

Increased integration, primarily by stronger model coupling, is thus identified by administrators as paramount to ensure that the foresight knowledge produced by these models is relevant to climate policymaking.

5.2 ...And resilient policy design

On the other hand, a much too uniform and homogenous information ecology is undesirable as it makes the integrated assessment process rigid, leaving it unable to deal with changes to values as opposed to changes to knowledge. Pressures toward robustness may for instance entrench the longevity and continuance of policies that favor incremental processes at the expense of large-scale changes. Although the above-mentioned efforts at improving robustness ensure that the action plan and the policies it embodies remain adapted to anticipatable risks, such an action plan may quickly become obsolete if it proves unable to respond to events that cannot so easily be anticipated by extrapolating from existing data. In its scrutiny of the government's first action plan from 2019, the Swedish Climate Policy Council (2020, p. 35–36, 46) identified the lack of an explicitly normative vision about how to become the world's first fossil-free welfare country as one of its most serious deficiencies, especially in light of Sweden's so-called generation goal, which has been formulated with the intent of providing "[...] guidance regarding the values that are to be protected and the changes in society that are needed if the desired quality of the environment is to be achieved" [Swedish Environmental Protection Agency, 2022a, p. 5]. Summarizing this as a disregard for the social drivers of net-zero transitions, the Swedish Climate Policy Council (2020, p. 30–31, 60) warned that the action plan relied much too one-sidedly on robust price estimations, to the detriment of changes to social values. Although estimating and reporting the economic costs of emissions was acknowledged to be a necessary condition for successful climate policy, the Swedish Climate Policy Council (2020, p. 48–49, 78) argued that it was not sufficient. Instead, it called for supplementary indicators to assess net-zero transitions as processes of parallel and interconnected changes to not only business models and technologies but behaviors and norms too (Lidskog and Sundqvist, 2022, p. 9–10).

A similar concern about the failure of imagination in Sweden's action plan, demonstrated by its negligence in addressing the social drivers of net-zero transitions, is expressed in Swedish Environmental Protection Agency (2019b) review of the National Institute for Economic Research's scenario analyzes of the transport sector. The Environmental Protection Agency points out that results from EMEC will be skewed by the model's inability to take disruptive innovation and changes in cultural norms and attitudes into account, which, the agency argues, risks severely limiting the government's vision on how Sweden's net-zero transition could take place. In fact, this concern even found its way into a government investigation under the Ministry of Climate and Enterprise [Swedish Government Official Report (SOU), 2016, p. 166], where the administrators noted that most of the Swedish emissions scenarios assume that today's economic and political relationships and trends will persist well into the future, and that the populace's values and behaviors will remain unchanged, with the exception that new technology is assumed to automatically gain acceptance and taken up without much further ado. A prominent attitude among administrators is thus that the social drivers of net-zero transitions need to be given, if not as much attention as economic and technological drivers, then at least more than is now the case.

Claims like these are made primarily from an output-oriented point of view, namely, that model parameterizations relying on excessively narrow definitions of feasibility simplify the complexities of net-zero transitions to an unhelpful degree and, as Riahi et al. (2015, p. 19) have warned, may thereby end up producing false expectations and sub-optimal results. As an example, modeling the Swedish energy system, TIMES-Nordic is more suited to reflect certain types of policy measures than others, and the impact of some options is therefore poorly represented—or, in some cases, not represented at all—when the Energy Agency's scenarios for energy supply and emissions are developed. If policy options that are poorly represented in models should turn out to be decisive for the Swedish net-zero transition, such oversights will introduce additional uncertainties into the model results. As investments into for instance wind power—which has variable electricity production, energy storage, and demand flexibility—become more pressing in the near term, it becomes increasingly important to also employ energy models with a more detailed time-division than TIMES-Nordic.

The problem, as Bankes (1993, p. 437) famously put it, is that there is "[...] a strong tendency to model in detail phenomena for which good models can be constructed and to ignore phenomena that are difficult to model, producing a systematic bias in the results [by] [...] emphasiz[ing] the aspects of a problem that can be best simulated." Since Sweden's climate policy design and assessment process is to a significant degree informed precisely by model-based scenario analysis, it is particularly sensitive to dominant assumptions about the feasibility of mitigation pathways that figure in the development of emissions scenarios, including the choice of parameters when formalizing assessments of feasibility into functionable models amenable to computer-based simulation (Low and Schäfer, 2020). Consumption, lifestyle changes, alternative growth paradigms, food and water security, and impacts on biodiversity are examples of parameters that have been reported by experts as at best severely underrepresented, and at worst absent, because of formal abstractions in modeling (Pedersen et al., 2022, p. 8). To ensure that models do not systematically underestimate facets of feasibility that are difficult to resolve within cost-optimization equations, or for which there is a lack input data to reliably do so (Tavoni and Valente, 2022), it is important that agencies actively reflect upon the inferential risks in encoding qualitative conceptions about net-zero transitions into quantifiable scenarios—which, at least in the Swedish case, they in fact do.

As a result, some administrators make the same claim but for reasons of input legitimacy, emphasizing how inclusive deliberations about feasibility are decisive for recognizing a diversity of values and enrolling stakeholders in such a way that they can articulate them in all their plurality. In 2016, the Swedish National Audit Office commissioned a report on the integrated model-efforts of Swedish climate policy impact assessment (Copenhagen Economics, 2016). Estimates of the economic consequences of climate goals, the National Audit Office noted, vary greatly between different scenarios; the projected cost of reducing emissions is highly dependent on scenario assumptions; narrow choices around the parameters to include in the models limit the measures available to reduce emissions; and the rate at which the measures can be implemented is sensitive to the values of those parameters. In fact, the Swedish National Audit Office (2013) had reviewed the use of scenarios in climate policy impact assessment three years prior and pointed out that, while EMEC is an important tool for producing foresight knowledge, this model alone, even if run in tandem with PE and sector specific models, cannot give sufficient clarity to the kind of questions that need to be explored in the event of major climate impacts. Instead, the National Audit Office recommended that results from EMEC regularly be supplemented with more detailed sociotechnical transition analyzes of the energy and transport sector, with expert elicitations about what measurements are needed to fulfill long-term climate goals at a reasonable cost, as well as with stakeholder participation in articulating Sweden's generation goal. In other words, since the choice of model specifications has consequences for policy, the sheer underrepresentation of social drivers in models will indirectly sideline policy options addressing aspects like consumer behavior and norms. It is the way in which the simulation of emissions scenarios shapes social expectations in real time that some sociologists have sought to highlight by attending to the performative dimension of modeling: model specifications frame the way in which policy is led to intervene into the modeled system by orienting users toward an actionable future (Beck and Mahony, 2018; Beck and Oomen, 2021).

To make the identification of robust policy options into the sole criterion of relevance would thus constitute a significant shortcoming in the Swedish climate policy impact assessment. Relying on models calibrated to measure outcome may overlook other values tied to the impact assessment process, such as how the cultivation of value disagreement with the help of sociotechnical transition analysis or expert elicitation may improve policymakers' insights about possible blind spots in the action plan, and in effect the agility of the action plan to adapt if foundational assumptions should turn out to have been implausible. Prominent economists such as Stern (2008, p. 11) have for instance warned about an overestimation of the role of abatement cost curves in policymaking concerning "[...] major strategic decisions for the world as a whole, with huge dynamic uncertainties and feedbacks." While risk assessments are an improvement upon cost-optimization methods, the foresight knowledge foregrounded by such indicators is still insufficient when we are faced with the wickedness of a changing climate, where the conditions for which these probabilities have been calculated may suddenly no longer apply (Weitzman, 2009; Pindyck, 2013).

Hence, if robustness denotes an insensitivity to quantifiable risks, then some administrators have put this measure of relevance into question by contrasting it with so-called resilient policy design, which refers rather to a preparedness for sudden punctuations that the quantification of risk, extrapolating from historical trends of incremental change, cannot aid in mapping out. The Swedish Environmental Protection Agency (2022b, p. 45) is explicit about this challenge:

> Existing models (both in Sweden and in other countries) in many cases lack the ability to analyze challenges and opportunities for a large-scale societal transformation, that is, analyzes of major shifts in, for instance, technology, norms, and behavior, as well as changes in how society is organized. Such transformative change stands in contrast to the linear, incremental, and stepwise change that proceeds from the prevailing social structures, which existing models have been developed to assess. We are aware that it will be very difficult—perhaps impossible—to describe and analyze transformative change through numerical simulation modeling. In many cases, these are changes that have not yet been observed, cannot be extrapolated from past conditions, and are insufficiently explored to be quantified in a way that can be used in models. [My translation].

A point of contention in the Swedish case is thus whether indicators ought to estimate future risks from trends, which requires the use of a consistent set of parameters with data rich enough to assess likelihoods, or whether they ought rather to diversify the parameters used, explicitly aiming to account for the contingency of the future.

6. Conclusions and discussion: sociotechnical information systems as sites for reciprocal capture

In the case of the Swedish climate policy framework, robustness has inspired administrators and seems to have become a guiding criterion for governing the complexity associated with climate change, directly factoring into impact assessment. Due to the ill-defined solution space that encompasses the collective action of climate change mitigation, administrators are faced with the challenge of uncertain linkages between policy measures and outcomes. This interest in robustness derives from an experience of increasing complexity, and from a growing recognition of the importance of measures that can mitigate against quantifiable risk. For administrators, this criterion is also consistent with those commonly used to manage other situations that cannot be forecast with certainty and have already been applied in many long-term planning contexts, such as that of water management (e.g., Dessai and Hulme, 2007; Groves and Lempert, 2007).

As we have seen, the models at administrators' disposal are incredibly powerful in shaping their collective matter of political concern into that of economic growth and efficiency. But while performance indicators, concerned with output legitimacy and to demonstrate the cost-effectiveness of policies (Scharpf, 1999, p. 16–28), have enacted key functions in Swedish climate policy impact assessment, their power has not gone unchallenged. While scenarios make available certain affordances at the expense of others (Beck and Oomen, 2021), the translation of qualitative conceptions about feasible mitigation pathways into a set of quantitative parameters and numerical model inputs is never indisputable (Alcamo, 2008, p. 143). Even though they provide the scientific basis for impact assessment, these measured quantities do not speak for themselves. Some administrators, including experts in the Swedish Climate Policy Council, have challenged the authority of robustness, emphasizing instead the value of resilient policy design as a potentially conflicting criterion for producing foresight knowledge of relevance to climate policymaking. What we know about climate change, these administrators and experts agree, is alarming enough, but what we do not know about the extreme risks could be far worse. As the burning of fossil fuels fills the carbon stock of the climate system to points of possible tipping, what we face is climate instability and disruption of everyday life. In other words, there is no means, no average, no return to normal—it is a one-way traffic into the unknown. While economic parameters that measure incremental changes to fuel prices and GDP feed perfectly into indicators like emissions abatement costs and policy measures such as carbon pricing, it risks institutionalizing a gradualism in responding to climate change that is entirely out of touch with the severity of the situation.

When it comes to relevance-making in Swedish impact assessment, the dialectical relationship between data and models thus highlights the need for attending to the sociotechnical systems through which the production of foresight knowledge takes place (Zimmerman, 2008). When enrolled in exploring, supporting, and legitimizing mitigation pathways, emissions scenarios are held in place by matrixes of administrative concerns, managerial boundary judgments, and technical practices, with the involved data being the result of constant interpretation. It means foregrounding the often-invisible practices of information system management, "[…] from sampling design choices to data collection methodologies, from calibration issues to quality assessments, from analysis algorithms to data presentations, from conceptual mappings to knowledge synthesis. From the diverse flows of information, forms of knowledge, and interrelationships between them, the view of an information ecology as an open system arises" (Baker and Bowker, 2007, p. 141). As foresight knowledge is produced through practices of numerical simulation modeling, its relevance is given meaning through the context and framing provided by these simulations, as well as through the way in which the flow of data through models makes agencies link up with each other in sociotechnical networks.

Such sociotechnical dynamics are expressed in ongoing boundary-work (Baker and Bowker, 2007, p. 137–138). As the case of Swedish climate policymaking demonstrates, the relevance of the foresight knowledge produced reflects the joint ability of models to give expression to a common set of indicators. Since it creates an exploitable space for differing interpretations in the quantification process, conceptual ambivalence within models can therefore be a threat to indicator validity. Indeed, the power of an indicator to overcome the polysemy of language is only ever as lasting as the network of actors engaged in the quantification process is held together by a consensus about its validity. In fact, the output of a model may very well be reliable, yet its policy-relevance contended on grounds that it has failed to evaluate the feasibility of net-zero transitions in a valid manner. To use Klenk and Meehan (2015) words, the "integration imperative" in Swedish climate policy impact assessment will not necessarily lead to a widened perspective for policymakers on the feasibility of mitigation pathways. Different indicators can be bound up with competing configurations of policy-relevance, and thereby also be contingent upon incompatible forms for sociotechnically organizing the government's integrated modeling-effort. Increased integration through stronger model coupling may for instance be a sound strategy for improving the robustness of policy options to quantifiable risks, useful for estimating the sensitivity of various sectors of the economy to price risks on fuels (Swedish Energy Agency, 2014; Swedish Environmental Protection Agency, 2015). However, such a strategy may not only be less useful but even outright detrimental to the ability of the Swedish action plan to address transformative change to cultural norms and behavior, simply because criteria for policy-relevance are configured by the organizational shape of the entire network of agencies. Even though indicator validity may be a question of potential controversy, there is an inertia to the network in the sense that the struggle between competing configurations of policy-relevance is as much of a social and technical as it is of a conceptual nature. These boundaries are not so easily drawn by any one agency, and they are not drawn exclusively in the heads of humans, but at least as much in technical inscriptions like parameters and model inputs, inscriptions that together constitute the information ecology within which these agencies can act.

Contrast this to the literature on the science-policy interface of integrated assessment, where dominant understandings of policy-relevance have tended to rely on an overly mechanistic notion of how scientific knowledge is organized and evaluated, one that assumes that all significant value judgments can be deferred to policymakers until after a select amount of feasible mitigation pathways has already been mapped out. Most proposals on the table for reforming integrated assessments of climate change draw inspiration from, and usually try to emulate, the ideal conditions of a deliberative model of scientific expertise. They involve changing formal rules and procedures to promote capacity building regarding devices, methods, and skills for integration and synthesis, or by coupling institutions to each other, such as by facilitating direct interaction between modelers and policymakers (Hulme et al., 2010; Edenhofer and Kowarsch, 2015; Kowarsch et al., 2017). While institutional rules and procedures can shape prospects for configuring policy-relevance, deliberative forums are ill-equipped to address how key indicators for political action are institutionalized through the choice and use of model parameters (Havstad and Brown, 2017, p. 108–115). Looking at the complexities of integrated modeling-efforts, and the ways in which these complexities interact with issues of outcome and assessment demarcation, it seems highly unlikely that the proper dimension on which to represent the feasibility of mitigation pathways can be determined without a thoroughly pragmatist interrogation of not only the "ends-in-view" (Kowarsch and Edenhofer, 2016, p. 302) but also the interdependency of means with these ends.

There is thus a need for an expanded understanding of policy-relevance, beyond institutional approaches and toward a process-based point of view, treating relevance as something in-the-making, whereby ongoing assessment demarcation on an information systems-level is at least as fundamental as the map of mitigation pathways that serves as the end-product of the assessment process (Aitsi-Selmi et al., 2016, p. 5–6). Emissions scenarios are important objects in this boundary-work. In the scenario analyzes of Swedish administrative agencies, there is a lack of agreed-upon standards for climate policy impact assessment (Swedish Climate Policy Council, 2020, p. 42–43), forcing these agencies to improvise.[7] By homing in on this balance between order and disorder, making the emergence of standardized forms of evaluation through scenario analysis into an object of study, we must consider how dilemmas of complexity and ambiguity in modeled representations of low-carbon futures are handled at the science-policy interface, such as the narrowing down of feasibility that indicators implicitly perform in assessing pathways toward net-zero emissions, or how the availability of the means to model certain dimensions of feasibility shapes the possible problem-solving conditions and determinants of success, such as through the choice and use of model parameters.

Such a change of perspective alters how sociotechnical interfaces in processes of integrated assessments are approached, treating model-based scenario analysis neither as the production of facts that can then inform value-based deliberations, as if scenarios merely communicate expertise about the means required to achieve a given set of ends, nor as an ideologically supported exercise of power on an unreliable basis of legitimation,[8] as if scenarios function exclusively as inscriptions of non-epistemic values, but rather as sociotechnical practices through which facts and values are simultaneously negotiated by administrators through the pragmatic navigation of their information ecology. Borrowing an expression from Stengers (2010, p. 42), these practices, from a process-based perspective on relevance-making, are better understood as giving rise to events of "reciprocal capture." To recognize sociotechnical information systems as sites for reciprocal capture is to assert that the configuration of policy-relevance that takes place at an information systems-level cannot be addressed by means of novel deliberative designs alone. On the contrary, a reciprocal capture emerges through a process of mutual interaction and is not engineered by one individual or group. Unlike institutional reform, information system-based boundary-work around processes for producing foresight knowledge involves diverse activities whose criteria for relevance emerge in the midst of those same activities. Rather than assume that scenario analysis can provide a range of different mitigation pathways given certain objectives and values, and then simply defer the decision between them to policymakers, this case study supports viewing the sociotechnical information systems that undergird the integrated assessment processes of Swedish climate policymaking through an ecological lens. Doing so points to the limitations of treating policy-relevance as the outcome of a sequential procedure, emphasizing instead the nonlinear and emergent nature of relevance-making.

7 In fact, historians of technology, such as Hughes (1989), have argued that a significant degree of flexibility is a necessary condition for the smooth function of large technical systems (LTS), whose development and maintenance over time requires the crisscrossing and renegotiation of boundaries.

8 What Pielke (2007, p. 3 *et passim*) refers to as "stealth issue advocacy."

Data availability statement

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

Ethics statement

Ethical approval was not required for the studies involving humans, because the information collected is not considered sensitive. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

JDA conceptualized and designed the study, collected the empirics, performed the subsequent analysis, wrote all of the sections of the manuscript, and also took care of manuscript revision, read, and approved the submitted version.

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Conflict of interest

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

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Balancing climate goals and biodiversity protection: legal implications of the 30x30 target for land-based carbon removal

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This article examines the legal conflicts between land-based carbon dioxide removal (CDR) strategies and the establishment of protected areas through the lens of international environmental law. We argue that the 2022 Global Biodiversity Framework's "30x30" target—which aims to protect 30% of global terrestrial and marine areas by 2030—constitutes a "subsequent agreement" under international law and thus clarifies the legal scope and content of the obligation to establish protected areas under Article 8 of the Convention on Biological Diversity (CBD). Since states have pledged 120 million square kilometers for land-based CDR, these commitments potentially conflict with the "30x30" target, especially if global cropland for food production is to be maintained. Consequently, some land-based CDR strategies may directly or indirectly impede the achievement of the "30x30" target, which could be deemed inconsistent with international law. However, as all international environmental law operates in a continuum, this does not imply that land-based CDR should be categorically ruled out. Rather, states should focus on emission reductions and implementing CDR options that provide the most co-benefits to climate mitigation and biodiversity protection efforts.

KEYWORDS

carbon dioxide removal (CDR), land-use, biodiversity protection, international law, protected area, Convention on Biological Diversity (CBD), Paris Agreement

Introduction

The adoption of the Kunming-Montreal Global Biodiversity Framework (GBF) in December 2022 marked a crucial milestone in the global effort to combat and reverse biodiversity loss. At the heart of this framework lies the ambitious "30x30" target, aiming to safeguard 30% of the world's terrestrial and marine areas by 2030 (CBD COP, 2022). Historically, parties to the Convention on Biological Diversity (CBD) have been unable to stop the rapid degradation of ecosystems around the world, as evidenced by the failure of the two previous biodiversity frameworks (CBD COP, 2002, 2010a; CBD Secretariat, 2020; Xu et al., 2021). Nevertheless, *in-situ* conservation measures, such as the establishment and maintenance of protected areas under Article 8 CBD, have remained high on the agenda of many policymakers concerned with biodiversity loss. The pursuit of the "30x30" target, however, gives rise to potential conflicts with land-based carbon dioxide removal (CDR) strategies employed by countries to achieve net-zero emissions.

In recent years, CDR approaches—which are also known as negative emission technologies (NETs)—have garnered much attention, as many countries plan to use them to achieve their declared net-zero goals (Schenuit et al., 2021; Hale et al., 2022; Jacobs et al., 2023; Smith et al., 2023). Yet, the literature has disputed their effectiveness in mitigating climate change, since the mitigation effects of CDR policies such as afforestation are sometimes overestimated (Markusson et al., 2018; McLaren, 2020; Grant et al., 2021a; Stubenrauch et al., 2022; Carton et al., 2023; McLaren et al., 2023). Currently, 99.9% of all carbon removals come from conventional land-based approaches (Powis et al., 2023; Smith et al., 2023). Some land-based CDR policies have the potential to provide multiple benefits, including mitigating climate change, restoring degraded ecosystems, and enhancing biodiversity (Daggash and Mac Dowell, 2019; Hilaire et al., 2019; Moomaw et al., 2019; Realmonte et al., 2019; Yang et al., 2019; Ekardt et al., 2020; Janssens et al., 2022; Stubenrauch et al., 2022). In practice, however, many land-based CDR approaches negatively impact ecosystems through land-use change and monoculture agriculture (Powell and Lenton, 2013; Stoy et al., 2018; Dooley et al., 2020; Tudge et al., 2021; Hanssen et al., 2022; Stubenrauch et al., 2022). Nevertheless, governments have pledged to dedicate 120 million square kilometers (Mkm^2) of land for land-based CDR, which is equivalent to the current extent of global cropland (Dooley et al., 2022). Given the fact that safe and just planetary boundaries on land use have already been exceeded due to the rapid expansion of land used for food production (Steffen et al., 2015, 2018; Rockström et al., 2023), it appears near certain that there are land availability constraints on the competing land-use approaches.

By applying an international legal perspective, this article aims to enhance the scholarly debate on conflicting land-use commitments and legal consequences for both biodiversity and climate law and governance. While there has been considerable research on the natural science and economic phenomenon of land use, land-use change, and land degradation resulting from competing commitments by countries to use land (Powell and Lenton, 2013; Dooley and Kartha, 2018; Dooley et al., 2018, 2020; Stoy et al., 2018; Creutzig et al., 2021), there has been little research on the legal rules relevant to this conflict (for exceptions, see Hennig, 2017; Stubenrauch et al., 2022). Thus, the article fills this research gap by addressing two key questions: First, how are the overlapping and competing commitments to land-based CDR and the establishment of protected areas viewed in light of the relevant rules of international environmental law? Second, can these rules help to reconcile the competing land-use approaches by balancing the related rights and obligations of the states involved?

Methodology and materials

Legal interpretation as methodology

Methodologically, this article employs a two-step approach to examine the conflicts arising from land-based CDR policies and the establishment of protected areas for biodiversity conservation. In the first step, we conduct a review of the relevant literature on land-based CDR strategies and protected areas policies. This review critically assesses the proven effectiveness, or lack thereof, of the land-use approaches in question and highlights the trade-offs associated with each policy. In addition, the scientific literature on current and projected land-use policies will be analyzed to determine whether there are in fact competing land-use claims or whether there is a projected physical shortage of land.

In the second step, we undertake a legal interpretation of the pertinent international environmental law. The analysis centers on the interpretation of international legal treaties and frameworks such as the UNFCCC, the PA, the CBD, and the GBF. It does so by relying on the traditional principles of interpretation as set out in Articles 31 and 32 VCLT (Dörr and Schmalenbach, 2012; Dörr, 2018), which include grammatical, systematic, teleological, and historical interpretation. This legal interpretation involves consideration of the relevant treaty provisions, their interrelationship, their genesis, their underlying purposes, as well as supplementary material (Ekardt et al., 2018b, 2022; Ekardt, 2020; Günther and Ekardt, 2022, 2023), in particular with respect to the issue of adverse environmental effects caused by intensive land use and land-use change. In common law countries, case law is typically used as an additional means of interpretation. However, we will not use this method of interpretation here, as there are no relevant cases or judgments on the specific issues at hand. By applying this methodology, the article aims to provide comprehensive insights into the conflicts between land-based CDR strategies and protected area policies, thereby linking the natural-scientific and legal dimensions of the issue.

Dual crises: climate change and biodiversity loss

Climate change, the Paris Agreement, and mitigation measures

In its recent AR6 Synthesis Report, the IPCC has stated that, given the slow progress in reducing emissions, "there is a rapidly closing window of opportunity to secure a livable and sustainable future for all" (IPCC, 2023, p. 53). It is highly likely that the 1.5°C limit set out in Article 2 para. 1 lit. a PA will be exceeded in the coming decades. Moreover, under a very high emissions scenario (SSP5-8.5), the average temperature may rise to 4.4°C by 2100 (IPCC, 2023). Such an increase in temperatures would endanger the sustained existence of the elementary preconditions of freedom—the basis for all human rights—as well as the likelihood of human civilization persisting as we know it.

Although states adopted the PA in 2015 in order to address the "wicked problem" (Lazarus, 2009; Levin et al., 2012; Incropera, 2016) of ever-accelerating climate change, the last decade has seen a net increase in GHG emissions (IPCC, 2022b). As the climate crisis continues to worsen (Armstrong McKay et al., 2022; Romanello et al., 2022; IPCC, 2023; Thompson et al., 2023), states are seeking complementary solutions (in addition to emission reductions) to achieve the temperature objectives under Article 2 para. 1 lit. a PA. In recent years, CDR approaches have gained popularity among decision-makers and academics as measures to complement emission reductions. There are several closely-linked reasons for this. First, they promise to offset residual emissions in sectors that are difficult to decarbonize, such as cement, steel, and chemicals (Luderer et al., 2018; Buck et al., 2023). Second, their large-scale deployment may help reduce atmospheric CO_2 levels and thus slow global warming (Gasser et al., 2015; Fawzy et al., 2020), although their feasibility in this regard has yet to be proven on a large scale (Anderson and Peters, 2016; Fuss et al., 2018; Hansen and Kharecha, 2018; Heck et al., 2018; Bednar et al., 2019; Grant et al., 2021b). Third, removals are crucial for countries to achieve net-negative emission targets in the long term (Allen et al., 2022; Smith et al., 2023, p. 9). Fourth, and most controversially, these approaches may be particularly attractive to those countries or companies that have relied on fossil fuels and see these technologies as a potential way to postpone their decarbonization efforts (Anderson and Peters, 2016; McLaren, 2020; Sands and Cook, 2021; Carton et al., 2023). However, a distinction must also be drawn here between the various CDR approaches, as some are better suited to advancing the aforementioned mitigation objectives, while others are more likely to lead to mitigation deterrence and carbon lock-in (Asayama, 2021; Strefler et al., 2021).

All CDR approaches (in contrast to solar radiation management) attempt to capture CO_2 or other GHGs from the atmosphere and store them for the long term. The IPCC defines CDR as:

> Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities (IPCC, 2021 p. 2,221).

In this context, it is important to distinguish CDR from other related approaches, such as carbon capture and utilization (CCU) and carbon capture and storage (CCS), as they share common technical elements but differ in their ability to achieve permanent net removals of CO_2 (Schenuit et al., 2022, 2023; Smith et al., 2023). There are also different ways of distinguishing between CDR methods—for example, between engineered and nature-based removals (Low et al., 2022). For the purposes of this article, we will focus on conventional land-based CDR activities, which include, *inter alia*, the following approaches: afforestation/reforestation, bioenergy with carbon capture and storage (BECCS), peatland management, biochar, carbon farming, and soil carbon sequestration (Lenton, 2010; Brack and King, 2020; Ekardt et al., 2020; Stubenrauch et al., 2022; Smith et al., 2023). Although Direct Air Carbon Capture and Storage (DACCS) may require a significant amount of freshwater (Realmonte et al., 2019), it does not necessitate large areas of land (Madhu et al., 2021; Ozkan et al., 2022). Therefore, we will not categorize it as a land-based approach to CDR.

Conventional land-based CDR approaches are notable in that they currently account for ~99.9% of all carbon removals (Powis et al., 2023; Smith et al., 2023). The majority of these activities come from afforestation/reforestation and other forestry activities. To date, these CDR activities are responsible for sequestering around 2,000 $MtCO_2$ per year—excluding BECCS and biochar, which account for only 1.82 $MtCO_2$ and 0.5 $MtCO_2$, respectively (Smith et al., 2023). Countries have already committed in their nationally determined contributions (NDCs) to deploy additional CDR activities in the range of 100–650 $MtCO_2$ annually by 2030 (Smith et al., 2023). However, these plans are likely to be insufficient if countries aim to limit global warming to 1.5 or 2°C as required by Article 2 para. 1 lit. a PA.

Current CDR deployment numbers stand in stark contrast to the weight given to CDR as a mitigation policy by integrated assessment models (IAMs). Virtually all scenarios consistent with the PA's net-zero goal rely to some extent on CDR (IPCC, 2022b). Between 2020 and 2100, some IAM scenarios predict that between 450,000 and 1,100,000 $MtCO_2$ will be cumulatively removed through CDR (IPCC, 2022b). Although conventional land-based CDR is expected to account for almost all removals by 2030 (Powis et al., 2023), it should be emphasized that many scenarios prefer BECCS as the most important CDR measure—especially in the second half of the century. According to a scenario in a recent IPCC report, BECCS is projected to be responsible for almost 50% of all CDR activities by 2100, with a cumulative total of 334,000 $MtCO_2$ by 2100 (IPCC, 2022b). Considering a temporary overshoot, this figure increases to 464,000 $MtCO_2$ (IPCC, 2022b). However, all IAM projections should be interpreted cautiously—especially regarding BECCS—since they are skewed toward cost-optimal mitigation solutions and use high discount rates (Gambhir et al., 2019; Köberle, 2019; Butnar et al., 2020; Ekardt et al., 2022). As a result of their susceptibility to various biases and their key set of incomplete assumptions, some academics have begun to question the importance of IAMs in determining countries' mitigation strategies (Low and Schäfer, 2020; Keppo et al., 2021; Hollnaicher, 2022; Rubiano Rivadeneira and Carton, 2022). This is particularly relevant in the case of CDR deployment, as the predicted removal rates of the different approaches would lead to a number of adverse effects, which we will highlight below.

Land-based CDR strategies have been scrutinized because their large-scale deployment would require significant land-use changes (Smith et al., 2016, 2019; Fuss et al., 2018; IPBES, 2019; Dooley et al., 2020; Honegger et al., 2021b). This in turn would result in further biodiversity loss and could exacerbate competition for land used for food crops (IPBES, 2019; Reid et al., 2020; Gvein et al., 2023). For example, a mitigation strategy that relies primarily on BECCS could theoretically be equal to or worse for certain ecosystems and species than the projected impacts of climate change under business-as-usual scenarios (Meller et al., 2015; Williamson, 2016; Hof et al., 2018). Similarly, large-scale forest plantations are also detrimental to biodiversity if they are managed as monocultures, as most afforestation projects currently are (Bonner et al., 2013; Hua et al., 2016; Stubenrauch et al., 2022).

It is important to note, however, that under certain conditions, land-based CDR activities can also be beneficial for biodiversity (Maljean-Dubois and Wemaëre, 2017; Smith et al., 2019; Nunez et al., 2020). Several studies have shown that the rewetting of peatlands, the restoration of degraded ecosystems, and the protection of existing primary forests are essential for the protection of biodiversity and provide substantial carbon sinks (Mackey et al., 2020; Stubenrauch et al., 2022; Gvein et al., 2023). Consequently, ecosystem-based approaches to CDR that focus on the conservation of existing forests and peatlands could overcome the perceived trade-offs between land-use pressures, climate mitigation policies, and biodiversity protection (Mackey et al., 2015; Stubenrauch et al., 2022). Nevertheless, the mitigation potential of ecosystem restoration is also limited by time constraints and by overestimation of its potential, and therefore cannot be utilized to reduce global peak temperatures (Littleton et al., 2021; Dooley et al., 2022). Drastic emission reductions in all sectors, specifically the drawdown of fossil fuels and the minimization of livestock farming, cannot be replaced by any type of CDR policy if countries wish to achieve a scenario consistent with the PA's 1.5°C limit (Ekardt et al., 2018b, 2022; Wieding et al., 2020).

Biodiversity loss, protected areas, and the Global Biodiversity Framework

Global biodiversity loss is occurring at an unprecedented rate. According to the 2019 IPBES's Global Assessment Report on Biodiversity and Ecosystem Services,

> human actions threaten more species with global extinction now than ever before. [...] Globally, local varieties and breeds of domesticated plants and animals are disappearing. This loss of diversity, including genetic diversity, poses a serious risk to global food security by undermining the resilience of many agricultural systems to threats such as pests, pathogens and climate change (IPBES, 2019, p. 10–11).

While several factors have contributed to biodiversity loss, land-use change and related land degradation are the dominant drivers (IPBES, 2019; Dooley et al., 2022). With more than 70% of the Earth's land surface significantly altered, and about 66% of the ocean surface experiencing increasing impacts (IPCC, 2019), the wellbeing of at least 3.2 billion people is already being adversely affected (IPBES, 2018). Of particular concern is the loss of over 85% of all wetlands, along with the disappearance of half of the previously existing forests and coral reefs since the 1870's (IPBES, 2018). All of these effects are strongly linked to agriculture and to a large extent driven by livestock production, as about 75% of the world's agricultural land is used directly or indirectly for livestock production (Ekardt et al., 2023). In addition, factors driven by or related to fossil fuels play an important role. This is the case, for example, with urbanization and expanding infrastructure. Climate change is another driver of global nature change, again fueled by fossil fuels and livestock, and it is increasingly exacerbating other drivers.

Besides addressing the drivers mentioned above, *in-situ* conservation is one of the most important strategies to combat biodiversity loss, as recognized in the CBD's preamble. According to Article 2 para. 13 CBD, *in-situ* conservation

> means the conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings and, in the case of domesticated or cultivated species, in the surroundings where they have developed their distinctive properties.

In short, *in-situ* conservation involves the preservation of biodiversity in the very habitats where organisms reside and interact with their surroundings. One of the primary ways of promoting *in-situ* conservation is through the establishment and maintenance of protected areas—such as national parks or biosphere reserves (Wolfrum, 2004; Jenkins and Joppa, 2009; Watson et al., 2014; Sands and Peel, 2018; Markus, 2022). Accordingly, Article 8 lit. a CBD stipulates that the contracting parties should "establish a system of protected areas or areas where special measures need to be taken to conserve biological diversity." Pursuant to Article 2 para. 14 CBD, a protected area "means a geographically defined area which is designated or regulated and managed to achieve specific conservation objectives." The establishment and maintenance of networks of protected areas ensures the conservation of highly valuable ecosystems and representative populations of significant species while also providing refuge from invasive alien species (Thomas and Gillingham, 2015; Gallardo et al., 2017). This also means that these protected areas should not be used for intensive agricultural or industrial purposes that could pose a significant threat to biodiversity.

Since the adoption of the CBD in 1993, there has been a steady increase in protected areas around the globe. As of 2023, protected areas cover ∼16% of the world's terrestrial area and 8% of the world's marine area (Gurney et al., 2023). Although the parties to the CBD adopted the Aichi Targets in 2010, setting themselves the (legally non-binding) goal of establishing protected areas on 17% of terrestrial and 11% of marine areas (CBD COP, 2010b), the literature generally agrees that countries have made substantial progress regarding protected areas – if recent commitments are taken into account (SBSTTA, 2021). However, many recently designated protected areas lack connectivity and are sub-optimally located (CBD Secretariat, 2020). In addition, critical areas for biodiversity conservation face significant protection gaps, with only about 20% being fully protected and around 39% lacking any legal protection (KBA Partnership, 2022). Parties to the CBD are therefore aiming to address this biodiversity deficit through the introduction of Target 3 of the new GBF, which encourages a significant increase in the area of protected areas.

The cornerstone of the GBF is Target 3—also known as the "30x30" target. According to this target, states aim to

> [e]nsure and enable that by 2030 at least 30% of terrestrial, inland water, and of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem functions and services, are effectively conserved and managed through ecologically representative, well-connected and equitably governed systems of protected areas and other effective area-based conservation measures.

In the run-up to the adoption of the GBF and thereafter, Target 3 has probably received the most public and scientific attention, as it is seen as the primary tool for halting biodiversity loss (Jetz et al., 2021; Dooley et al., 2022; Dudley et al., 2022a,b; Gurney et al., 2023). This is partly because the significance of Target 3 lies not only in the realm of biodiversity preservation but also in its crucial role in mitigating global warming. Establishing and maintaining protected peatlands, forests, and soils have the additional benefit of generating negative emissions (Matocha et al., 2012; Melillo et al., 2016; Ekardt et al., 2020; Roberts et al., 2020; Stubenrauch et al., 2022). For instance, the total amount of emissions avoided through the establishment of forest protected areas is equivalent to ~1 year of annual global fossil fuel emissions (Duncanson et al., 2023). Yet, while it has been hailed as a significant achievement, Target 3 may not be ambitious enough, as research suggests that more than 50% of the Earth's land and oceans would need to be protected to stabilize the climate at the 1.5°C limit and effectively halt and reverse biodiversity loss (Dinerstein et al., 2019; IPCC, 2022a).

Other researchers have cautioned against over-reliance on protected areas to address the biodiversity crisis for several reasons. First, the literature is divided on whether a so-called "land-sparing" approach to biodiversity—in which 50% of terrestrial areas are protected, while agricultural and industrial activities can be intensified on the other half of the Earth's surface—is a sound biodiversity conservation strategy (Phalan et al., 2011; Cohn et al., 2014; Fischer et al., 2014; Carter et al., 2015; Kremen, 2015). However, a strict land-sparing approach has been shown to exacerbate biodiversity loss and social inequalities, as increased agricultural intensification would lead to further deforestation (Dooley et al., 2020, 2022; Obura et al., 2021). Second, and related to the first point, the majority of biodiversity loss—from a historical perspective—has not occurred through the conversion and degradation of high-value ecosystems that protected areas are intended to cover. Instead, the main driver of biodiversity loss has been land-use change and associated degradation of rural lands that were previously managed in a more sustainable manner (Ellis et al., 2021). Third, the success of establishing and managing protected areas in order to halt biodiversity loss remains disputed (Watson et al., 2014; Dooley et al., 2022; Meng et al., 2023). States themselves can determine what constitutes a protected area. As a result, many countries have favored a quantity over quality approach to protected areas—so-called "paper parks" (Di Minin and Toivonen, 2015; Relano and Pauly, 2023), which means that endangered species are not adequately covered (Venter et al., 2014). Moreover, studies have shown that the positive effects of protected areas remain limited if they lack connectivity (Loos, 2021). Finally, so-called "fortress" protected area policies have historically violated a range of human rights by displacing indigenous peoples and restricting the use of their traditional lands (Angelstam et al., 2021; Nagrath et al., 2022).

Conflicting land-use targets

In the previous two sections, we have shown that both climate change commitments and biodiversity conservation policies depend on land use. Addressing the climate crisis and biodiversity loss will therefore require coordinating and transforming current and future approaches to land use (Ekardt et al., 2010, 2018a; Stubenrauch et al., 2021). While some climate change mitigation strategies are also beneficial for biodiversity conservation, other land-based mitigation strategies are likely to conflict with the need to establish more protected areas due to the limited amount of land available.

In order to assess the extent to which the "30x30" target of the GBF conflicts with NDCs (on land-based CDR) under Article 4 para. 2 PA, it is first necessary to determine how much land is available in total and how much land would have to be converted. However, there are some caveats that need to be addressed. Data on global land use and related projections of future land use are fragmentary and often of variable quality (Verburg et al., 2011). Moreover, the dynamic nature of land-use practices presents a constant challenge for making precise predictions about future land-use developments (Meyfroidt et al., 2022). As a result, we will not attempt to prove that there is an evident physical shortage of terrestrial land, or that climate change mitigation and *in-situ* biodiversity policies are competing for specific areas of land. While it is difficult to identify a present physical shortage of land due to conflicting land-use policies, the underlying conflicts are already visible today (Dooley et al., 2022). The UNFCCC, the CBD, and human rights law in general have all incorporated some form of the precautionary principle—which requires that action be taken to avoid long-term, cumulative, or uncertain harm (Gardiner, 2006; Sands and Peel, 2018; Ekardt, 2020). The implication is that there need not be a current threat of competing land-use claims that may violate specific rights or obligations under international law. Rather, states must act prudently to avoid such conflicts in the future.

Although the data on global land use and land-use change may be incomplete, numerous studies provide evidence, all of which conclude that the proportion of land untouched by human influence is rapidly shrinking and that the land already in use is deteriorating (IPBES, 2018; IPCC, 2019; UNCCD, 2022). As mentioned earlier, the great majority of human impacts on land are due to the various agricultural and agroforestry practices (IPCC, 2019) that are pushing a number of planetary boundaries beyond their limits (Steffen et al., 2015, 2018; Campbell et al., 2017; Rockström et al., 2023). Of the global ice-free land surface−130 million square kilometers (Mkm²)—~50 Mkm² are used for agriculture and 30 Mkm² for agroforestry (IPCC, 2019, p. 8). As food production has increased by nearly 240% since the 1960's (IPCC, 2019), the relative and absolute share of land used for agriculture has also increased significantly to meet rising food demand. From 2000 to 2019 alone, the annual rate of cropland expansion saw a 58-fold increase, which also adversely impacted existing protected areas (Meng et al., 2023). This agricultural expansion has resulted in one-third of the global land area being affected by land-use change (Winkler et al., 2021), and is responsible for 80% of deforestation (UNCCD, 2022). In this context, it is also notable that 75–80% of global agricultural land is used for livestock production—including grazing land and cropland used to grow animal feed—while only 18% of the total calorie supply comes from meat and dairy products (Poore and Nemecek, 2018; Weishaupt et al., 2020). Studies estimate that the threshold for sustainable global cropland use is ranging between 10 and 15 Mkm² (Springmann et al., 2018; Willett et al., 2019). Since current global cropland covers around 12.44 Mkm² (Potapov et al., 2022), further expansion will inevitably exceed global sustainability thresholds.

In addition to the prediction that more land will be needed for food production in the future if diets do not change, there is also an expectation that land will be used as a resource to combat climate change and conserve biodiversity. In terms of land-based CDR, parties to the PA have already pledged to use ~12 million

Mkm² of land for carbon sinks or other NETs by 2060 (Dooley et al., 2022). These pledges would almost amount to four times the total area of India. Over half of this land committed to land-based CDR will be used to plant new forests or plantations, which will require land-use changes with negative impacts on biodiversity (Dooley et al., 2022). Most of these envisaged pledges by countries are to be realized by 2030 (4.5 Mkm²), while there are few (but significant) land-based CDR commitments for 2050 (5.3 Mkm²) and 2060 (2 Mkm²; Dooley et al., 2022). Whether countries would be able to meet these ambitious goals is uncertain (Brack and King, 2020; Quiggin, 2021). Unlike renewables, such as solar and wind, land-based CDR faces a "hard technical constraint" (Dooley et al., 2022, p. 22) in terms of projected land-use requirements. In the future, countries may be tempted to focus more on solar power as a mitigation strategy, which is 100 times more energy efficient than bioenergy per unit of land area (Searchinger et al., 2018).

Commitments to establish protected areas and restore degraded lands to conserve biodiversity also exacerbate the competition for global land use. As of 2023, around 17% of the Earth's terrestrial area is covered by protected areas, equivalent to 12.3 Mkm² (Gurney et al., 2023). Under Target 3 of the GBF, parties to CBD aim to increase this figure to 30%, or 23 Mkm², by 2030. The international community has further pledged to restore nearly 10 Mkm² of degraded land, including around 20% of existing cropland and 10% of forest land (van der Esch et al., 2022). While these targets are ambitious, it is unclear how countries will allocate an additional 20.8 Mkm² of land for protected area establishment and degraded land restoration if they also want to expand food production and land-based CDR (Dooley et al., 2022). In addition, the "30x30" target may not even be sufficient to halt biodiversity loss. As Allan et al. estimate, a minimum of 44% of global land (64 Mkm²) is needed to be covered by protected areas to effectively conserve biodiversity (Allan et al., 2022). However, 1.8 billion people currently live on this land, precluding any strict "fortress" protected area policies.

However, the ostensibly overlapping land-use commitments could be harmonized if the two primary strategies of both climate protection and biodiversity conservation were consistently implemented: a sharp reduction in livestock farming and a phase-out of fossil fuels (Stubenrauch et al., 2021). The latter could slow down urban sprawl and infrastructure construction, the former would free up a large part of agricultural land. Thus, the assumed land conflict between CDR and biodiversity areas could be reduced to a large extent. In addition, there is also the possibility of shaping the remaining agriculture in such a way that it both serves biodiversity and sequesters more carbon, for example through approaches such as crop rotation or legume cultivation (Dooley et al., 2022). Furthermore, as described above, there are also synergy effects between climate and nature conservation for certain non-large-scale CDR approaches such as peatland rewetting (non-monocultural), afforestation, biochar, or low-till farming. All these measures primarily serve the dual purpose of benefiting biodiversity and climate protection, potentially minimizing the conflict between the two treaty regimes to a great extent.

Results: legal analysis of overlapping land-use claims under international law

CDR and the international climate change law

Neither the terms CDR nor NETs are mentioned in any of the relevant international climate law treaties. However, the drafters of UNFCCC did include the concept of "sinks" in the 1993 UNFCCC. According to Article 4 para. 1 lit. d UNFCCC, the contracting parties should, in accordance with their common but differentiated responsibilities,

> [p]romote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems [...].

The Convention further defines sinks as "any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere" under Article 1 para. 8 UNFCCC. Consequently, the drafters foresaw the possibility of carbon removals through the conservation and enhancement of sinks. Although the ordinary meaning of the terms "conservation" and "enhancement" of "sinks" does not cover engineered removals, such as BECCS and DACCS, it would be contrary to the Convention's ultimate objective under Article 2 UNFCCC to exclude these approaches, as they are theoretically capable of contributing to the objective of stabilizing greenhouse gas concentrations in the atmosphere (Craik and Burns, 2016; Fuglestvedt et al., 2018; Lin, 2018; Krüger, 2020; Honegger et al., 2021a).

As in the case of the Convention, the PA also lacks provisions that address specific types of CDR. The most important provision concerning CDR deployment can be found in Article 4 para. 1 PA, which mandates that the contracting parties should

> undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty.

Moreover, according to Article 5 para. 1 PA, "[p]arties should take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases as referred to in Article 4, paragraph 1 (d), of the Convention, including forests." Although some commentators interpret these provisions as strengthening the role of CDR as a mitigation option (Bodansky, 2016b; Horton et al., 2016; Chen and Xin, 2017; Reynolds, 2018; Mayer, 2021), Article 4 para. 1 PA and Article 5 para. 1 PA cannot be construed as constituting an obligation directly requiring states to implement a particular type of CDR within a specific timeframe, as they lack legal prescriptiveness and precision. Instead, Article 4 para. 1 PA only imposes an obligation on states to "aim" to meet this goal, which cannot be considered an obligation of result (Krüger, 2020). As such, it does not require states to pursue large-scale land-based CDR policies. Similar to the Convention, the Agreement maintains a relatively impartial position regarding the utilization of CDR (Kalis et al., 2021).

Since CDR approaches are considered as removals via "sinks" under both the UNFCCC and the PA, we can likewise conclude that all land-based CDR measures are considered "measures to mitigate climate change" under Article 4 para. 1 lit. b UNFCCC. As a mitigation measure, land-based CDR approaches are therefore placed in the same category as policies that reduce emissions (Honegger et al., 2021a). This does not mean, however, that emission reductions and CDR approaches should be equated from a legal perspective. Rather, the UNFCCC, the PA, and other provisions of international environmental law mandate that emission reductions are the primary course of action, while CDR is seen as a complementary set of measures (Beyerlin and Marauhn, 2011; Lin, 2018; Mayer, 2018; Wieding et al., 2020; Markus et al., 2021; Stoll and Krüger, 2022). This normative hierarchy of mitigation measures can be derived from, *inter alia*, the ultimate objective of the UNFCCC and the legally binding 1.5°C limit under Article 2 para. 1 lit. a PA (Ekardt et al., 2018b, 2022; Ekardt, 2020; Wieding et al., 2020). Although both emissions reductions and sinks are mitigation measures, emission reductions are the most the effective means of achieving the Convention's target of stabilizing GHG emissions (IPCC, 2018, 2023). It follows that due to concerns about the permanence of CDR approaches, they are *prima facie* not as effective in achieving the UNFCCC's ultimate objective (Güssow, 2012; Krüger, 2020; Stoll and Krüger, 2022). Moreover, based on a reading of Article 2 para. lit. a 1 PA, as well as on human rights law, parties must deploy those measures that are most effective, while also causing the least side effects on the relevant interests and rights. Such measures are emission reductions, such as the rapid phase-out of fossil fuels and the minimization of livestock farming (Ekardt et al., 2018b, 2022; Ekardt, 2020; Wieding et al., 2020). A similar conclusion was reached by the German Federal Constitutional Court in its landmark 2021 climate ruling, where the judges underlined the primary role of emission reductions and emphasized the uncertain and limited role of CDR approaches (Kotzé, 2021; Ekardt and Heß, 2023).

The normative hierarchy of mitigation measures under the UNFCCC and the PA remains unaltered by their "nationally determined" nature, as stipulated in Article 3 PA. Contracting parties are, in theory, free to decide which mitigation measures they wish to adopt. However, Article 3 PA explicitly states that parties need to adopt measures in order to comply with the temperature limits specified under Article 2 para. 1 lit. a PA. Consequently, the concept of nationally determined contributions is inherently bounded by the overarching obligation in Article 2 para. 1 lit. a PA, which seeks to limit global warming to 1.5°C (Ekardt et al., 2018b). Given the escalating likelihood of exceeding this critical temperature threshold in the near future (IPCC, 2023), contracting parties must prioritize mitigation measures capable of fulfilling this binding mandate (Ekardt et al., 2018b, 2022). Presently, it seems highly improbable for parties to meet this obligation primarily through the reliance on CDR measures alone, without simultaneously implementing substantial emission reductions. Conversely, reducing emissions across all sectors is imperative for achieving the 1.5°C target in the remaining timeframe (IPCC, 2023). While CDR policies are also necessary, as stipulated in Article 4 para. 1 PA, the legal priority is in favor of the obligation under Article 2 para. 1 lit. a PA, and its indirect mandate to curtail emissions (Ekardt et al., 2018b). In sum, while each contracting party does indeed have discretion when adopting mitigation measures, these measures must be aligned with the legally binding objective under Article 2 para. 1 lit. a PA, essentially necessitating the initial adoption of emission reduction strategies.

Protected areas and international biodiversity law

Article 1 CBD contains a legally binding obligation to halt biodiversity loss (Ekardt et al., 2023). According to the preamble of the CBD,

> the fundamental requirement for the conservation of biological diversity is the *in-situ* conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings [...].

Thus, *in-situ* conservation measures—notably protected areas—have normative priority among the Convention's various policies, which is also reflected in the language and context of Articles 8 and 9 CBD (Bowman et al., 2010; Boyle and Redgwell, 2021). This normative priority of *in-situ* measures is due to the fact that they address all five levels of the biodiversity hierarchy—"(1) whole systems such as landscapes or ecosystems, (2) assemblages such as associations or communities, (3) species, (4) populations and (5) genes" (Bowman et al., 2010, p. 599). In contrast, ex-situ measures under Article 9 CBD—i.e., policies outside the original ecosystem, such as maintaining gene banks or zoos—only address biodiversity levels three to five (Wolfrum, 2004; Bowman et al., 2010; Boyle and Redgwell, 2021). Land-based CDR policies are *prima facie* ranked even lower because their direct impacts will be detrimental to all five levels of biodiversity in many scenarios. Ultimately, *in-situ* measures are the more effective measures with fewer side effects on the relevant legally protected interests. We can therefore conclude that, just as emission reductions are preferred in the UNFCCC and its successor treaties, *in-situ* measures are normatively favored by the CBD.

While Article 8 CBD is commonly viewed as the centerpiece of the CBD's substantive obligations (besides the obligation to halt biodiversity loss), its provisions—including the obligation to establish protected areas under Article 8 lit. a CBD—are qualified by the formulation "as far as possible and as appropriate." As a consequence, the contracting parties are said to have considerable discretion when implementing the obligations under Article 8 CBD. Some commentators have even argued that the qualifiers in the CBD effectively allow parties to circumvent to fulfill their obligations (Humphreys, 2005; Lim, 2021). However, the CBD is legally binding as a whole under international law. More relevant, therefore, is the question of the specific legal effect of Article 8

CBD. Whether or not a provision in an international treaty creates a legally binding right or obligation depends on its degree of prescriptiveness and precision.

The concept of prescriptiveness refers, *inter alia*, to the degree of the obligatory nature that is conveyed by the verb that is used in a provision (Oberthür and Bodle, 2016). To illustrate, provisions that use the verb "shall" convey precise and legally binding requirements and are therefore classified as hard obligations (Bodansky, 2016a; Böhringer, 2016). Conversely, flexible obligations often use verbs such as "should" or "encourage," which leave discretion to the parties involved and potentially enable non-enforcement (Bodansky, 2016a; Böhringer, 2016; Rajamani, 2016). In the case of Article 8 CBD, the *chapeau* includes the term "shall," indicating a sufficient level of prescriptiveness.

The precision of a norm hinges on two factors. Firstly, the norm must identify the intended recipient, be it an individual, a group or an institution, thereby establishing specific obligations (Bodansky, 2016a; Oberthür and Bodle, 2016). Secondly, the norm should define the specific requirements or expectations through methods such as setting measurable targets or specifying precise timeframes (Oberthür and Bodle, 2016). However, the precision of the content of a norm may be limited by qualifiers like "as appropriate," as exemplified in the *chapeau* of Article 8 CBD (Rajamani, 2016). Beyond the use of qualifiers, the obligation to establish protected areas under Article 8 lit. a CBD is relatively vague. Although it is clear that the contracting parties are the intended addressees of the norm, the legal content is rather imprecise. Article 8 lit. a CBD does not prescribe any minimum criteria that the area in question must meet before it can be designated by the contracting party as a protected area under its domestic law. As a result, any contracting party could theoretically comply with the obligation under Article 8 lit. a CBD by establishing a protected area on any site—regardless of its ecological status. Due to the aforementioned lack of precision in the wording of Article 8 lit. a CBD, the legal effect of the provision may be questioned.

However, we argue that the "30x30" target of the GBF is a clarification of the legally binding provisions of the CBD—including the obligation to establish protected areas under Article 8 lit. a CBD (Ekardt et al., 2023). While the GBF itself is not a legally binding treaty under Article 2 lit. a VCLT, the GBF can be considered as a "subsequent agreement between the parties regarding the interpretation or the application of its provisions" of the CBD pursuant to Article 31 para. 3 lit. a VCLT. This is because it meets the three conditions necessary to be deemed such a "subsequent agreement." Firstly, unanimous adoption by all contracting parties according to Article 1 para. 1 lit. g VCLT. Secondly, it was adopted by the parties "subsequently" to the adoption of the CBD (Berner, 2017). Thirdly, it is directly relevant for "the interpretation of the treaty or the application of its provisions," as it increases the precision of several obligations of the CBD by clarifying objectives, timeframes, or legal terms. While some authors argue that the parties must additionally be aware of and expressly confirm the legal clarifications in the context of a subsequent agreement (Linderfalk, 2007; ILC, 2018; Minnerop, 2020), we posit that this sole purpose doctrine relies too heavily on subjective factors, which undermines the legal relevance of provision (Berner, 2017). Instead, we suggest that Article 31 para. 3 lit. a VCLT is inapplicable only if the parties explicitly exclude the subsequent agreement from clarifying the interpretation and application of the treaty. In the case of the GBF, the parties have declared that the framework should not "modify the rights and obligations of a Party under the Convention" (CBD COP, 2022, p. 6). As the processes of treaty modification and treaty interpretation are distinct concepts (Moloo, 2012), the GBF can thus be considered as a subsequent agreement pursuant to Article 31 para. 3 lit. a VCLT.

Considering that the GBF clarifies the legally binding provisions of the CBD, we argue that the "30x30" target also clarifies Article 8 lit. a of the CBD. The "30x30" target sets a quantifiable target and specific timeframe: by 2030, at least 30% of terrestrial and marine areas should be effectively conserved and managed through well-connected and equitable protected area systems. It is important to note, however, that the GBF's legal clarifications do not override or modify the existing and ambitious commitment to halt and reverse biodiversity loss under Article 1 CBD. Similarly, the introduction of two new timelines (2030 for targets and 2050 for goals) in the GBF does not change the original obligation under Article 1 CBD, which has required immediate action since the CBD entered into force in 1993.

In addition, the "30x30" target limits the impact of the "as appropriate" qualifier in the *chapeau* of Article 8 CBD. It specifies, in accordance with the relevant findings of the scientific community, the actions that parties must take to mitigate the loss of biodiversity under Article 8 CBD. While the qualifier "as far as possible" still modifies the provision to ensure that certain parties with limited administrative and financial capacity are able to meet the obligations (Krohn, 2002; Marschall et al., 2008), it does not justify the claim that there is no obligation at all. Even if some countries are unable to implement the necessary measures within their territory, they can still assist other countries in achieving the overall target through financial assistance and technological cooperation.

Resolving the conflict between international climate and biodiversity law

Both the deployment of land-based CDR and the establishment and maintenance of protected areas are supported by provisions of international environmental treaty law. On the one hand, the international climate regime generally encourages the utilization of land-based CDR, even if the obligations are vague and there is no legally binding duty or specific timeframe for CDR deployment other than the overarching net zero target under Article 4 para. 1 PA. On the other hand, the CBD obliges its contracting parties to establish protected areas under Article 8 lit. a CBD. Although this obligation also leaves a wide margin of discretion to the contracting parties, the GBF's "30x30" target considerably clarifies the legal content of Article 8 lit. a CBD. As we have shown above, there is only a limited amount of land available either for land-based CDR deployment or for biodiversity conservation purposes if the demand for food production is to be met. Notwithstanding the fact that current land-use practices already exceed safe and equitable planetary boundaries (Steffen et al., 2015; Rockström et al., 2023), it is highly likely that countries will continue to utilize previously unused areas of land or implement land-use changes in order to meet their international obligations under the UNFCCC, PA, or CBD. How can these competing land-use claims, which are also conflicting legal rules, be resolved? From the perspective of international law, the relevant treaty provisions are, *prima facie*, equal and cannot override one or the other (Jacquemont and Caparrós, 2002). However, there are rules and legal balancing mechanisms embedded in the relevant treaties that can be used to reconcile the conflicting legal norms.

One possible argument is that certain land-based CDR approaches could actually benefit biodiversity, particularly in the case of ecosystem restoration and the protection of existing sinks (Ekardt et al., 2020). This means that such policies could contribute to the sub-objective of conserving biodiversity as defined in Article 1 CBD. Consequently, there may be no legal contradiction between implementing some form of land-based CDR techniques and maintaining protected areas, as both could be implemented on the same parcels of land. However, it could also be argued that the threat to biodiversity posed by climate change itself is far greater. If countries continue to emit GHGs under a business-as-usual scenario, there would be severe consequences for all ecosystems and species (Nunez et al., 2019; Habibullah et al., 2022). Tackling climate change is therefore a critical priority for biodiversity conservation (Ohashi et al., 2019). Conversely, both Article 2 and Article 4 para. 1 lit. d UNFCCC explicitly refer to ecosystems as relevant legally protected interests (Jacquemont and Caparrós, 2002). Any effective mitigation measure—including land-based CDR—can also be regarded as benefitting biodiversity in the long term (Williamson et al., 2012), thereby reconciling the ostensible conflict between the two land-use approaches.

Consequently, some authors argue that the sub-objective to conserve biodiversity under Article 1 CBD should not just be interpreted as limiting the deployment of CDR but also as encouraging its use (Honegger et al., 2013; Reynolds, 2014; Du, 2018; Krüger, 2020). This viewpoint holds merit, particularly in the context where land-based CDR strategies can contribute to biodiversity preservation by stabilizing GHG levels. However, this perspective is compelling only insofar as the CDR policies in question are implemented in a sustainable manner that does not pose significant threats to biodiversity. In the case of some large-scale BECCS applications, for example, the impact on certain species and ecosystems may be even worse than in business-as-usual climate scenarios—in which limited emission reductions occur and temperatures continue to rise rapidly (Hof et al., 2018). This does not mean that all BECCS approaches have detrimental effects on biodiversity conservation. The environmental footprint of a specific BECCS plant typically hinges on the sourcing of its fuels, which can involve not only monoculturally-sourced plants but also secondary biomass materials, like municipal waste (Pour et al., 2018). Nevertheless, there are emission reduction measures available that are both more effective at curbing global warming and also would provide large net-benefits for biodiversity conservation—most notably by phasing out fossil fuels and minimizing livestock production (Phelps et al., 2012; Weishaupt et al., 2020; Almaraz et al., 2023). As long as the totality of effects associated with certain large-scale CDR deployment scenarios on biodiversity is uncertain—specifically regarding land-use change—countries should, in the first instance, rely on emission reductions as they are more effective and have multiple benefits for biodiversity (Phelps et al., 2012). There is no doubt that BECCS and other land-based CDR methods have a role to play in the overall mitigation portfolio. However, arguing that these approaches are beneficial to biodiversity does not resolve the legal dispute over conflicting land-use commitments.

A related argument is that land-based CDR policies could theoretically constitute the "sustainable use" of biodiversity, which is the second sub-objective under Article 1 CBD. If that were indeed the case, there would be no contradiction between the UNFCCC and the CBD, since the practice of land-based CDR would also be protected under the CBD. In theory, maintaining peatlands, planting trees, or cultivating bioenergy crops in order to permanently remove CO_2 from the atmosphere could be understood as sustainable use practices or even as beneficial use of biodiversity, provided that the land is not managed monoculturally (Donnison et al., 2020, 2021; Giuntoli et al., 2022). However, according to Article 2 para. 16 CBD, "sustainable use" means

> [t]he use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations.

Thus, a party cannot justify activities that are harmful to biodiversity by invoking that the activity in question may be regarded as "sustainable use" under the second sub-objective of Article 1 CBD (Glowka et al., 1994; Krüger, 2020). In this regard, the Convention has incorporated a specific notion of sustainability, understood as a practice that balances global cross-border and intertemporal interests and rights. Thus, the use of biodiversity cannot be considered sustainable if it would imply a long-term decline in biodiversity. Some land-based CDR policies implemented at the scale foreseen by many IAMs are likely to be detrimental to biodiversity and may likewise infringe upon several human rights of present and future generations (Günther and Ekardt, 2022). Consequently, it is challenging to categorize these large-scale policies as inherently constituting a "sustainable" utilization of biodiversity's components as defined in Article 1 CBD in most scenarios. In contrast, smaller-scale policies that employ sustainable resourcing methods or focus on ecosystem protection and restoration have the potential to align with the concept of "sustainable use" under the Convention. However, this assessment is contingent upon the specific local context and the manner in which the policy is implemented.

Another way to potentially reconcile the conflicting legal norms is through Article 22 para. 1 CBD. The article states that

> [t]he provisions of this Convention shall not affect the rights and obligations of any Contracting Party deriving from any existing international agreement, except where the exercise of those rights and obligations would cause a serious damage or threat to biological diversity.

It follows that a party to the CBD can argue that the obligation under Article 8 lit. a CBD "shall not affect the rights and obligations" of parties under the UNFCCC. Since land-based CDR policies are considered mitigation measures to achieve the ultimate objective under Article 2 UNFCCC (Honegger et al., 2021a), it is arguable that Article 8 lit. a CBD should not affect the use of CDR as encouraged under the UNFCCC. Article 22 para. 1 CBD is applicable in our case because the UNFCCC entered into force before the CBD and is therefore an existing international agreement under Article 22 para. 1 CBD. However, Article 2 UNFCCC does not contain a positive obligation to utilize CDR because it prioritizes emission reductions over other secondary measures (Stoll and Krüger, 2022). More importantly, Article 22 para. 1 CBD does not apply in cases "where the exercise of those rights and obligations would cause a serious damage or threat to biological diversity." Hence, any large-scale land-based policies implying significant damages to biodiversity are not justified under Article 22 para. 1 CBD. Concerning smaller-scale land-based measures that are implemented in a way that does not adversely impact biodiversity, Article 22 para. 1 CBD could only be applicable in cases where a party substantiates the existence of an explicit obligation under the CBD to employ a particular form of land-based CDR.

Finally, the ultimate objective of the UNFCCC underscores the point that mitigation measures must also be consistent with the protection of biodiversity, thereby effectively limiting some forms of large-scale deployment of land-based CDR through further land-use change. The ultimate objective of the UNFCCC, according to Article 2 UNFCCC, specifies that the atmospheric GHG concentrations must be stabilized in order to "prevent dangerous anthropogenic interference with the climate system." Furthermore, mitigation is necessary "to allow ecosystems to adapt naturally to climate change," implying that ecosystems are a legally protected interest under the UNFCCC. It follows that if countries wish to pursue land-based CDR measures—which are permitted but secondary to emission cuts—they should use approaches that are most consistent with biodiversity protection. In practice, this means that parties to the UNFCCC and CBD should prioritize the CDR approaches that are most compatible with *in-situ* conservation, such as ecosystem restoration and the protection of existing sinks (Ekardt et al., 2020; Stubenrauch et al., 2022). Conversely, states should reassess potential large-scale land-based CDR measures if doing so would unduly impede their ability, or the ability of the international community, to effectively achieve the "30x30" target by 2030. If a country nevertheless decides to pursue such a unilateral large-scale land-based CDR policy, this could potentially constitute a breach of "good faith" under Article 1 CBD in conjunction with Article 26 VCLT.

Some may argue that the conflicting legal rules have not really been considered in an entirely balanced manner but are rather tilted in favor of *in-situ* biodiversity conservation to the detriment of land-based CDR policies. Given the present and future damage that will be wrought by climate change, we might reasonably ask whether this conclusion is justified. We argue that it is, because one cannot compare mitigation and conservation measures in isolation but must always consider the alternative courses of action in each specific policy area that are potentially as effective and less intrusive on relevant rights. In our case, the normative hierarchy of mitigation and conservation measures anchored in the different treaty regimes is crucial for interpreting the relevant legal rules. Notably, the UNFCCC and the PA give precedence to strategies focused on emission reductions (Ekardt et al., 2018a; Lin, 2018; Mayer, 2018; Stoll and Krüger, 2022), whereas the CBD favors *in-situ* conservation and protected areas (Bowman et al., 2010; Boyle and Redgwell, 2021). In contrast (land-based), CDR approaches are of secondary importance in the international climate regime (Güssow, 2012; Krüger, 2020; Wieding et al., 2020; Ekardt et al., 2022; Stoll and Krüger, 2022; Ekardt and Heß, 2023), while the CBD may discourage those approaches that are not implemented in a sustainable manner.

This result, however, does not necessarily indicate that the entire array of diverse mitigation approaches falling under the category of land-based CDR policies is fundamentally incompatible with the CBD. Thus, there is no immediate imperative for states to abstain from their implementation. Instead, it is crucial to acknowledge that all principles within international environmental law inherently entail specific limitations and inescapable trade-offs. For example, despite the widespread membership in the CBD, it is noteworthy that the United States (US), has chosen not to become a contracting party. Even though the US issued an executive order recommending the conservation of at least 30% of domestic lands and waters by 2030 (White House, 2021), the order is not grounded in international environmental law. Consequently, it does not intersect with the previously mentioned realm of potentially conflicting land-use commitments governed by international law. In addition, the CBD is characterized by its use of soft language and constructive ambiguity (Harrop and Pritchard, 2011; Boyle and Redgwell, 2021), which serves as a hallmark of flexibility and pragmatism in international environmental law—although there is a legally binding obligation to halt biodiversity loss (Ekardt et al., 2023). The CBD, acknowledging the diverse national interests and priorities of its parties, uses legal language that allows for interpretation and adaptation to varying contexts and circumstances (Fajardo del Castillo, 2021; Lim, 2021). Thus, in situations where there are competing land-use commitments under international climate change and biodiversity law, this ambiguity can offer parties a degree of latitude to navigate norm conflicts without necessarily having to rely on the specific rules and balancing mechanisms mentioned above. For instance, some parties to CBD may deem certain land-based as sustainable mitigation approaches and, therefore, may not consider it imperative to align them with their *in-situ* conservation commitments under the CBD. This again exemplifies the notion that each land-based CDR approach must be evaluated in its specific implementation context. Furthermore, even if a particular land-based CDR policy impacts certain elements of biodiversity, it does not inherently constitute a breach of the responsible party's obligations under the CBD.

Discussion and conclusion

In a 2021 study, Meyfroidt et al. postulated several claims about the sustainability of global land systems (Meyfroidt et al., 2022).

According to the researchers, "humanity lives on a used planet where all land provides benefits to societies." However, "land-use change usually entails trade-offs between different benefits—"win-wins" are thus rare" (Meyfroidt et al., 2022, p. 1). The aim of this paper is to show how these benefits and trade-offs of land-use and land-use change approaches, i.e., conflicting land-use pledges to land-based CDR and protected areas, are translated in terms of international environmental law.

Although safe and just planetary boundaries for land use have already been exceeded due to the expansion of cropland (Steffen et al., 2015, 2018; Rockström et al., 2023)—which is expected to increase in the future—countries have committed themselves to use additional areas of "unused" land or to redesignate existing areas through land-use change. Commitments for land-based CDR and the establishment of protected areas are likely to result in overlapping or conflicting land claims, assuming that cropland used for food production is left untouched (Dooley et al., 2022).

In a legal analysis, we have shown how rules of international environmental law may be used to resolve these competing claims, although there will always be some limitations and trade-offs involved due to the inherent constraints of the pertinent treaty regimes. Under the relevant treaty rules of international environmental law (land-based), CDR policies are normatively subordinate to emission reductions (Krüger, 2020; Wieding et al., 2020; Ekardt et al., 2022; Stoll and Krüger, 2022; Ekardt and Heß, 2023). In contrast, *in-situ* conservation approaches, such as the establishment of protected areas, are the primary measures for achieving the CBD's objective of conserving biodiversity (Bowman et al., 2010; Boyle and Redgwell, 2021). Moreover, the GBF's "30x30" target constitutes a "subsequent agreement" pursuant to Article 31 para. 3 lit. a VCLT, thereby clarifying the legally binding obligation under Article 8 lit. a CBD. It follows that some commitments to large-scale land-based CDR, which would either directly or indirectly undermine the achievement of the "30x30" target, may be inconsistent with the CBD.

What does this mean for countries wishing to pursue these land-use policies? It is essential to clarify that our previous analysis does not inherently deem any of the discussed land-use policies incompatible with international law, nor does it suggest that countries should entirely abandon a particular set of land-use policies. The assessment of legal compatibility remains contingent upon the specific circumstances of each case. Nonetheless, our analysis underscores the fact that there are instances where the international frameworks for climate change and biodiversity preservation do not seamlessly align. Thus, parties need to continuously (re)assess their mitigation strategies in order to fulfill their commitments under both legal regimes. Furthermore, the dual commitment to limiting global warming to 1.5°C and halting biodiversity loss places a fundamental obligation on public authorities to seek synergies between climate and biodiversity protection wherever feasible, as previously mentioned. This approach has the potential to significantly mitigate related land-use conflicts. Given these observations, policymakers should consider the following key considerations:

First, to mitigate climate change, nations must focus on real and significant emission reductions across all sectors. Ambitious climate action—by rapidly phasing out the use of fossil fuels and minimizing livestock production—is the most effective way to limit global warming to 1.5°C, as required by Article 2 para. 1 lit. a PA (Powell and Lenton, 2013; Ekardt et al., 2018b; Weishaupt et al., 2020). By those means, the assumed land conflict between CDR and biodiversity areas could disappear at least to a large extent because this would free up a significant amount of land for both CDR and biodiversity conservation. Furthermore, these kinds of emission reductions would render it unnecessary to make land-use changes that negatively impact both climate and biodiversity, while reducing the risk of food and water scarcity in the long term (Hasegawa et al., 2021).

Second, land-based CDR policies will still be necessary to achieve the 1.5°C limit under Article 2 para. 1 PA (IPCC, 2023; Smith et al., 2023). However, states should focus on those CDR policies that effectively sequester GHG while also providing the most benefits to biodiversity protection (Aguirre-Gutiérrez et al., 2023). It is evident that there is no CDR panacea, meaning that there will always be trade-offs involved when balancing CDR mitigation ambition and biodiversity protection concerns. Nevertheless, CDR should primarily be employed to offset process emissions in hard-to-abate industrial sectors rather than as large-scale mitigation policies (Wieding et al., 2020; Ekardt et al., 2022; Ekardt and Heß, 2023). Moreover, certain CDR options, such as ecosystem restoration and the preservation of existing natural sinks, prove particularly advantageous and thus should take precedence over large-scale monocultural approaches that promote land-use change.

Thirdly, there is a need for reshaping current agricultural practices in a manner that not only benefits biodiversity conservation but also enhances CO_2 sequestration. This can be achieved through methods such as crop rotation, low-till farming, and the cultivation of legumes (Dooley et al., 2022). As restoring natural vegetation is generally more cost-efficient and avoids the negative biodiversity impacts of planting new trees or crops, any land-based CDR policy should focus on protecting or restoring existing ecosystems, for instance with regard to forests and peatland (Ekardt et al., 2020; Weishaupt et al., 2020; Stubenrauch et al., 2021, 2022).

Finally, this ecosystem-based approach would also be most compatible with the establishment and maintenance of protected areas. Protecting key biodiversity areas is critical to halting the accelerating rates of extinction and the spread of invasive alien species (Kullberg et al., 2019). However, countries should not focus solely on establishing new protected areas in order to meet the "30x30" target by 2030, since spending on the management of existing protected areas is often a better investment for biodiversity than establishing new ones (Adams et al., 2019). Furthermore, protected areas must always respect the rights of indigenous peoples in order to achieve sustainable and equitable environmental outcomes.

Data availability statement

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

Author contributions

PG: Conceptualization, Investigation, Writing – original draft. FE: Conceptualization, Project administration, Supervision, Writing – review and editing.

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Conflict of interest

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

Publisher's note

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Modeling the measurement of carbon dioxide removal: perspectives from the philosophy of measurement

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This paper explores how recent developments in the philosophy of measurement can frame and guide the way we measure successful carbon sequestration in carbon dioxide removal (CDR) projects. Recent efforts to mitigate carbon emissions, e.g., the forest offset program implemented in California, have been revealed to systematically over-credit projects relative to the benefits they produce for the climate. In this paper I utilize concepts from the philosophy of measurement, primarily those surrounding models of the measurement process, to diagnose this problem of over-crediting in the broader context of concerns about uncertainty and impermanence in CDR. In light of these measurement models, I argue for absolute measurement targets in favor of the standard comparative targets, the latter of which are significantly dependent on tenuous baseline projections. I go on to consider which contemporary approaches to CDR are successful in light of lingering uncertainty about the future, which puts particular emphasis on the permanence of carbon sequestration. Independent of the specific argument developed here, the paper also serves to introduce concepts from the philosophy of science and measurement to a broader audience, in the hopes they will benefit other areas of research.

KEYWORDS

carbon dioxide removal, carbon offsets, philosophy, measurement, climate, models

1 Introduction

Climate mitigation efforts have increasingly come to focus on carbon dioxide removal (CDR). The promise of CDR is that through the development of technologies and corresponding social incentives, national economies can smoothly transition toward an overall decrease in the quantity of carbon being released into the climate system. Considered technologies include afforestation, improved forest management, carbon dioxide mineralization, direct air capture, and many more (see Hovorka et al., 2021 and Pilorgé et al., 2021 for a general discussion of these technologies).

However, there are outstanding issues in the measurement and modeling of real-world outcomes of CDR technologies (Chay et al., 2022) arising from uncertainty in the application of these technologies and their underlying theory. The former, *execution uncertainty*, emerges when the operation of a project deviates from expectations, or when errors occur in the calculation or reporting of outcomes. As such, execution uncertainty is primarily error in implementation, "mitigated through careful deployment of existing tools and practice," (Chay et al., 2022). The latter, *scientific uncertainty*, emerges from an inadequate understanding of the relevant natural systems or processes. How would Atlantic Ocean circulation, for example, change in response to an influx of 250 billion tons of meltwater per year? Scientific uncertainty of this sort calls for research efforts directed toward novel analytic methods and improved understanding of the relevant systems.

There is also a third kind of uncertainty for CDR technologies (Chay et al., 2022), *counterfactual uncertainty*. We can only understand the benefits of CDR in the context of counterfactual scenarios where the technology was not implemented: *what would have happened to the carbon in a particular instance of CDR if it had not been removed?* Such counterfactuals play an indispensable role in establishing claims about baselines and additionality: what is the counterfactual *baseline* quantity of carbon sequestered without CDR and what *additional* carbon is sequestered as a result of the implementing the technology? However, there are deep challenges in the determination of baseline and additionality, challenges that require more than the kind of engineering and empirical solutions needed to address execution and scientific uncertainty. Indeed, some have argued that methods for estimating baseline and additionality values are inherently subjective (e.g., Gifford, 2020 in the context of forest carbon offsets). On top of this, even ignoring the potential subjectivity of these counterfactuals, errors due to over-crediting arise when credits do not correspond to real additionality (Badgley et al., 2022a).

Assessing the relative merit of a particular CDR method will require consideration of all three forms of uncertainty: execution, scientific, and counterfactual. Each form of uncertainty introduces distinct challenges for predicting how a project will perform in the future. While the ideal method would exhibit low degrees of uncertainty across the board, it will more often be the case that there are trade-offs between different kinds of uncertainty. As such, funding and policy decisions will ultimately need to be made on the basis of which uncertainties are more tolerable than others.

In this paper I approach the problem of uncertainty in CDR technologies from the perspective of the philosophy of measurement, with particular attention to issues of counterfactual uncertainty. My aim is to apply theoretical insights from the philosophy of measurement (e.g., Mari et al., 2017; Tal, 2017; Wilson and Boudinot, 2022) to address fundamental questions about the application and incentivizing of CDR technologies, mitigating some of the aforementioned uncertainties in carbon-crediting while suggesting a new way forward for conceptualizing CDR technologies. I argue that specific targets for CDR are more sensitive to counterfactual uncertainty than others. Indeed, the aforementioned subjectivity of additionality and baseline is partly a product of the specified target for carbon offsets being appropriately comparative, i.e., determined by comparison with a counterfactual baseline indicating what would have happened in the absence of the project. Alternative targets for CDR may thus be capable of mitigating some of this subjectivity. Ultimately, the paper uses ideas in the philosophy of science to frame and guide improvements for the quantification of carbon in environmental policy with the further aim of introducing those ideas that are useful to the broader group of experts interested in the climate. As such, I intend this paper to serve as an open invitation for further discussion and communication about the philosophy of carbon measurement, rather than as a definitive or conclusive proposal. I hope the arguments in this paper can get the ball rolling.

In Section 2 of the paper, I investigate the problem of over-crediting in California's forest carbon offset programs (Badgley et al., 2022a), in which standards failed to promote real climate benefits. A program only produces real climate benefits when its implementation results in a genuine reduction or removal of carbon in the atmosphere. I use California's forest offset program as a case study for raising a number of empirical and philosophical problems with the comparative approach to carbon measurement. In Section 3, I discuss some ideas from the philosophy of science, focusing on the development of models of the measurement process. These models facilitate measurement by appropriately representing the features of the world that make a difference to the measurement target and the apparatus used to get that measurement. Many shortcomings in carbon offset programs can be understood as a failure to capture the right difference makers. In Section 4, I develop an alternative framework for the valuation of carbon inspired by measurement models discussed in the philosophy of measurement. I argue that real climate benefits, the target of financial incentives, are better understood in terms of absolute carbon over comparative carbon. In Section 5 I evaluate CDR technologies in terms of their permanence, highlighting which methods are less vulnerable to remaining uncertainty about the future.

2 Diagnosing over-crediting in carbon offsets

Sections 2–4 of this paper are dedicated to identifying an appropriate measurement target for assessing CDR technologies. In short, what is it about the world that we are intending to learn when we conduct our carbon measurement, and does it correspond to our intended goals? In this Section I will consider California's forest carbon offset program as a case study for contemporary carbon markets. The program comprises the largest compliance market in operation, thus making it a useful case for drawing out some of the problems that arise when taking a *comparative approach*. Among other things, programs utilize a comparative approach when awarding credits or financial benefits on the basis of comparison with a counterfactual baseline or projection that indicates what would have happened in the absence of the program. First, I will discuss how California's offset program is vulnerable to a problem with over-crediting as a result of targeting inappropriate metrics for carbon sequestration (Section 2.1). That is, relying on standards derived from cross-species and cross-regional averages has led to systematic over-crediting in California's forest carbon offset program (Badgley et al., 2022a). This empirical problem arises because the utilized standards fail to capture the appropriate measurement target: the carbon target must result in real benefits to the climate. On top of this, I suggest several additional problems that limit the ability of California's offset program to produce real climate benefits, specifically problems resulting from methodological subjectivity, upfront crediting, and uncertainty about the future (Section 2.2). While I do focus on California's forest carbon offset program, the discussed problems for the comparative approach should generalize to programs that share in these features. I argue that some are endemic to the comparative approach. In a later section (Section 4) I develop an alternative approach to mitigate these problems, an approach partly inspired by work being done in the philosophy of measurement (Section 3).

2.1 California's forest carbon offsets and real climate benefits

Carbon offset programs are intended to distribute credits to projects that reduce the amount of carbon in the atmosphere. They achieve this by either reducing emissions or removing carbon that is already there. Importantly, these carbon credits can regularly be used by polluters to emit more carbon than would otherwise be legally permitted. The owner of some wetlands may agree to preserve the land over the next century in favor of developing it, generating carbon credit. A coal refinery may then purchase that carbon credit so that it can expand emissions beyond legal limits in accordance with what is offset by the credit. If carbon offset programs allow polluters to generate more carbon emissions, then it is imperative that carbon credits correspond to genuine differences in carbon emissions. Credits ought only to be issued when a project produces real benefits to the climate, located with some real carbon in the world. The *real climate benefits* of a program are thus the quantity of net total carbon that is removed or reduced as a result of the program's implementation. We will see that there are a number of ways to make the notion of real climate benefits more precise. These real climate benefits are typically contrasted with intentional manipulation or statistical artifacts that generate a discrepancy between "real" benefits and the purported benefits indicated by a particular metric.

Indeed, there is evidence that the largest compliance market in active operation, California's forest offset program, systematically over-credits the carbon reduced by improved forest management projects (Badgley et al., 2022a). Credits are awarded to projects whose projected carbon stock doesn't fall below *common practice*. Common practice is a regionally specific baseline developed using the US Forest Service Forest Inventory and Analysis (FIA) database. The higher this projected carbon average (over common practice), and the lower the project's initial carbon stock, the more credits are earned. Common practice estimates are determined by applying the FIA data to specific geographic regions (*supersection*s), which are subdivided into smaller regions represented by the dominant tree species (*assessment areas*). Within the Northern California Coast supersection, for example, all parcels are assigned to either the Oak Woodland assessment area or the Redwood/Douglas Fir Mixed Conifer assessment area based on which tree species are prominent. Estimated carbon stocks are determined by what the FIA data suggests about the carbon properties of these species.

However, in fixing each parcel to only one specific assessment area (*either* Redwood *or* Oak), species heterogeneity within a region is ignored. Badgley et al. (2022a) use an alternative assessment of common practice based on project specific reporting of local species to provide a more accurate representation of species diversity. With this alternative assessment, the authors discover higher baseline carbon estimates for the majority of the IFM projects involved. Single species carbon estimates were systematically lower than what we would expect in the diverse forests found in the real-world. In total, Badgley et al. (2022a), suggest that over thirty percent of upfront credits awarded by California's forest offset program are not grounded in real climate benefits, reflecting a statistical artifact of the chosen methodology for measuring carbon quantities. A significant portion of the credits do not correspond with a real quantity of sequestered carbon in the world. Local conditions differ from regional averages, and so accurately calculating how much carbon a project sequesters above baseline requires (among other things) "a more granular analysis of average carbon stocks across species and geographies" (Badgley et al., 2022a, p. 1443).

This analysis of systematic error in California's forest offset program highlights some basic ideas surrounding the more general project of carbon dioxide removal (CDR). CDR projects aim to produce real climate benefits, articulated in terms of reducing the amount of carbon that ends up in the atmosphere. One way in which these CDR projects can be prone to error is when their measures for success come apart from real climate benefits. In the case of forest offsets, the carbon estimates for a region's trees can come apart from the real carbon in those trees. Species designation can misrepresent the real species distribution of the region. In the following section (Section 3) I will consider more specifically how we should understand this "coming apart" from the perspective of the philosophy of measurement. For the remainder of this section, I investigate how California's forest offset program represents real climate benefits, and some further problems for the program.

2.2 The comparative approach and further challenges

California's forest carbon offset program provides a *comparative* quantification of real climate benefits. Credits are awarded to projects insofar as the sequestered carbon is greater than some designated common practice baseline. In ideal cases this baseline provides an empirically supported approximation for how much carbon would be sequestered in a counterfactual scenario in which there was no significant intervention on the land for the designated period of time. A real benefit to the climate is quantified as the (positive) difference between this status quo "do-nothing" baseline and the project.

This comparative approach falls in line with comparative accounts of harm in the philosophical literature. Comparative accounts of harm (Feinberg, 1984; Parfit, 1984) claim that an event harms someone if and only if the event makes her worse off than she otherwise would have been. I am harmed by a poisoned apple because eating the apple makes me worse off than I would have been had I not eaten the apple. Conversely, comparative accounts of benefit claim that an event benefits someone if and only if the event makes her better off than she otherwise would have been. I benefit by eating a non-poisoned apple because it makes me better off than I would have been had I not eaten the apple (assuming that had I not eaten the apple, I would have eaten nothing instead). One way of cashing out climate benefits, then, is the comparative approach suggested above: a project benefits our climate if the climate is better than it would have been without the project. Put another way, if a project puts us in a better position than the baseline condition, then it produces real climate benefits.

I suspect that something like the comparative approach is true for characterizing whether a project is genuinely beneficial or harmful. However, it is not immediately clear which of our chosen potential projects will achieve this comparative benefit. Furthermore, there are significant challenges in determining the baseline condition. As such, there are concerns with the comparative approach if it is to provide prescriptive guidance for policy and action. We've already seen with California's offset program how empirically imprecise methodologies can lead to systematic error in calculating baseline scenarios. Similarly, in contexts where multiple accounting protocols are permitted developers can earn unwarranted credits by selecting the most financially favorable method (Gifford, 2020). Project developers are in many cases told to "choose an accounting protocol that addresses a desired outcome" (Gifford, 2020, p. 296), introducing a kind of subjectivity into the measurement task that encourages systematic error. Developers are free to pursue specific metrics merely on the basis that they output the highest quantities of carbon. While concerns regarding subjectivity are not particular to the comparative approach, insofar as such subjectivity is permitted in the calculation of baseline carbon, we should expect baseline determinations to diverge from real climate benefits.

Nearby philosophical concerns also arise when we understand the baseline to represent the "status quo," as *what would have happened otherwise*. In particular, it is unclear whether we are positioned to reliably identify baseline conditions for what would have happened otherwise in the near future. Furthermore, it is unclear whether there is a singular baseline condition with which to compare future project estimates. Since the aim of California's forest carbon offset program is to reduce greenhouse gas emissions on timescales of decades and centuries, an estimate of what would have happened in the absence of the program (of how some particular forests would fare) will require some assumptions about how the earth's climate will progress over the next several decades. However, there are a number of different scenarios that the Intergovernmental Panel on Climate Change (IPCC) consider to be possible given our current circumstances. The IPCC utilizes several emissions scenarios in their projections of the future representative concentration pathways (RCPs) ranging from optimistic (limiting warming to 1.5C) to disastrous (exceeding 4C) warming by 2,100 (IPCC, 2023). It is unclear which specific RCP scenario we should understand ourselves to be currently tracking, and so it is unclear under which scenario we should interpret and project baseline conditions.

Even worse, once we decide which scenario best represents our current trajectory, there is still the issue of robust model disagreement for features of the climate that will influence carbon sequestration (e.g., mid-latitude precipitation change discussed in Zappa et al., 2021). If our goal in determining the baseline is to identify status quo carbon projections, we are not epistemically situated to determine a reliable baseline. Moreso, if we take the IPCC RPC pathways to illustrate real possibilities, trajectories that are still possible for us to achieve if we take the corresponding actions, then there is in fact no singular baseline.

Crediting projects upfront for projected baseline quantities generates a more pragmatic concern regarding uncertainty in the permanence of that carbon. While uncertainties about the future can induce counterfactual uncertainty of the sort just mentioned, they also induce a factual uncertainty about the future of the project that is closely tied to execution uncertainty. Even if no fault lies with project managers, there are systematic factors beyond the manager's control that threaten the successful performance of CDR projects. Baseline comparisons are made on the presumption that carbon will be successfully sequestered for the duration of the program. It is presumed that projects will store carbon for the entire century. However, in the case of forest carbon sequestration this ignores the relevant possibility that carbon is released as a result of forest destruction via wildfire, pests, and drought. In order to accommodate this expected loss of carbon, California's forest carbon offset program creates a buffer pool of additional carbon. So long as the carbon lost does not exceed the carbon in the buffer pool, the program will result in net positive carbon storage (some amount of real climate benefit). This has the effect of diluting how much actual carbon there is per credit, but the more concerning problem is that estimated losses are soon expected to deplete the buffer entirely. Estimated wildfire losses in the next decade would consume ninety-five percent of what has been set aside for wildfires throughout the next century (Badgley et al., 2022b). It is thus incredibly likely that significant quantities of credited carbon will make its way back into the atmosphere.

It is common (mandatory in compliance markets) for managers of forest carbon projects to purchase insurance for the loss of carbon that occurs during such events. However, this insurance only serves to remediate financial loss, doing nothing to resolve the disparity between carbon credits and real climate benefits. That is, insurance permits a project to continue claiming carbon credits, even while the designated carbon roams freely in the atmosphere (Macintosh, 2013; D'Alisa and Kallis, 2016; Gifford, 2020). Insofar as projects are credited upfront in accordance with baseline estimates and are permitted to keep those credits in the case that the sequestered carbon is lost (in conjunction with some minor cost), carbon estimates and their associated credits come apart from real climate benefits.

In short, empirical imprecision, subjective methodology, and factual uncertainty about the future are all ways that a CDR project can fail to generate real climate benefits. On top of this, any baseline-driven comparative approach will run into challenges determining a reliable counterfactual baseline. While I have focused on a specific implementation of forest carbon sequestration, we should expect the lessons to generalize for any carbon removal techniques (e.g., enhanced weathering, direct air capture, ocean alkalinity enhancement) that exhibit these features. Problems determining counterfactual baselines are necessarily bound up with uncertainties about the future climate, making it difficult or impossible to answer what we should expect to happen to a natural system in the absence of any project. Given the pervasiveness of these uncertainties, I argue that it is more beneficial to consider which CDR methods are capable of sequestering carbon across a wide range of environmental circumstances. Some CDR methods are more insulated from the influences of the surrounding environmental changes, providing a more permanent method of carbon sequestration. I will return later (Section 5) to discuss respective permanence.

In light of these problems, it is incumbent on the environmentalist to seek solutions and alternatives. In the following two sections I will look to the philosophy of measurement for a theoretical framework that characterizes the over-crediting problem in California's forest carbon offset program (Section 3) and guides the development of an alternative approach to real climate benefits (Section 4).

3 Models of the measurement process

In this section I detail some of the work being done in the philosophy of science, with particular attention to the broader role of measurement models (Section 3.1). Importantly, models of the measurement process require a target phenomenon and an understanding of what systemic features influence variation in that target, i.e., *difference makers*. If we hope to reliably measure quantities of carbon, for example, then we will need to understand which natural processes and properties correspond to differences in carbon quantity. Models of the measurement process thus provide a useful theoretical framework for articulating the epistemic ideals of measurement, how workers work toward those ideals, and how to identify and resolve measurement problems. Within this framework I characterize the current problem of over-crediting in carbon offset programs (Section 3.2). While the empirical problem has been conceived in terms of being a problem of averages, I argue that it is more accurately a problem about standardizing the *wrong* average, averages that fail to capture the appropriate difference makers. However, since measurement models are necessarily grounded on theoretically sound dependencies, capturing the influence of difference makers, it is true that certain counterfactual claims are indispensable for any form of measurement. I will argue that these counterfactuals are not subject to the aforementioned *subjectivity* (Gifford, 2020) or *counterfactual uncertainty* (Chay et al., 2022).

3.1 The philosophy of science and measurement

Philosophers of science have shown a renewed interest in the investigation of measurement throughout the last few decades.[1] Expanding on earlier advances in the philosophy of scientific models (e.g., Cartwright, 1983; Giere, 1988; Giere et al., 2006; Godfrey-Smith, 2006), recent philosophical work has focused more specifically on the theoretical machinery required to ground scientific measurement. This work has led to a more careful understanding of what constitutes measurement and how it can be reliably achieved. What is it about a mercury thermometer, for example, that enables a user to reliably measure the local temperature? Different philosophers disagree (of course) on precisely how to understand the measurement process, though there seems to be increased attention to the need for *models of the measurement process*.

Models of the measurement process provide a rich description of the system in which our desired measurement target is present. As such, the models capture the components of the system and their interactions that are relevant to the measurement task. If our aim is to measure the ambient temperature of a room with our classic mercury thermometer, for example, then a model of the measurement process will represent the relevant features of the column of mercury, its material container, the air in the room, and their important dynamic relationships. By capturing these features and their interactions, the model will generate specific values for the ambient temperature of the room, given a specific height of the mercury column (as well as specific values for the height of the mercury column, given a particular ambient temperature). In this way, the model of the measurement process produces a framework for understanding how targeted interventions on specific variables would influence the system (a la Woodward, 2003). A model for a specific thermometer could imply, for example, that if the ambient temperature rises 3 degrees Celsius, then the height of the mercury column should grow 3 millimeters.

It is the robustness of this model of the measurement process that allows us to reliably use a thermometer. A thermometer works for us because we understand, across a variety of environmental conditions, the regular and robust dependency between the height of mercury and ambient temperature. It is in this context that Tal (2017) argues that the target outcome of a measurement will be the best predictor of the instrument indication given the model of the measurement process. As such, Tal grounds the reliability and objectivity of measurement in robust prediction. The mercury in a thermometer can be understood to measure ambient temperature because, given the model of the measurement process, ambient temperature is the best predictor for changes in the height of mercury. Among other things, the model of the measurement process captures how ambient temperature makes a difference to the height of mercury, and vice versa.

Mari et al. (2017) emphasize the role of background theory in the proper construction of a model of the measurement process. The first step, once the measurement task is identified, is to produce a general model constructed using the general laws that pertain to the general properties of the target system. For our thermometer, this means that thermodynamic laws pertaining to temperature, molecular motion, conductivity, and thermal expansion will be incorporated into a general model. It is thus important for Mari et al., that measurement be grounded, first, in established scientific laws. From here, we go on to specify the general model for the kind of object to be measured. This is where any necessary idealizations and approximations are introduced. A specific model for measuring the temperature of my living room, for example, will likely need to presume a homogenous temperature throughout the room even if there are in fact slight temperature variations throughout. Next, a model of the measuring system is constructed to include the instruments and techniques needed to identify the target property. The mercury thermometer and my living room are modeled (in accordance with prior general and specified models) to permit the calculation of my living room's temperature from the height of mercury in the thermometer.

For Mari et al. (2017), arriving at a model of the measurement process thus requires that workers first implement their

1 Much of the credit for this resurgence in the philosophy of measurement belongs to Chang (2004) for his excellent and thoughtful investigation into the history of measuring temperature.

general physical understanding of the target, then introduce approximations to accommodate the specific features of the target, and finally integrate models of the measurement apparatus with models of the target. Reliable and objective measurement is the product of a model-building process that is grounded on general scientific laws and requisite idealizations. We should trust the dynamic relationship in the model, which represents how features of the system make a difference to other features of the system, because the relationship is derived from independently supported background theory.

For an instrument to provide a reliable measure, however, the influence of confounding factors must also be included in the measurement model. For the mercury in a thermometer to indicate temperature, and only temperature, the mercury must be held at a constant pressure. Variation in temperature *and* pressure both influence the volume of a fluid. Boudinot and Wilson (2020) and Wilson and Boudinot (2022) argue that standard measurements like the thermometer achieve this through *physical* control, while proxy measurements like tree rings or oxygen isotopes require *post-hoc* analysis, or *vicarious* control, to account for the influence of confounds. Whether standard or proxy, a reliable and robust model of the measurement process must represent those features of the real-world system that make a difference to the output, especially those that are distinct from our measurement target.

In addition to modeling and controlling confounds, we may also consider our measurements to be reliable when multiple independent methods and techniques converge on similar results. Woodward (2003) calls this convergence *measurement robustness*. Insofar as different measurement devices are constructed employing different theoretical principles and different methodological assumptions, it is unlikely that the devices will fall victim to the same kinds of error. Because the errors are expected to be independent, there is unlikely to be something fundamentally wrong with the measurement results when agreement is achieved across distinct devices. Instrumental agreement in such cases would require an implausible convergence of independent errors. We should thus have increased confidence in our temperature measurement if our mercury thermometer agrees with a thermistor, constructed in accordance with electrical principles, since their agreement would require an unexpected agreement of independent error across the devices. In this way multiple models of the measurement process, models of distinct apparatus, can work together to improve the overall reliability of our measurements.

Taken together, these ideas from the philosophy of measurement help provide a framework for understanding reliable scientific measurement. Models of the measurement process provide a sufficiently detailed description of the target system, facilitating a prediction of the desired target using some indicator (e.g., temperature from a mercury column). The objectivity of these models should be constructed in accordance with empirically supported background theory, capturing the features of the system that make a difference on the target. As such, controls should be implemented to account for the influence of known confounding causes. Meanwhile, confidence in our measurements can be bolstered with the use of independent measurement techniques, so long as the results are robust.

3.2 Measurement problems as inadequate models of the measurement process

We can frame what has gone wrong with California's forest carbon offset program using this understanding of models of the measurement process. Remember that Badgley et al. (2022a) claim that over thirty percent of upfront credits awarded by California's forest offset program are the result of actual local conditions varying from regional averages. Common practice estimates were determined by "averaging dissimilar tree species across arbitrarily defined geographic regions" (Badgley et al., 2022a, p. 1442). Some have been quick to point to the problem as relating to statistical artifacts in the generation of averages (Badgley et al., 2021), though we should be careful not to think the problem is inherent to the methodology of averages.[2] Of course any application of FIA data will appeal to carbon averages of some sort, whether they be tree-species averages, averages for a tree-species within a specific region, or something more fine-grained. It is more precise to understand the fault here to be a reliance on the *wrong* average. What makes something the *wrong* average, I will show, is a failure to model the relevant difference makers in the measurement of real-world climate benefits.

California's forest carbon offset program affords credits on the basis of how well a project's carbon stock exceeds its projected baseline. This baseline is partly determined by the regional average of dissimilar trees. However, insofar as a region contains a variety of landscapes with a variety of diverse tree species, the regional average will wash away the influence of relevant difference makers. This is why, in addition to the over-crediting, some projects assessed by Badgley et al. were assessed to be a victim of under-crediting. If a region is comprised of diverse landscapes, with diverse species distributions over its numerous parcels, then a regional average will fail to capture the factors that influence the quantity of carbon stock in a given parcel of land. The regional average fails to capture features of the system that background scientific theory implies are important for determining forest carbon stock. The distribution of tree species is a crucial determinant of the amount of carbon, and the regional average (of necessity) ignores the real-world deviation from the mean. As a result of this, regional averages fail to provide a robust prediction of the forest carbon present at smaller scales within the region. The regional average is the *wrong* average to use in assessing baseline of a local project because it is a poor measure for forest carbon stock. Species variation within the region makes a difference to the carbon stock, and the measurement model ignores species variation.

Rather, an appropriate average must consider the sorts of real-world processes that make a difference to the target phenomenon. Hypothetically, if the primary difference maker for the carbon stock of a parcel is the presence of freshwater lakes, then a project's

2 I suspect Badgley et al. (2021, 2022a) would agree with this point, though the framing of the issue on the CarbonPlan site might be misread as suggesting that averaging over diverse landscapes is sufficient for deviation from real climate benefit. Even if I am reading too much into the stated "problem with averages", we can understand my philosophical contribution to be that of making explicit what makes a *good* average.

baseline should be determined partly in accordance with whether the land does or does not contain freshwater lakes. There should at least be a carbon stock average for lake-containing land and one for land without lakes. Similarly, if the distribution of tree species is the primary difference maker for carbon stock, then a project's baseline will need to account for the distribution of trees. One could use the average carbon stock from land with 25% Douglas-Fir and 75% Oak to determine the baseline for land that is *evaluated as containing about 25% Douglas-Fir and 75% Oak*. Certainly, the species composition of a forest is one difference maker for the forests carbon stock, and for this reason it is a scandal that policy makers ignore local species composition when fixing the baseline.

In other words, we can say that the measurements of a site's carbon stock failed to be appropriately correlated to the site's *actual* carbon stock. The FIA informed regional averages failed to provide robust estimates of the quantity of carbon, and their application ignored species-based difference makers in carbon suggested by background theory. There is no robust model of the measurement process forthcoming that correlates a site's actual carbon with the current FIA informed regional averages.

The other problems with California's forest carbon offset program (Section 2.2) can also be viewed through the lens of measurement models. The difference between a project's carbon stock average over the next century and the counterfactual "do-nothing" average over the next century is difficult to estimate when: (1) a project's carbon stock is subject to hazardous uncertainties, threatening the permanence of the carbon stock, and (2) there is no single counterfactual scenario to consider. Uncertainties regarding the future generate uncertainties in the quantities that constitute the target of measurement, and so we do not know enough about the world to construct a reliable model of the measurement process. The way our climate system evolves in the near future will make a significant difference to the performance of particular CDR projects, and our best climate science suggests a significant range of viable possibilities. It isn't clear what epistemic reason we have for discriminating among the different possibilities, whether such possibilities are articulated in terms of emissions scenarios or individual model performance (given model disagreement). As such, it isn't clear what the model of the measurement process should look like, which features of the world need to be included and how to understand their dependency. It is like committing to the temperature indicated by a mercury thermometer fifty years in the future, even though there is a reasonable chance that the glass of the thermometer breaks and some of the mercury is lost.

Further concerns arise when we start awarding money and permitting pollution on the basis of such measurements, since it is not that unlikely for the quantity of sequestered carbon corresponding to the award or permitting the excess pollution to also end up in the atmosphere. Suddenly it turns out that the financial resources intended to mitigate the harms of climate change are achieving nothing, or, worse, have resulted in more carbon in the atmosphere than there would have been if we had done nothing at all. In short, the financial awards intended to drive mitigation efforts may no longer be making a difference in the right direction when a project is awarded upfront, failing to appropriately respect uncertainty about the future in the measurement model. Ultimately, it is the imperative to model all significant difference makers that will guide the development of an alternative *absolute* approach I advance in the next section (Section 4).

When Gifford (2020) raises concerns of *subjectivity* in carbon accounting, she cites several distinct ways in which carbon measurements might come apart from real benefits. We've already discussed the variability across interpretations of baseline and additionality, which Gifford flags as being "deeply subjective." Part of what Gifford is highlighting here is the distinct problem of *counterfactual uncertainty* as it relates to determinations of baseline and additionality. CarbonPlan describes these counterfactual uncertainties as those arising from "assumptions about what would have happened in the absence of a project" (Chay et al., 2022). A robust model of the measurement process ought to mitigate the impact of counterfactual uncertainty, but as mentioned above (Section 2.2) there are a number of deep counterfactual uncertainties that cannot be theoretically resolved or sufficiently constrained at the moment.

Gifford's concern over subjectivity isn't just that there are different viable interpretations in the calculation of baseline and additionality, however, but that standards are sufficiently permissive as to encourage the systematic influence of self-interest. The Greenhouse Gas Management Institute (GHGMI) is one of the major organizations offering training and certification for the measurement and accounting of greenhouse gas emissions. However, accounting standards are flexible enough that participants in accounting courses offered by the GHGMI are instructed to select (or *create*) a method and criteria for quantifying carbon that "addresses a desired outcome" (Chay et al., 2022, p. 296). A robust model of the measurement process could not permit such a strong influence of "subjectivity" on the measurement of carbon, insofar as the subjective processes confound the relationship between measurement outcomes and actual carbon stock. A better approach should thus control the influence of these "subjective" processes (a la Wilson and Boudinot), better constraining the relationship between financial incentives and real-world climate benefits. To be clear, these concerns regarding subjective confounds are not specific to the comparative approach, but rather highlight the general need for measurement standards to better accord with our nuanced scientific understanding of the system.

It is true, however, that certain counterfactuals must be included in the measurement model if it is to capture the dynamic relationship between the indicator and the measurement target. We shouldn't understand the problem of counterfactual uncertainty as being a problem with counterfactual reasoning in general. For example, a good measurement model will help workers predict the quantity of carbon stock for any potential distribution of known tree species. But this is just a form of counterfactual reasoning. *If* the land contained a 50/50 split of Oak and Douglas Fir, it *would* contain such-and-such amounts of carbon. There is nothing problematic about such counterfactuals, since their truth can be empirically and theoretically supported, which is indeed what the construction of the measurement model is all about. Some conditional counterfactuals about the future can even be mitigated through the use of empirically and theoretically grounded simulation models, or appropriately targeted paleostudies (Wilson, 2023). As such, counterfactuals themselves are not a problem for the reliability of assessing CDR technologies, rather it is significant unresolved uncertainties that are the problem.

In this section I have drawn some important ideas from the philosophy of measurement, primarily those pertaining to the model of the measurement process and its implications for the relationship between a measurement target and the measurement outcome. Ultimately, I take this framework to highlight how an approach to carbon measurement that is less vulnerable to the financial speculation or manipulation engendered by counterfactual uncertainty, and more beholden to theoretically supported empirical methods for carbon measurement, would be preferable to the kind of comparative approach we find in the California forest carbon offset program. In the next section I explore what one such approach might look like.

4 An alternative approach to real climate benefits

As Cooper (2015) highlights, *"The work of metrology is fundamental to defining the 'thing' to be exchanged in a market through the assignment and verification of particular characteristics."* However, if the *thing* currently being exchanged does not adequately achieve our aims, then we can consider an alternative thing, with alternative characteristics, to be the target for environmentally oriented financial policies. More straightforwardly, if we are unhappy with how carbon measures currently credit carbon, then we can consider an alternative approach. In this section I will discuss one such alternative inspired by our consideration of models of the measurement process, an alternative way to understand the measurement of carbon and real climate benefits. This absolute (vs. comparative) approach quantifies real benefits in terms of *actual* carbon sequestered. I will argue that this absolute approach is less vulnerable to challenging counterfactual uncertainties, resulting in a model of the measurement process that more strongly links financial incentives to sequestered carbon. Furthermore, I will argue that taking this absolute perspective on carbon serves to better promote the ideal of *permanent* carbon storage.

An alternative approach to real climate benefits for carbon dioxide removal projects does not attempt to determine a status quo baseline for the next century, but rather interprets climate benefits exclusively in terms of the quantity of carbon that is presently sequestered. While comparative approaches understand benefit relative to some projection for the future, the proposed alternative quantifies climate benefits in terms of actual carbon. In short, the more carbon is sequestered the better it is for the climate. Instead of tying financial incentives to how well a project is expected to exceed average common practice over the next century, financial incentives would be tied to how much carbon is presently observed to be sequestered. Credits would thus be doled out on a regular (e.g., annual) basis in proportion to extant carbon, such that only actual carbon reserves would be paid.

Consider this hypothetical sketch of such a program. You own 20 acres of forestland, each acre containing 20 metric tons of carbon in aboveground biomass. You intend to manage the land, increasing the carbon that it will hold, and so you sign up for the carbon sequestration reward program. Suppose the program requires you commit to a century of management. Your land is estimated to contain 400 metric tons of carbon on the first annual assessment of carbon stock, and so you are awarded 400 (tons of carbon) divided by 100 (total year commitment) units of credit for the 1st year of your project.[3] If nothing changes, then the full 400 tons of carbon are rewarded by the time the century-long commitment is up. If improved management increases the amount of aboveground carbon every subsequent year, then more credits are earned at each annual assessment in proportion to the increase. If hazards strike, decreasing the carbon stock of the land, then fewer credits are earned at each annual assessment in proportion to the loss.

While many of the details of this hypothetical program are free to vary, it will continue to utilize the absolute approach to climate benefits insofar as it credits *actual* quantities carbon based on the *amount sequestered*. Neither counterfactual uncertainty about the future nor inadequate baseline determination will drive a wedge between real climate benefits and financial awards. Switching the target of measurement to *actual* carbon stock enables the construction of a more reliable and robust measurement model so far as empirical techniques are capable of deriving reliable carbon estimates from the observable properties of the land. Projections about the uncertain future are not necessary for generating a measurement model for financial awards. Instead, a much greater emphasis is placed on theoretically constrained empirical estimates for how a project was executed (execution uncertainty), given existing theoretical uncertainties (scientific uncertainty). Whereas many important counterfactual uncertainties are intractable, execution and scientific uncertainty can be tackled with careful application of tools and practices alongside targeted research efforts (as discussed by Chay et al., 2022).

A further upshot to this alternative approach to climate benefit is how it incentivizes a careful and persistent consideration of the carbon stock, over more ambitious (yet risky and empirically tenuous) projects. One major problem with providing upfront credits conjoined with insurance policies that do not remediate carbon loss is the failure to incorporate the *permanence* of carbon sequestration into the valuation (Macintosh, 2013; D'Alisa and Kallis, 2016; Gifford, 2020). A project is always overcredited if the carbon stock goes up in flames. I suspect that the financial structure that emerges from the alternative absolute approach affords more value to the permanence of carbon sequestration. With financial reward being tied to total carbon stock over longer intervals of time, managers are motivated to protect the carbon already being sequestered and implement reliable conservationist techniques for increasing carbon stock. The financial value of the asset (in the carbon-credit sense) is more directly tied to

3 Let me note that the payout structure of this example will almost certainly need to be complicated to account for discounting and other economic realities (perhaps providing a greater payout for carbon near the end of the program). Furthermore, as I highlight later in the section, I also expect that such a program would need to be conjoined with a carbon tax to avoid the emergence of certain perverse incentives (to protect carbon stock after the policy duration has elapsed). However, the simplified example will suffice for instructive purposes.

the quantity of sequestered carbon, and the financial reward is disbursed throughout the desired period of sequestration.

Many financial aspects remain to be determined, like the credit value to be ascribed to a unit of carbon and the temporal structure of the award. I leave most of this task to the economists, though the pricing must ultimately suffice to incentivize sequestration over alternatives. The ultimate aim of establishing carbon markets is to guide agents, acting in their own self-interest, to act in ways that sequester carbon. Whatever else is true of the price of carbon, it must be such that land managers see a commitment to grow and preserve carbon stocks as a worthwhile or generally preferable financial option. The alternative is to admit that carbon markets are incapable of serving conservationist aims and ought to be scrapped in favor of more firm-handed environmentalist policies. Optimistic that there is some suitable approach to a regulated carbon market, I leave ironing out the details to the economists.

There are also a number of costs for the absolute approach that come along with a more focused attempt to link sequestered carbon to credits. First, I suggested above that the absolute approach puts a greater emphasis on resolving execution and scientific uncertainty, since it turns on more precise and developed models of the target. This means that successful implementation will place greater demands on background theory and engineering practices, encouraging potentially costly research efforts when error arises. While current approaches are also in need of targeted research efforts, a greater degree of precision and understanding may often be required for the more precise models of the measurement process encouraged by the absolute approach. This means that the absolute approach may expect more out of our scientists and engineers than competing approaches, making it more likely that workers will in practice bump up against the limits of our scientific understanding and engineering prowess.

Second, the absolute approach is likely to be less attractive to investors, making it a less marketable approach all other things being equal. Disbursing credits at more regular intervals on the basis of actual achievements, instead of disbursing them upfront on the basis of projections, places a respective limit on how much immediate financial gain is possible. Furthermore, tying carbon quantities more directly to credits also means that a loss in carbon should induce a corresponding financial loss. This exposes project managers to significant financial risks that were previously forgiven by insurance (remember that project managers could retain their credits even in the case of total carbon loss).

Third, the absolute approach would plausibly require additional policies to function as intended. A carbon tax would be needed to prevent perverse incentive structures from arising, e.g., incentivizing landowners to preserve carbon stock even after their policy lapses and there are no more credits to be gained. In this sense participation in the carbon market would be compulsory to a certain extent: while incentivized to participate in projects that award benefits for carbon storage, landowners would be legally required to pay for carbon losses. Furthermore, implementing the requisite regulatory infrastructure would be a fairly massive undertaking, requiring the collaborative efforts of stakeholders like policymakers, governmental agencies, environmental organizations, environmental lawyers, and so on. As such, a significant amount of additional work would be required to, both, iron out the details for the necessary policies (local, state, national, and international) and get the policies adopted within their respective locale. That is, while all carbon mitigation efforts require some intervention on policy, the absolute approach should require greater effort than approaches that rely primarily on features of the existing political-economic landscape.

While I am confident that each these costs help enable the absolute approach to better constrain the relationship between carbon sequestration and its financial incentives, I suspect that it is for some combination of these reasons that comparative approaches are more commonly discussed.

In this section I have outlined an alternative approach for understanding real benefits to the climate system, one that focuses on the absolute quantity of carbon over time instead of comparison to a baseline average. The approach places an emphasis on the regular and accurate measurement of actual carbon over projections, overgeneralized estimates, and regional averages. However, since the absolute approach imposes a greater financial risk to project managers, imposing greater costs in the case a projects carbon is lost, it is worth considering the degree to which specific CDR methods are vulnerable to future climate uncertainty. In the following section I consider the relative permanence for different CDR methods.

5 Permanence in carbon dioxide removal

Insofar as actual carbon stock is the target of measurement, and its sustained maintenance the aim of environmental financial policies, we can consider which are the most promising of the major approaches to carbon dioxide removal (CDR). Even if financial awards have been disentangled from counterfactual uncertainty, uncertainties about the future (including scientific and execution uncertainties) still impose a risk to CDR projects. Our goal is to sequester carbon and do it, all else being equal, for as long as possible, and so we might consider which methods of CDR best approach the ideal of permanence. The natural systems in which carbon is sequestered exhibit different degrees of sensitivity to surrounding environmental conditions, and so are more or less vulnerable to environmental uncertainties about the future. As such, models of the measurement process will exhibit differing degrees of robustness or permanence in the face of such uncertainties. I argue that we can divide methods for CDR into three broad categories with regard to their permanence: those that are *permanent* with respect to typical century and millennia timescales, those that are *risky*, and those that are *transient*.

Among the *permanent* methods are those that promote the geological storage of carbon via terrestrial mineralization or weathering, and direct air capture. What makes these methods permanent is ultimately their utilization of geological storage. Storage in causally isolated and inert, underground geological formations protects the sequestered carbon from the influence of destructive natural processes. This will typically result in carbon dioxide that is trapped in the pores of the rock (Krevor et al., 2015), dissolved in brine residing in those pores (Emami-Meybodi et al., 2015), or mineralized with rock and pore fluid (Matter et al., 2016; Zhang and DePaolo, 2017; Kelemen et al., 2019). This allows more reliable projection of the carbon stock going into the future, producing a simpler model of the measurement process: the measurement model must account for the dynamic processes influencing the measured quantity of carbon stock, and carbon sequestered in the right geological formations will be subject to fewer dynamic processes. If carbon is to be traded in an offset program, permitting the exchange of excess emissions for increases in carbon sequestration elsewhere, then these permanent CDR methods should be preferred in virtue of their minimizing the potential for unforeseen destructive processes. This carbon more precisely corresponds to real world climate benefits (i.e., less carbon in the atmosphere).

Terrestrial mineralization occurs when natural silicates or alkaline industrial mining waste mineralizes carbon. This can occur in *ex-situ, in-situ* (e.g., underground minerals), or surface contexts. *Ex-situ* use involves the extraction of the alkaline material for use "off-site" in locations like high pressure and high temperature reactors that permit enhanced reactivity (e.g., Pan et al., 2020). *In-situ* use keeps the alkaline material "on-site," producing subsurface mineralization by way of circulating carbon rich fluids through the alkaline rock (e.g., Wilcox et al., 2017). Surficial use emphasizes ambient weathering of alkaline mining waste (e.g., mafic and ultramafic mine tailings) via surface atmospheric and hydrological processes like precipitation (e.g., Mervine et al., 2018). All mineralization efforts result in the production of carbonate rock. This carbonate can then be stored in the appropriate geological contexts, removed from destructive natural processes, sequestering the carbon for as long as the geologic formation remains impermeable and isolated. The mineralized carbon can also be sold as building materials, or used to fertilize soil, though both uses significantly reduce the permanence of the carbon sequestration. Fertilizer qualifies as what I will be calling *transient* carbon storage.

Direct air capture (DAC) utilizes a variety of alternative chemical approaches to the capture of ambient carbon dioxide (Kumar et al., 2015; Keith et al., 2018). DAC devices are constructed so that fans circulate air to put it in contact with water-based solvents or synthetic sorbents. Carbon dioxide in the air ultimately binds with the reactive agent to form carbamate or carbonate bonds, while the remaining components (primarily nitrogen and oxygen) of the air circulate through the device unchanged. The chemical bonds are later broken to extract the collected carbon dioxide, before being compressed and transported. Insofar as this carbon is transported into the appropriate geological formations, the carbon is stored permanently.

Methods that are *risky* with regard to permanence include ocean alkalinity enhancement, and both terrestrial and coastal biomass sinking. What makes the methods *risky* is that the sequestered carbon stock remains well integrated in the uncertain and destructive natural processes occurring near the surface of the earth. As such, models of the measurement process need to incorporate the influence that these confounding causal processes will have on carbon stock in order to generate reliable projections of the future. We will see that while carbon stock is stable under a certain set of model assumptions, for each risky method there is at least one potential threat to permanence that our best scientific understanding of the climate suggests is reasonable to worry about.

Among terrestrial sinking projects is where we find the improved forest management methods credited in California's carbon offset program, as well as afforestation and reforestation efforts. The method should be fairly clear by now: forests are sites where a significant quantity of biotic carbon is stored. Thus, the generation of new forests, the regeneration of old forests, and the improved management of existing forests serves to increase the stock of terrestrial carbon. I suggested earlier that financial programs ought to incentivize project managers to protect and promote the development of such carbon stocks. However, there are relevant uncertainties in the preservation of forests: the possibility of wildfire or pests generates an existential threat to the carbon stock of a flourishing forest. Uncertainty in future precipitation patterns exacerbate those wildfire worries while generating additional concerns (Zappa et al., 2021): how permanent will a forest be if it no longer receives adequate rainfall? As such, there are a number of uncertain processes that threaten the reliable projection of terrestrial carbon stock.

Marine and coastal biomass sinking projects suffer a structurally similar concern, though the processes threaten at decidedly slower rates. Plants and soils in coastal ecosystems provide another source for the sequestration of biotic carbon stock in the generation and management of seagrass meadows, mangrove forests, marshes, and other coastal wetlands (Pendleton et al., 2012; Kroeger et al., 2017). While these landscapes are not particularly vulnerable to wildfire, impending changes in sea level, temperature, salinity, nutrient availability, and even pollution do threaten the stability of coastal ecosystems. Our inability to better constrain the changing of our oceans into the next century thus generates a similar concern regarding our measurement models of coastal carbon. While we can be confident that things will change, the specific changes for many coastal regions cannot be sufficiently pinned down for biomass sinking projects to be permanent.[4]

Ocean alkalinity enhancement, our last of the *risky* methods, works to increase the uptake of carbon dioxide by the ocean itself, primarily by expanding and accelerating the dissolution of carbonate and silicate minerals into carbonate and bicarbonate ions (and their associated cations). Methods for increasing alkalinity include the deposition of alkaline minerals (Renforth et al., 2013) and the construction of seawater reactors to promote weathering (Rau, 2011). The result is carbon dioxide that is sequestered in the water itself. This method is *risky* with regard to permanence, however, because carbonate ions in the ocean are used by marine organisms in the construction of their calcite shells, a process that itself releases carbon dioxide [It is also risky in the more traditional sense with regard to potential impacts on ocean ecosystems (e.g., Bach et al., 2019)]. Thus, biological calcite formation serves as a negative feedback on the storage of carbonate ions in the ocean, resulting in an ever-present leak that is proportional to the concentration of carbonate ions (given the presence of shell-forming organisms).

The remaining *transient* CDR method is biomass energy with carbon capture and storage (BECCS). I refer to BECCS as *transient* because the carbon, as biomass *energy*, is sequestered with the intention of being released again into the atmosphere. Workers treat BECCS as a method for CDR when the carbon drawn from the atmosphere is more than is released in the production and utilization of biomass energy. While there are a number of methods

4 Ultimately, there may be additional scientific reasons to be concerned with the viability of coastal carbon efforts (Williamson and Gattuso, 2022).

for producing biomass energy, one promising approach lies in capturing the carbon dioxide emitted in the production of ethanol via fermentation (e.g., Lynd et al., 2017). For example, yeast or bacteria can be used to ferment corn products into ethanol, and the carbon dioxide released in the process may be captured for storage. Thus, it may be more precise to understand BECCS as conjoining two carbon-relevant processes: (1) the generation of biomass energy and (2) the storage of carbon dioxide emitted during the process. It is biomass energy that qualifies as *transient*, shortly to be used as fuel and returned to the atmosphere. The captured emissions may qualify as permanent, being a form of DAC described above, so long as the carbon dioxide makes its way to one of our trusty geological formations.

So, there we have our three categories of permanence for CDR techniques. Insofar as our goal is to promote more permanent carbon sequestration over less permanent carbon storage, we should prefer CDR methods that are permanent to those that are risky, and those that are risky to those that are transient, all else being equal. But of course, not all else is equal, and there are finite spaces available for geological storage. As such, in providing this analysis I do not mean to suggest that CDR methods achieving relative permanence ought to, for that reason alone, be preferred to more risky or transient methods of CDR. Rather, I mean to highlight that the contribution of certain CDR methods to the goal of keeping carbon out of the atmosphere will be more readily quantifiable, such that a project's carbon stock is more reliably tied to real world climate benefits. The carbon removed in the generation of biomass energy should not be credited, for example, if it is soon to be released back into the atmosphere. Carbon should be evaluated differently depending on how securely it is sequestered.

6 Concluding remarks

In this paper I have investigated some problems with California's forest carbon offset program, including problems pertaining to uncertain future performance, subjective methodologies, and the establishment of wrong averages, as well as problems determining baseline arising from counterfactual uncertainty. These latter problems emerge for any comparative approach that quantifies baseline estimates in terms of what would happen over the course of the next century in the absence of a specific project. Confronted with these problems, I have drawn from some ideas from the philosophy of science, many from the philosophy of measurement, to provide a general theoretical framework for reliable measurement. This framework focuses on the development of a robust model of the measurement process, which represents the features of the world that make a difference to how the measurement target relates to our measurement technique. In this framework we can understand the sequestered carbon necessary for real world climate benefits to be our measurement target, while understanding the noted problems in California's forest offset program to introduce error and uncertainty into our model of the measurement process. One of the key insights afforded by this framework is that current over-crediting in the program is not the result of standardizing averages, but the result of standardizing the wrong kinds of averages. Standardized averages must be appropriately sensitive to the real-world processes that make a difference to the measurement target, unlike current forest carbon standards that coarsely represent the distribution of tree species in a region.

Problems quantifying counterfactual baselines are specifically intractable, and so in striving to reduce the error in our model of the measurement process, I sketch an alternative proposal to the comparative approach of carbon valuation. This absolute alternative does not rely on comparison with counterfactual baselines to determine financial awards, but rather looks to quantities of actual sequestered carbon in the present. While this alternative does have its constraints, it seeks to minimize error in our model of the measurement process predominantly by linking financial awards more directly to actual carbon quantities over time. However, while the absolute approach better links financial metrics to real climate benefits, uncertainties about the future still impose varying levels of risk for particular methods for carbon dioxide removal (CDR). In light of this, I conclude with a consideration of the relative permanence of the carbon sequestered by different CDR methodologies. Different physical systems will exhibit differing degrees of sensitivity to general sorts of changes we expect the earth's climate to experience in the next century, suggesting that a model of the measurement process for each method will incorporate more or fewer potential causal confounds (e.g., destructive wildfires or pests in the case of forest sequestration). In short, in the face of uncertainty about the future, some CDR methods will be more secure as a result of being causally insulated from certain environmental phenomena.

An incidental upshot of my argument, though perhaps its most important consequence, is that in engaging with CDR from a philosophical perspective (primarily from the philosophy of measurement), the kinds of ideas, insights, and frameworks that have been useful in more general philosophical theorizing might travel and find use across disciplinary boundaries. While admittedly abstract, I suspect that many workers will find it helpful to have a general schema for what goes into reliable measurement, and how to interpret and address measurement problems. The notion that measurements and quantitative estimates require a model of the measurement process with particular properties may provide a useful lens through which workers can view some of their work. Addressing climate change is a wildly transdisciplinary task, requiring the cooperation of experts across numerous domains, and so it is beneficial in the assessment and application of CDR methods that researchers have access not just to empirical results from other fields but also the ideas, insights, and frameworks that have been fruitful in other domains. I hope this paper helps further the present transdisciplinary discussion of climate change and environmental policy.

Data availability statement

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

Author contributions

JW: Conceptualization, Writing – original draft.

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Conflict of interest

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

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Responsible innovation in CDR: designing sustainable national Greenhouse Gas Removal policies in a fragmented and polycentric governance system

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In the assessment of climate policies, the social sciences are sometimes assigned a restricted instrumental role, focused on understanding and mitigating social and political "constraints" seen to impede the fullest achievement of a particular technological imaginary. The work presented in this paper draws on an alternative intellectual tradition, in which the technical, social and political dimensions of the problem are seen as closely intertwined, shaped by values and interests specific to each jurisdiction. The Greenhouse Gas Removal Instruments and Policies Project (GRIP), applied this approach to the design of policies for carbon dioxide removal (CDR) in the United Kingdom. GRIP explored what policy incentives and pathways might improve the societal assessment of different CDR technologies for further development and potential deployment. Here we analyze the views of UK policy actors questioned on different CDR options, and outline policy pathways to incentivize the research and demonstration processes necessary to determine what role CDR techniques should play in climate policy. We conclude by discussing recent policy developments in the UK, and the contours of a research agenda capable of supporting a responsible evaluation of CDR options.

KEYWORDS

responsible innovation, carbon dioxide removal (CDR), Greenhouse Gas Removal (GGR), bottom-up governance, policy pathways, United Kingdom (UK)

1 Introduction

1.1 Framing: defining responsible innovation in the development of CDR

Tackling climate change poses different challenges in different political jurisdictions. The decentralized nature of the processes set in motion by the Paris Agreement is realistic in acknowledging these differences. That agreement signaled that the planetary problem of rising temperatures is best addressed through agendas of action that are formulated locally and respond to the political, socio-economic and environmental diversity of the world. One would expect that this approach to climate policy would result in a radical change in scientific agendas, with research focused on building nuanced portfolios of ecologically and socially balanced climate actions, driven by local capacities and concerns.

Yet current policy research on carbon dioxide removal (CDR) options remains universalistic in tone, focused on the generic potential of individual technologies, with matters of public or political acceptability being regarded as external constraints on those idealized technological trajectories. In this context, the social sciences often have a narrow instrumental role in characterizing and allaying public resistance or opposition to those expected technological developments (Victor, 2015; Carton et al., 2020; Markusson et al., 2020).[1] These universalistic models of research and policy design have become increasingly inadequate as the need for realistic scenarios for CDR deployment grows.

In contrast to what we might characterize as a *planetary* approach, the GRIP project was firmly grounded in a *world* perspective. It takes the view that the social sciences should be equal partners in the process of building interdisciplinary research agendas—agendas centered on issues of governance, and capable of balancing top-down planetary perspectives with bottom-up portfolios of climate action built one at a time, jurisdiction by jurisdiction. Table 1 summarizes the contrast between these two perspectives.

In the case of the UK, the centrality of governance to the public assessment of CDR options is well-established in policy discourse. The early and influential 2009 Royal Society report *Geoengineering the climate: science, governance, and uncertainty* concluded that "the greatest challenges to the successful deployment of geoengineering may be the social, ethical, legal and political issues associated with governance, rather than by scientific and technical issues" (Royal Society and the Royal Academy of Engineering, 2018, p. xi). It recommended that "the governance challenges posed by geoengineering should be explored in more detail, and policy processes established to resolve them" (Royal Society and the Royal Academy of Engineering, 2018, p. 60). A House of Commons Select Committee responded by establishing in 2010 an enquiry into geoengineering governance. The Oxford Principles (Rayner et al., 2013), developed in conjunction with this enquiry, were accepted by the Commons Committee, and became widely adopted after the 2010 Asilomar conference on Climate Intervention Technologies (Lezaun et al., 2021). A bottom-up, jurisdiction by jurisdiction approach to the assessment and development of CDR was further elaborated in the Hartwell Paper (Prins et al., 2010), which concluded that "decarbonization will only be achieved successfully as a benefit contingent upon other goals which are politically attractive and relentlessly pragmatic." Further UK work on climate geoengineering governance, bringing together social scientists, ethicists and lawyers (Climate Geoengineering Governance Project, 2015), developed the "principles and protocols" model of climate governance, it consisting of: (a) general governance principles (such as the Oxford Principles); (b) technology-specific protocols related to the opportunity and risk profiles of particular CDR approaches; and (c) geopolitical considerations related to the environmental, social and political characteristics of each country or jurisdiction where the deployment of a particular technology is being considered.[2] A further commitment, following on from the second Oxford Principle, is to deliberative engagement and multi-criteria mapping with publics and stakeholders. This has two purposes: first, to maintain a broad range of criteria and framings in the assessment of CDR options, avoiding premature closure around certain approaches, assumptions or interests (Bellamy et al., 2013); second, to ensure that the portfolios of potential CDR techniques developed in each jurisdiction fully respond to local resources and priorities. This approach establishes a cultural and social *realpolitik* of locally based research, experimentation, regulation and action; a model in which the local has the initiative in framing as well as in responding to international governance and law.[3]

A growing number of studies exemplify the injunction to "govern CO_2 removal from the ground up" (Bellamy and Geden, 2019). The State of CDR report (Smith et al., 2023) combines a global assessment of CDR development with studies of relevant policy-making in different national jurisdictions. Schenuit et al. (2021) offer a comparison of early-stage CDR policies across nine OECD countries, arguing for "niche" national CDR initiatives that respond to local environmental, governmental and industrial capacities. Boettcher et al. (2023) describe the emergence of CDR policy in Germany, mapping how actors and positions evolve as a new domain of policy takes shape. Other studies zero in on policies for specific forms of CDR in individual countries (e.g., Fridahl and Bellamy, 2018; Fridahl et al., 2020; Hansson et al., 2020; Fuss and Johnsson, 2021; Bullock et al., 2023), or compare stakeholder preferences across different jurisdictions. Bellamy et al. (2021), for example, compare the views of policy actors on bioenergy with carbon capture (BECCS) in Sweden and the UK. Samaniego et al. (2021) examine four CDR approaches in relation to their potential economic and environmental contribution across Latin America and the Caribbean. Some recent studies explore the fit of specific CDR techniques with the priorities and capabilities of sub-national levels of government, as in Wedding et al.'s (2021) analysis of the potential role of blue carbon in California's climate strategy. In some valuable cases, new or speculative forms of CDR are placed in the context of longer historical experiences of carbon sequestration and removal (Carton et al., 2020; Kreuter and Lederer, 2021).

1 The Markusson et al. (2018) paper is of particular interest in that it brought together social scientists that had been working individually to contribute to the assessment of different technologies within the UK's first dedicated CDR research programme, who set out a common position for a more critical, socially and politically sensitized approach, grounded in work in the social sciences and humanities.

2 One consequence of this geopolitical dimensions is the need to recognize that broad sets of principles, such as the Oxford Principles or key tenets of the Responsible Research and Innovation programme (Stilgoe et al., 2013; Stilgoe, 2015), embody liberal democratic assumptions that may not always apply (Wong, 2016).

3 Elsewhere, we have argued that such a narrative of responsible innovation should replace the overwhelming emphasis on control in research governance (Bellamy and Healey, 2018). Responsible innovation, from this perspective, requires not only an acknowledgment of the risks and uncertainties raised by particular techniques, the means of mitigating them, and clarity about remaining uncertainties, but also work to determine potential steps to implementation in particular environmental and social contexts.

TABLE 1 A social-science led approach allowing world rather than planetary perspectives on CDRs/GGRs in climate action.

Dimension	Planetary perspective	World perspective
Overall framing and approach	Climate physics and climate economics are the basis for universalistic climate scenario modeling. Local scenarios based on increasing model resolution. Either entirely apolitical and asocial, or assume that key social parameters are fixed spatially or temporally.	Rooted in belief that more ambitious climate actions are only likely to be adopted if they are congruent with local conditions and linked to local strategies for the remaining sustainable development goals (SDGs).
Geographical/epistemological focus	Focus on global potential. Particular CDR approaches considered individually. Assessment of global potentials leading to identification of local targets. Use of burden-sharing approaches based on top-down assessments of local potentials ('under-utilized land', etc) to allocate national targets.	Focus on local potential; culturally and politically sensitive to local environmental and human resources and their synergies and trade-offs. Assessment of local potentials leading to identification of global contributions.
View of social and political agency: role assigned to governments and stakeholders	As consultees in granting 'social license to operate', often in terms of consent for experimentation or deployment of a particular CDR technique (although sometimes inappropriately extended to other places and times).	As customers for scientific and governance capacities to set CDR portfolio strategies in line with other development requirements; co-working with interdisciplinary science/social science researchers.
Wider social engagement, outreach and dissemination	Primarily an 'end-of-pipe' add-on	An integrated function of the co-creation of locally appropriate CDR portfolios and their governance.
Broader legacy of research	Restricted application. Applicability to national portfolio building typically, beyond scope of approach.	Multidimensional mapping allows broad general conclusions and knowledge transfer, but always subject to local test.

1.2 Aims of the GRIP study and the purpose of this paper

GRIP was the Greenhouse Gas Removal Incentives and Policies Project, carried out at the University of Oxford between 2016 and 2019, with the intention of providing an initial country case study of CDR potential within the Principles and Protocols approach. GRIP was funded by two US based philanthropic foundations, and its central objective was to explore what policy incentives and policy pathways might facilitate the responsible development and potential deployment of CDR in the UK.

In this study, the CDR techniques considered were improved agricultural practices for carbon sequestration and storage (including new approaches to soil management), afforestation, peat bog enhancement, biochar, enhanced weathering, ocean alkalinity enhancement, ocean fertilization, bioenergy and carbon capture and storage (BECCS), ocean afforestation (chiefly seen as marine BECCS but with some claimed co-benefit for fisheries), and direct air capture and storage of carbon dioxide (DACCS). This list survived the interviews intact, with the partial exception of peat bog enhancement.[4] We were not looking for definitive assessments of these technologies, but for an initial view on whether they might individually be candidates for inclusion of a UK CDR research, development and demonstration portfolio.

GRIP included two components: interviews with a set of informed stakeholders drawn from UK government, academia, industry, and non-governmental organizations, and a set of public engagement exercises designed to characterize perceptions on different CDR technologies and policies (Bellamy et al., 2017, 2019, 2021). In this paper we present and analyze the materials obtained in stakeholder interviews.

2 Materials and methods

Here we present results from 35 interviews: 11 government (public or civil servants), drawn from different government departments or agencies; four parliamentarians, drawn from the House of Commons, the House of Lords and officers of the Parliamentary Estate; five people drawn from NGOs/Civil Society; four from industry; and 11 academics (the majority, but not all, natural scientists). Interviewees from industry, academia and NGOs had all contributed to academic and public discourse on Greenhouse Gas Removals; government and parliamentary representatives had either similarly contributed, or held roles that were concerned with climate policy. The interviews were carried out jointly by Tim Kruger, a natural scientist, and Peter Healey, a social scientist, between Autumn 2016 and Spring 2017.[5] An initial list of individuals in each category was expanded through asking each interviewee for further suggestions.

The interviews covered the criteria that might be employed to assess the various techniques, and the regulatory, financial and communication strategies that might be used to develop or inhibit them as appropriate. Interviews lasted roughly 90 min each, and were conducted using a semi-structured schedule (see Annex 1). The interviewers alternated in leading on the different sections of the schedule. At predetermined points, show sheets (see Annex 2) were used to prompt interviewees on the full range of possible responses to a question. This approach might have

4 Several interviewees suggested that peat bog enhancement focuses on the restoration and maintenance of carbon stocks in peat bogs, and that the very slow pace of expansion of this stock puts it beyond consideration for policies concerned with expanding carbon drawdown.

5 Before each interview, Kruger declared his interest in Origen Power, a company developing a technology that aims to combine carbon capture and power generation, and which could in principle benefit from some of the policy proposals set out in this paper.

led to a certain convergence of interviewee responses. However, although we worked from a predetermined set of questions, we often followed up on particular responses that reflected individual interests or expertise. Together with respondents' own choices as to what to give emphasis to, this meant that not all questions were answered by all respondents, and similarly not all CDR techniques were assessed by each interviewee.

Toward the beginning of the interview, we asked each interlocutor whether they agreed with the working assumption of the project—namely, that appropriate and permanent CDR technologies would need to be deployed, along with mitigation and adaptation strategies, to stabilize our climate—and, if so, whether they would say that CDR techniques and policies were being developed at an appropriate pace. Given that we had framed our research in this way we thought it appropriate to find out if our informants agreed with us. Toward the end of the interview, we asked them whether they thought that CDR was becoming more or less salient over time.

For the more detailed analysis of CDR techniques reported below, NVivo was used to help identify 422 evaluative comments associated with particular techniques, ranging from 19 comments on ocean afforestation to 73 comments on agriculture and forestry. Each of these was coded by one author on a five-point scale, ranging from −2 to +2, based on whether the comment was positive or negative about the technique being addressed, and the strength of the comment. Additionally, a score of two (positive or negative) was given to multiple comments lying in the same direction; a score of one to a single comment. A comment would receive a zero score either for a neutral opinion, or for a comment which raised a negative issue about a technique, but then pointed to its solution. Repetitions of the same point by the same respondent were scored only once; if the same positive or negative point was made by different respondents, it would be scored in each case. A total score for the acceptability of the technique was defined as the total of all positive scores minus the total of all negative scores. The method is analogous to that by which approval ratings of politicians have long been assessed. In parallel with the scoring, the first two authors working together noted recurring positives and negatives about each technique, together with suggested steps to progress the technique/reduce uncertainties. Results are reported in Sections 3.1–2.

In addition, we analyzed the interview responses with the aim of determining which potential policy pathways might fruitfully be applied to the development and assessment of different CDR approaches, although here the interviews provided less guidance. We used this analysis as the basis for our views on potential UK strategies to develop and deliver responsible CDR, which we report in Section 4.1.

3 Results

3.1 General conclusion: growing salience and uncertainty, in a context of slow research, development, and demonstration

Greenhouse Gas Removal presents particular challenges in that policy-makers need to make decisions about technologies which mostly do not yet exist as full socio-technical propositions (or even, in many cases, as full technical propositions), and which in consequence cannot yet be fully assessed for their potential role in climate policy. Reflecting this challenge, most of our interviewees agreed with two statements: that CDR techniques were not developing at an appropriate pace; and that, at the same time, CDR was growing in policy salience as emissions reductions were not keeping pace with the targets set in the Paris Agreement. Some interviewees sharpened the paradox by combining these judgments with a third one: that, in the minds of policymakers, the uncertainties surrounding CDR techniques were increasing.

3.2 Views of the individual potential of CDR techniques in detail

3.2.1 Results of the scoring of comments

The overall analysis of interviewees' comments showed a strong tendency toward negative comments: 118 were scored positive, against 156 negative. Further, the use of comments that were scored "very negative" (−2 score) exceeded the "very positives" (+2 score) by more than 2 to 1 (28 to 11). Possibly even more significantly, the number of comments reflecting neutrality or uncertainty about techniques, 148, nearly matched the negative total. Overall, only 28% of the comments made by interviewees were positive, and although we are reluctant to give too much significance to relative technique scores given current gaps in our knowledge, only three techniques by this assessment—DACCS, peat bog restoration, and agriculture and forestry—attracted net positive scores. Despite these qualifications, we see it as significant that none of our interviewees was willing to rule out *any* technique as a possible candidate for deployment in some possible scenario, subsequent to further research, development and demonstration.

3.2.2 Results of the qualitative analysis of comments focused on possible ways forward for each technique

Interviewees offered diverse views as to the main requirements for each technique to progress, pointing to a possible future agenda for further research and more appropriate governance. The results of the detailed analysis of respondents' views on each technique are set out below. For each technique a characteristic positive and negative comment are given, together with a summary assessment of the main requirements identified by interviewees for that technique to progress to a point when it could be fully assessed for deployment. Actual quotes from the interviews were considered too long to be included here in full, but all the comments on one technique—enhanced terrestrial weathering—is available as Annex 3 to conveys something of the richness of views offered by interviewees. The full set of views are available on request as a source for independent secondary analysis, and has already been used by Boettcher (2020).

Abbreviations used in the text are CCS, Carbon Capture and Sequestration; MRV, monitoring, reporting and validation;

ETS, emissions trading scheme(s); IMO, International Maritime Organization.

3.2.2.1 Ocean fertilization

Main positives for this technique

- A framework for regulation of ocean fertilization is already in place through the International Maritime Organization (specifically, through the London Convention/London Protocol);
- Possible co-benefits to fish stocks;
- Micro experiments may be possible, but these would be very difficult to assess.

Main negatives for this technique

- There are questions about our present capacity to measure the effectiveness of the technique;
- This is further hindered by the lack of a marine MRV framework;
- It would be even more difficult to assess complex ecological impacts.

Requirements for this technique to progress

- R&D focused on the science of nutrient distribution and impacts;
- Local experiments emphasizing impacts and costs may be useful in places where the oceanic flux is geographically contained;
- Further IMO work to establish a framework for the assessment of impacts.

3.2.2.2 Ocean alkalinity enhancement

The positives and negatives for ocean alkalinity enhancement closely followed those for ocean fertilization: on the possible extension of the IMO London Convention/London Protocol case-by-case approach to the governance and assessment of ocean fertilization to this technique; on the difficulties of assessment, especially of second and third order impacts on complex oceanic ecology; and on the need for work on alkaline distribution. As a potential positive, increasing alkalinity would counter ocean acidification and this might benefit some species.

3.2.2.3 (Terrestrial) enhanced weathering

Main positives for this technique

- The chemistry and scalability are broadly known;
- Use of industry waste (e.g., mine tailings) could reduce costs and improve acceptability;
- Claimed co-benefits in crop yields.

Main negatives for this technique

- Potential energy costs involved in milling, transportation and distribution;
- The challenges and costs of identifying and removing contaminants;
- The efficiency/safety trade-off in particle size;
- Other environmental impacts of marine or land distribution.

Requirements for this technique to progress

- Progress with MRV and adoption of acceptable proxies for effectiveness;
- Life-cycle assessment to establish costs and benefits under different assumptions of mining industry inputs and scales;
- Regulation on contaminants and particulates;
- R&D on possible co-benefits and co-costs;
- Public engagement to test acceptability, especially in areas of environmental sensitivity.

3.2.2.4 Bioenergy with carbon capture and storage (BECCS)

Main positives for this technique

- Potential use of waste feedstocks, especially from pulp and paper;
- Industry interest suggests routes to scale-up;
- Also suggests local, integrated applications.

Main negatives for this technique

- Life cycle assessment critical;
- Potential land use competition with food and biodiversity;
- Might be limited application in the UK on local feedstocks;
- Challenges of longevity, safety and acceptability of CO_2 storage.

Requirements for this technique to progress

- R&D on different feedstocks and their different potential uses in energy/heat production;
- An adequate and stable CO_2 price;
- Carbon transport and storage infrastructure—state provision of these could subsidize costs.

3.2.2.5 Biochar

Main positives for this technique

- Provides long-term capture;
- Claimed co-benefits to soil quality;
- Potential local integrated use;
- Commercial models of use are available.

Main negatives for this technique

- Difficult to assess benefits;
- Risks of soil contamination or air-borne particulates;
- Irreversibility of soil additives;
- Application at high rates (the Royal Society/RAE report 2018 cites 50 tons per hectare) over very large land areas would be required to yield a significant contribution to CDR.

Requirements for this technique to progress

- R&D to establish efficacy, claimed co-benefits and scalability;

- Standards and regulation to protect soil safety, especially where crops are grown, and to protect the public against particulates;
- Carefully assessed local demonstrators might be useful in assessing impact and reversibility.

3.2.2.6 Ocean afforestation

Main positives for this technique

- IMO regulatory framework in principle in place;
- Claimed co-benefits to fish stocks;
- Micro experiments would be possible in contained environments.

Main negatives for this technique

- Nutrient loss resulting from growing macro-algae will be amongst wider ecological impacts which will be hard to assess;
- These assessment challenges are compounded by the lack of a marine MRV framework;
- Possible energy costs of drying macro-algae;
- Challenges of longevity, safety and acceptability of CO_2 storage.

Requirements for this technique to progress

- Importance of life cycle assessment;
- Further IMO work on regulation;
- Local experimentation emphasizing impacts and costs.

3.2.2.7 Direct air capture and storage (DACCS)

Main positives for this technique

- No point sources of CO_2 needed.
- Can be located over storage facility.
- Least environmental/social impact.

Main negatives for this technique

- No co-benefits.
- May involve high energy and water resources.
- Process chemicals may raise issues of supply and disposal.
- Needs large/heroic cost/ton reductions.

Requirements for this technique to progress

- Innovation incentives driving R, D, and D.
- Probably big industrial involvement to drive down costs in scale-up.
- CCS infrastructure.

3.2.2.8 Peat bogs

Main positives for this technique

- Peat bogs are well-represented in the UK;
- They enjoy a culturally/socially positive status;
- They have strong environmental co-benefits;
- They represent a possible step to paludiculture—wet agriculture—which may be more environmentally sustainable.

Main negatives for this technique cited

- They are more about greenhouse gas retention—about maximizing and maintaining existing sinks—rather than new capture.
- Peat bogs are vulnerable to climate change (e.g., if they dry out they release methane).

Requirements for this technique to progress

- Specially protected status, ideally international;
- Work to calculate net carbon benefit and the impacts of exposure to climate change in the longer term;
- Targeted R&D on paludiculture.

3.2.2.9 Agriculture and forestry

Main positives for this technique

- "Natural" technique;
- High on social acceptability;
- Many potential co-benefits, including agro-forestry.

Main negatives for this technique

- Benefits and co-benefits depend on forest design: species selection, harvesting schedule and use of timber/harvested crop, etc.;
- Potential land-use competition between forests, food, and fuel;
- MRV issues—history of local and state cheating;
- Limited UK scope;
- Developing and applying UK policy is complicated by diversity of UK soils.

Requirements for this technique to progress

- R&D on MRV and proofing of benefits against the impacts of future climate change;
- Work on financial and informational incentives and regulation.

4 Discussion

4.1 A potential UK strategy for assessing and developing carbon dioxide removal

One of our research aims was to develop, and to feedback to our respondents, a potential UK strategy for developing CDR broadly consistent with the views expressed in the interviews and our own assessment of the UK's innovation environment and policy pathways.[6] The proposed strategies set below, along with other

6 Of course, treating the UK as unified entity is itself a simplification, since environmental capacities vary and policies affecting some CDRs (notably

project findings, were fed back to interviewees in the last quarter of 2019. Subsequent significant developments since then are covered in Section 4.4.2.

4.1.1 A national adaptive learning strategy for CDRs

Before decisions on CDR deployment are made, research, development, and demonstration projects need to be more fully employed to reduce uncertainties (and acknowledge which uncertainties are irreducible). We do not see the function of the state as picking winners among CDR technologies, but as the source of a legal and policy framework that will allow a national adaptive learning strategy on the possible utilities, co-benefits and co-costs of a diverse set of CDR options. Such a framework should comprise an overall consistent national narrative for CDR in the context of climate policy, mechanisms for public deliberation, incentives for the emergence of "winners," and the formulation of any necessary regulatory constraints. This should create opportunities to progressively strengthen collaboration and mutually shared expectations among all the parties involved: government, industry, academia, civil society organizations and wider publics. We accept the message a number of interviewees put to us that industry in particular needs both a clear direction of travel and predictable incentives to lower the risks of innovation with these technologies. Whilst policy needs to be neutral as to technologies and minimize lock-in and path dependency for those eventually selected for deployment, a degree predictability is necessary to facilitate the necessary investments.

4.1.2 A key reference point for policy—the carbon price

One of the radical policy initiatives that has been proposed and which received a broad level of assent from interviewees was a carbon price set at a relatively high level (at the time we were thinking of something of the order of $50/ton). This price would operate as a tax on emissions, would be zero-rated for net zero emission technologies, and act as a rebate/positive payment for net negative CDR systems. This could be revenue neutral as far as the UK Treasury is concerned, and indeed could be organized to avoid payments passing through the government accounts at all, as is the case with some payments under waste disposal policies (see policy pathway 2 below). It would be designed to ensure that the carbon polluter pays, but also that those capturing carbon were rewarded at a level that would prompt innovation and thus hopefully draw down the cost of capturing and storing greenhouse gases over time (and thus the scheme's floor price).

Interviewees were generally supportive of such a scheme *in principle*, but were conscious of some of the possible implementation problems. Notably, that it would make sectors of British industry and transport uncompetitive (this risk might be partially mitigated by basing it on carbon budgets allocated to individual consumers, but this would introduce additional complications). Brexit played both ways on this and indeed on most possible policy interventions on CDRs: it allows the UK more policy freedom but also exposes it to more risks if policies were not applied simultaneously across major economic competitors. Further, as the Royal Society/Royal Academy of Engineering pointed out in its comprehensive report on Greenhouse Gas Removal, "as carbon emissions are reduced (in consequence of the scheme's success) the income from an emissions tax could fall, while GGR [CDR]levels would need to be maintained, or even increased" (Royal Society and the Royal Academy of Engineering, 2018, p. 81). Although such a scheme is not immune to such perverse incentives and unintended outcomes, the steps we set out below are referenced to this aspirational policy.

4.1.3 An innovation environment that will enable the responsible development of CDRs

The key task remains: to develop what are, by and large, immature technologies along the research development and demonstration chain, until they can be assessed as fully specified sociotechnical options. The initial stages of the strategy we advocate calls for the development of an innovation environment, because a primary purpose is to ensure that a wide range of competing potential technical options emerge. Over time, this approach will evolve capacities for demonstration, scale up and potential deployment, involving the skills and capacities of larger-scale industry, encouraging a process of consortia-building and the development of an active market in relevant intellectual property. Crucially, the state will also be responsible for setting standards for measuring, reporting and verification (MRV) and other regulatory requirements as each technique evolves. It would also of course have a responsibility in addressing market failures, or limits to the market's willingness to bear costs and risks. One such issue that will need to be tackled at an early stage is the public provision of relevant infrastructure, in the form of pipelines and storage facilities, for example (Oxburgh et al., 2016).

4.2 Potential policy pathways: contracts for difference and producer responsibility obligations

Here we discuss two potential general policy pathways to advance this agenda, drawing on our interviews and recent policy proposals to incentivise CDR development (Cox and Edwards, 2019; Jenkins et al., 2021, 2023; Burke and Gambhir, 2022).

4.2.1 Contracts for difference

The central financial mechanism to advance this agenda is analogous to the *contracts for difference* (CFD) successfully employed to incentivise the development of low carbon electricity generation within the UK. As described by the UK Department for Business, Energy and Industrial Strategy et al. (2022; BEIS—currently the Department for Business and Trade), a generator party to a CFD is paid the difference between the "strike price"—a price for electricity reflecting the cost of investing in a particular low carbon technology—and the "reference price"—a measure

grounded in land use changes), are the responsibilities of the devolved administrations in Wales, Scotland, and Northern Ireland.

of the average market price for electricity in the UK market. In the case of electricity generation, the stated aim is "to give greater certainty and stability of revenues to innovator electricity generators by reducing their exposure to volatile wholesale prices, whilst protecting consumers from paying for higher support costs when electricity prices are high."

In the case of CDRs, the strike price would be the cost of carbon capture and long-term storage and the reference price would be the carbon price operating in the EU Emissions Trading Scheme (or a UK national alternative). We propose that the strike price should be set initially at a price high enough to incentivize innovation—for illustrative purposes $50/ton, but limited at around this figure in order to weed out some of the more high cost propositions. Contracts for difference would commit actors to deliver stored carbon at a stated date at the contracted price.

As innovation and competition intensified, one might expect the strike price to be driven lower. There would be a clear advantage, however, in not letting the market concentrate around a single winner too early. For a range of reasons: the emergence of unanticipated problems or externalities with that particular technological configuration; the fact that the mix of technologies advanced under the Paris Agreement targets is likely to be different in countries with different geographies, geologies and priorities; and the possibility that slower to develop technologies might ultimately prove more cost-effective and/or publicly acceptable.

In many cases CFD contracts would themselves cover the costs of R&D&D leading to a capacity to capture and store carbon; but in some cases, where there are no offers to do so for an otherwise promising technique, it may be appropriate for further R&D efforts to be carried on the public purse by direct government expenditure. It will also be necessary to maintain R&D capacity on the public purse to ensure that the development of standards for measuring, reporting and verification (MRV) keep pace with technological development.

A second phase of the CFD policy pathway will allow the gains of the innovation stage to be utilized in the wider economy. It is at this second stage, that we would propose the introduction of a significant tax on emissions, relating this to the then CDR strike price. This change will have been clearly signaled at the same time that phase one on innovation was launched, together with as much detail as possible about its terms of operation. The knowledge that this was coming will itself have incentivized industrial investment in phase one. We suggest that the tax should be introduced in phases through the use of a "emissions tax escalator," starting at a low level but converging with the strike price after a further 5 years.

Industries that face special challenges in reducing emissions might be offered concessions in the form of a less steep convergence slope over a longer period, plus the possibility of emissions trading for that period (trading that would include CDRs). Other than these exceptional cases, we believe that including CDRs in emissions trading is problematic. On the one hand, an emissions trading scheme that allows CDR may increase demand for some techniques and speed up their introduction at the right price; on the other hand, such a market may lower the incentive for industries to decarbonize and thus postpone, potentially indefinitely, the successful decarbonization of the economy.

4.2.2 Producer responsibility obligations

The GRIP project also explored whether regulations designed to manage waste could be adapted to address excess greenhouse gases in the atmosphere. One example is the adoption of Producer Responsibility Obligations (PROs) similar to those used for the management of packaging waste. Packaging is one of several areas which are governed by such regulations, which were developed by the UK Government in response to the obligation, under the EU's Waste Framework Directive, to meet targets for the recovery and recycling of waste.

The key elements of the Packaging PROs are a registry of packaging producers, material-based recycling targets, and an obligation on packaging producers to demonstrate that they have achieved the relevant recycling target. This recycling can be achieved by a third party. Under a PRO scheme, the principle of "the polluter pays" is applied. The regulations provide an incentive to producers of waste to reduce the amount of waste that they produce, and an incentive to recyclers of waste to innovate. The specific material-based recycling targets can be tightened as the capacity of the recycling industry increases. Furthermore, the regulator does not directly dictate the price—the system creates a market-clearing mechanism whereby there is a transfer of resources from the producer of waste to the recycler of the waste. The regulator can indirectly influence the price, however, by setting the tightness (or looseness) of the material-based recycling targets.

Under the provisions of UK and EU law, all companies that handle packaging above a *de minimis* threshold are required to register. A producer of waste must demonstrate that a certified recycler has recycled the required proportion of produced waste. The price of the certificates that demonstrate recycling are set through a market mechanism where demand for the certificates is determined by the amount of waste produced multiplied by the material-based recycling target, and supply of the certificates is determined by the capability of the recycling companies. Money thus flows from the producer of waste to the recycler of waste, with the government's role limited to the formulation and enforcement of regulations, the setting of materials-based recycling targets, and the collection of registration fees.

How could such a scheme be used to incentivize CDR? The first step would be to establish a register of emitters of greenhouse gases (Companies are already required, above a *de minimis* threshold, to report emissions of greenhouse gases as part of The Companies Act 2006). The government would then need to set a Removal Fraction (the proportion of emissions that is required to be stored) for each greenhouse gas. These fractions would be analogous to the material-based recycling targets for packaging waste. Initially the Removal Fraction would be set at a low level and would increase as the capability to store greenhouse gases develops.

Obviously, the removal and storage of greenhouse gases raises a number of specific issues. Not all greenhouse gases can be treated in the same way, and it may be necessary to start the system with carbon dioxide and develop separate regulatory structures for other greenhouse gases at a later date. The requirement for a significant investment in infrastructure (namely pipelines to transport carbon dioxide to suitable storage sites offshore) is likely to be a significant barrier to achieving storage. The Oxburgh

Report of 2016 recommended the creation of a government-backed company tasked with delivering transport and storage infrastructures. This is in recognition of both the large amount of investment required (especially in the context of an absence of commercial incentive), and of the fact that pipelines are often natural monopolies that require regulation.

Those companies that would receive payment from emitters for storing carbon dioxide may seek to obtain high-purity carbon dioxide from sources such as ammonia production facilities and bioethanol plants, as these sources would be cheaper to treat and store than more dilute sources (such as the flue gases from a natural gas fired power plant). As the Removal Fraction increases, those companies that store carbon dioxide would use increasingly dilute sources of carbon dioxide. This approach would work with both "conventional" CCS from concentrated sources of emissions, such as the flue gases of fossil power generation plants and industrial processes, and also CDR techniques that remove carbon dioxide from the atmosphere. Indeed, proposed CDR techniques could hypothetically enable the Removal Fraction to increase to beyond 100% at some future point.

4.3 Comparative geopolitical perspectives on CDR policy

To explore how early-stage CDR policy in the UK compared to developments elsewhere in the world, we commissioned reports from experts in India, Sweden, Germany and the EU as a whole. Several key themes emerged from this work. First, that there was no one-size-fits-all model—each jurisdiction has its own unique issues and approach, and policy development is of necessity country-specific.

At the same time, there was a significant gap between policy objectives and actions required to achieve those objectives in all jurisdictions. Many countries want to see themselves as climate policy leaders, but they are unwilling to actually lead on CDR, despite evidence that CDR will be needed to meet climate targets.

There is a bias toward approaches that have "perceived naturalness"—despite concerns about effectiveness, scalability, and potential side-effects on food supply, biodiversity and land tenure. There were also concerns about the potential for LULUCF accounting criteria to be gamed and be used as a way to offset emissions from other sectors. There was, moreover, an emphasis on techniques that create co-benefits. This can be seen through both economic and political lenses—if they entrench, for example, pre-existing vested interests with strong lobbying capacity such as farmers and land owners.

CCS confronted significant political challenges in all jurisdictions, which undercuts many CDR techniques. If CCS is not an option politically, many CDR techniques are off the table, including BECCS, which underpins many of the integrated assessment models (IAMs) that inform policy. There is furthermore widespread concern about emphasis of CDR undermining efforts on emission reduction.

There is a willingness in many jurisdictions to see CDR undertaken in geographies other than their own—a sort of national NIMBYism—such as the UK importing biomass from North America for BECCS; Sweden looking to purchase certified carbon reductions from other countries; Germany being unwilling to countenance CCS in its own country while leading the development of integrated assessment models that imply vast quantities of BECCS; or India seeing the obligation of CDR as chiefly residing with countries which have greater historic emission responsibilities. It seems that countries wish to garner the benefits of CDR whilst ensuring that the detriments are borne by others.

Overall, there seemed to be few incentive structures in place to motivate development of CDR, and the creation of such structures was not anticipated in the short term. This gap has remained despite the proliferation of commitments to achieve net zero emissions in the second half of the century.

4.4 Recent developments in UK CDR policy

Schenuit et al. (2021) see the UK as a typical case for their ideal type of *proactive policy entrepreneurship*, and note that "none of the [eight] other countries studied have such explicit policy support for the development and deployment of CDR methods." Is their positive assessment justified?

In the period since the start of the GRIP project several factors have changed the external environment of climate policy: a rapid growth in global average temperatures and increased incidence of extreme weather events; increasing awareness of climate change as a problem and increasing salience of public mobilization (School Strikes for Climate, Extinction Rebellion, Just Stop Oil, legal challenges to country and corporate climate policies); the publication of the IPCC's Special Report on One Point Five Degrees, which highlighted the damage resulting from a 1.5C rise and the need to achieve net zero emissions in the near future; a ratcheting up of climate ambition in terms of the adoption of Net Zero targets, first in Sweden (2017), followed by the UK (2019) and the G7 (2021).

In the UK, policy action on climate change in general, and CDR in particular, has been impacted by the socio-economic shocks of the past few years: the implementation of Brexit has increased the burden on policymakers, diverting attention from other priorities; the severe consequences of the COVID-19 pandemic have constrained economic resources and the bandwidth for policy development; and the "cost of living crisis" threatens to fracture the broad political consensus about the Net Zero goal. Opinion surveys, however, give little indication that popular support for climate action has diminished (European Investment Bank, 2023).

The UK Government started to seriously consider removals in the Clean Growth Strategy (published in 2017 and amended in 2018; UK Department for Energy Security and Net Zero, 2017). It made two recommendations: (i) "A Government programme of research and development," and (ii) "The Government will consider the scope for removing barriers and strengthening incentives to support the deployment of CDR."

The GRIP project played a role in the development of the first of these recommendations. An engagement exercise convened by one of the authors and interviewers (Tim Kruger) and one of the interviewees (Richard Templer) involved a series of meetings with senior representatives of government departments and research councils (many of whom were themselves people we had interviewed as part of this study). These meetings highlighted the lack of resources for research, development and demonstration in the UK, and led to the proposal of a programme of work through the UK's Strategic Priorities Fund. In due course, £31.5 m of funding was secured for a range of CDR Demonstrator projects and a coordination hub to research the development of policy to responsibly incentivize the deployment of CDR techniques. Subsequently, the amount of resources dedicated to CDR research and development was boosted to £100 m, with resources being used to support a wider range of early-stage CDR techniques.

The second recommendation is in the process of being fulfilled, albeit slowly. A consultancy report commissioned by the government from Vivid Economics (Vivid Economics, 2019) laid out a broad array of potential policy mechanisms and the Government recently published the results of two consultations, one on business models to support Power BECCS and the other on business models to support other engineered CDR techniques. The UK Government is minded to support the development of CDR techniques by providing a mechanism similar to the Contracts-for-Difference approach. However, further development continues to be hampered by a number of factors, including a lack of clarity as to what actually constitutes a qualifying removal, and slow progress on CO_2 pipeline development (both the physical infrastructure itself and the supporting regulations.

The *Biomass Strategy* (UK Department for Energy Security and Net Zero, 2023), which is intended to determine the appropriate uses to which the supply of biomass in the UK should be allocated, was belatedly released in August 2023. While the strategy continues to affirm that BECCS will have a role in the UK's approach to achieving Net Zero, it highlights the wide range of unresolved issues rather than resolving them—or indeed detailing the process or timeline for such resolution. Finally, there have been repeated delays in announcing the details of a business model that would allow businesses to determine whether to invest in deployment.

In addition, while there is a stated ambition to take a "technique-agnostic approach," the indications in the consultation briefings suggest different levels of support for different techniques. This approach would inevitably lead to technology developers gaming the system to fit themselves into the most generously supported "technology bucket," rather than focusing on delivering the lowest-cost system.

The approach the UK Government is taking draws inspiration from the processes that were used to support the diverse range of approaches to producing renewable electricity. However, renewable electricity and CDR are sufficiently different in character for this extrapolation of policy approach to present serious challenges. Electricity generation is constrained in both space and time—to be efficient it needs to be generated close to where it is to be consumed, and supplied in a manner that balances supply and demand on a second-by-second basis. Neither of these constraints is pertinent for CDR. From a climate perspective it does not matter where in the world CO_2 is removed from the atmosphere—the atmosphere is well-mixed and a ton of CO_2 removed from the air above the UK is fungible with a ton of CO_2 removed from the air above, say, Australia. With regards to the time considerations, unlike electricity generation CDR does not need to be balanced on a second-by-second basis.

The UK Government is proposing that individual CDR projects will negotiate bilateral cost-plus contracts, as a way of stimulating a wide range of proposed techniques. This will inevitably lead to cost padding; complication, uncertainty and delays resulting from the negotiation process; and will result in gaming of the system, if not outright corruption. Cost-plus contracts will constrain price-discovery and foster subsidy-dependence rather than promoting innovation which could drive down costs.

It is important to consider the UK's lack of progress on policy in the context of policy developments elsewhere. In particular, the Inflation Reduction Act (IRA) passed in 2022 in the United States provides an incentive of $180 per ton of CO_2 removed from the air (Global CCS Institute, 2022). This stimulated the EU to develop the Net Zero Industry Act (NZIA), an initiative to provide support for technologies essential to achieve net-zero emissions. At this point in time, the NZIA is in the process of development and it is still unclear whether or not there will be policies specifically focused on accelerating the development and deployment of CDR techniques. In addition, the US Department of Energy has allocated funding of up to $1.2 billion for two direct air capture demonstrators or "hubs," each of which is expected to remove more than 1 million tons of CO_2 from the atmosphere and permanently store it (US Department of Energy, 2023).

The cost-plus approach favored by the UK Government contrasts unfavorably with the fixed price approach of the US Government. This contrast means that lower-cost approaches would prefer to operate in the US, while higher cost approaches would prefer to operate in the UK. For example, if the UK were to apply a cost-plus-20% approach while the US applies a flat-rate $180 per ton approach, this would mean that a technique that costs $100 per ton of CO_2 removed from the air would locate in the US (they can make a profit of $80 per ton, while profits would be limited to $20 per ton in the UK), whereas a technique that costs $300 per ton would locate in the UK (they would make a profit of $60 per ton in the UK and a loss of $120 per ton in the US). At vast expense, the UK would subsidize costly processes and incentivize cheaper processes to relocate abroad. This can be described as a process that separates the wheat from the chaff—by throwing away the wheat while keeping the chaff.

The UK established an early lead in this space—it was the first major economy to commit to Net Zero and established a strong start in CDR research and development. Yet it has been leapfrogged by other jurisdictions that provide the required policy clarity. In the absence of a rapid acceleration in policy action in the UK, it can be expected that CDR will become yet another industry sector pioneered in the UK but commercialized elsewhere.

5 Conclusion: what we have learned, and what remains to be studied

The GRIP project is far from being a complete example of a bottom-up country study. The missing elements include a full exploration of how competition between interests and for limited resources might be resolved in a national portfolio of candidate CDRs and a road map for their development toward possible deployment. Nevertheless, the project provided a first detailed empirical case study of possible CDR policy instruments and pathways in one jurisdiction.

A notable finding from the interviews was the degree of discrimination our respondents showed in assessing different CDR techniques. The interviews were also striking for the unanimity with which a range of stakeholders supported further research, development and demonstration (even on the least favorably assessed approach) to test the scope of their possible contribution to climate action. This needs to be taken together with the significant finding from the public engagement work that an initially favorably assessed CDR technique could be rejected if coupled with a financial incentive structure that was not favored (Bellamy et al., 2019). This emphasizes the importance of assessing each possible deployment of CDR as unique and complete sociotechnical proposition, inseparable from its environmental and political context.

Stilgoe (2015), invites us to think of geoengineering as a "verb" rather than a "noun," as a process "inviting new discussions of responsibility, ethics and experimentation," involving "care rather than control" and applying the four key principles of responsible innovation: anticipation, inclusivity, reflexivity and responsiveness (2015, p. 205–6; see also Stirling, 2014). Our study suggests that central sites for such activity are the national or sub-national contexts where CDR may be developed or applied. The fullest application of responsible innovation to CDR faces significant challenges, however. At a general level, the commitment of financial and technoscientific resources requires large scale, multi-year mobilizations, involving "imaginaries" or "grand challenges" in which the results are pre-sold politically in advance, and applicants for funds are encouraged to minimize the risks of failure to achieve them (which quite often involves tightly controlling the range of actors allowed to influence the outcome). A second complication applies specifically to CDR. Here, particularly at the "nature-based solution" end of the spectrum, powerful "nouns" already exist, in the shape of highly socially embedded technologies, such as forestry and agriculture, whose purposes are not primarily CDR, but which could contribute to it. In these cases, the process of developing portfolios of candidate CDRs—reconciling different resource and stakeholder demands—becomes extremely complex.

Can a different model of research and research funding be devised to allows a more tentative process of socio-technical learning? Will central governments, or for that matter international policy and funding bodies, be willing to accept the degree of humility needed for more open, inclusive and contingent processes of policy formulation? Will all such refinements be swept aside by renewed framings of extreme policy urgency, driven by evidence of rapidly shrinking carbon budgets as the world stubbornly refuses to reduce emissions?

The development and application of CDR techniques will be essentially an issue of polycentric governance, and studies of individual jurisdictions are critical in finding a way forward. We believe such studies should ground their work in the policy constraints and development priorities of individual countries. They should include for analysis a core group of CDR approaches, sufficiently diverse as to their environmental demands and interactions and stages of technological readiness to respond to these varying contexts, and ensure that social acceptability and environmental sustainability factors are central in the assessment process. The governance issues involved in each stage of CDR development must be fully explored, from the design and conduct of experiments through to the standards, regulations and reporting and verification procedures. We need to make special efforts to develop our understanding of the processes of bargaining around the composition of national portfolios of CDRs, and the distribution of those portfolios' effects. Finally, it is important to make sure that the local focus still allows for interaction with international political and industrial capacities that will need to be mobilized if early-stage CDRs are to be scaled up to the point where they can make a useful and safe contributions to climate action at a global level.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Central University Research Ethics Committee, University of Oxford. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

PH: Formal analysis, Investigation, Writing – original draft. TK: Investigation, Writing – original draft. JL: Conceptualization, Writing – review & editing.

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Conflict of interest

TK declares his interest in Origen Power, a company developing a technology that aims to combine power generation with carbon capture, and which in principle could benefit from some of the policy proposals set out in this paper.

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

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2023.1293650/full#supplementary-material

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Whose negative emissions? Exploring emergent perspectives on CDR from the EU's hard to abate and fossil industries

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Net zero targets have rapidly become the guiding principle of climate policy, implying the use of carbon dioxide removal (CDR) to compensate for residual emissions. At the same time, the extent of (future) residual emissions and their distribution between economic sectors and activities has so far received little attention from a social science perspective. This constitutes a research gap as the distribution of residual emissions and corresponding amounts of required CDR is likely to become highly contested in the political economy of low-carbon transformation. Here, we investigate what function CDR performs from the perspective of sectors considered to account for a large proportion of future residual emissions (cement, steel, chemicals, and aviation) as well as the oil and gas industry in the EU. We also explore whether they claim residual emissions to be compensated for outside of the sector, whether they quantify these claims and how they justify them. Relying on interpretative and qualitative analysis, we use decarbonization or net zero roadmaps published by the major sector-level European trade associations as well as their statements and public consultation submissions in reaction to policy initiatives by the EU to mobilize CDR. Our findings indicate that while CDR technologies perform an important abstract function for reaching net zero in the roadmaps, the extent of residual emissions and responsibilities for delivering corresponding levels of negative emissions remain largely unspecified. This risks eliding pending distributional conflicts over residual emissions which may intersect with conflicts over diverging technological transition pathways advocated by the associations.

KEYWORDS

Carbon Dioxide Removal (CDR), Carbon Capture and Storage (CCS), EU climate policy, net zero, mitigation deterrence, decarbonization, low-carbon transition, hard to abate

Introduction

Net zero targets have emerged as a new guiding principle of climate policy, replacing emission reduction targets (Net Zero Tracker, 2023). Conceptually, net zero targets imply the use of carbon dioxide removal (CDR) to compensate for continued residual emissions.[1] Most modeled scenarios limiting global warming to 1.5°C but also 2°C in line with the Paris agreement envision large-scale CDR deployment, including CDR technologies such as Bioenergy with Carbon Capture and Storage (BECCS) or Direct Air Carbon Capture and Storage (DACCS), to compensate for residual, "hard to abate" emissions and, in select scenarios, reduce the temporary overshoot of temperature targets across the late century (Luderer et al., 2018; IPCC, 2022, 2023a). CDR is also increasingly mainstreamed within and recognized as an important component of national net zero strategies (Smith et al., 2022; Buck et al., 2023). To date, however, literature on CDR is dominated by techno-economic perspectives which do not adequately address the societal complexities and challenges, and—particularly—the politics and inherently conflictive nature of (future) large-scale CDR deployment (Carton et al., 2020).

Nascent social science debates on CDR have highlighted the potential of projected, hypothetical large-scale deployment of CDR technologies to undermine or delay emission reduction efforts (often termed "mitigation deterrence"; Markusson et al., 2018; Brad and Schneider, 2023; Carton et al., 2023), and analyzed how different stakeholder positions on CDR shape emergent patterns in CDR policy-making, what conflict cleavages may arise from this (Schenuit et al., 2021; Boettcher et al., 2023) and what governance principles could guide CDR policy design development (Honegger et al., 2022). Most recently, the concept of 'residual emissions' presupposed in net zero targets has been subjected to critical scrutiny (cf. Armstrong and McLaren, 2022; Buck et al., 2023; Lund et al., 2023). Buck et al. (2023) find that while countries' long-term mitigation strategies project a substantial levels of residual emissions which will need to be balanced by CDR residual emissions have so far remained ill-defined and largely unexplored. Also in the academic debate, there is currently no widely established definition of residual emissions. While Buck et al. (2023, p. 1) define them as "emissions that are regarded as hard to abate and will need to be compensated via carbon removal," Schenuit et al. (2023, p. 4) understand residual emissions as "a quantity that simply describes which emissions actually enter the atmosphere in and after the net-zero year," explicitly delineating the term from hard to abate emissions. Here we use the term residual emissions to refer to a specific quantity of emissions in reference to a net zero year which will necessitate negative emissions. As such residual emissions typically require justification as to why they cannot be abated. As Lund et al. (2023) and Schenuit et al. (2023) highlight, this implies potentials for conflicts and contestations regarding the crucial question what actors can legitimately claim residual emissions and which economic and social activities are considered socially necessary yet economically and/or politically "hard to abate" technically or politically from today's perspective. However, while these contributions have carved out that residual emissions are not objectively given but discursively constructed, legitimated and—ultimately—contested, different claims to residual emissions and corresponding requirements for CDR deployment (and the related distribution of negative emissions) have so far hardly been investigated empirically.

We explore what functions CDR plays in achieving net zero targets from the perspective of trade associations of four economic sectors in the EU which, besides agriculture, are considered to account for most residual emissions in the International Energy Agency's (IEA, 2021a) Net Zero by 2050 scenario and in the scenario studies analyzed in the IPCC Sixth Assessment Report (IPCC, 2023b), i.e., cement, steel, the chemical industry and aviation (cf. Buck et al., 2023). We also investigate the perspectives of the gas and (fossil) fuel industry as highly emission-intensive incumbent industries on possible functions of CDR in reaching net zero targets. As the business model of these industries is existentially threatened by climate change mitigation (Colgan et al., 2021), authors have argued that these industries may have an interest in CDR to slow down decarbonization (Carton, 2019) and possibly also to re-invent themselves as a carbon disposal industry based on its geological and engineering expertise (Hastings and Smith, 2020). We excluded shipping and agriculture from our analysis for methodological reasons as we did not find any net zero roadmaps or scenario documents from the main trade associations of these sectors (European Community Shipowners' Association, COPA COGECA), which we used as the main empirical basis for analysis and comparison of the other sectors in this study (for more details on our methodological approach see Section 3).

We adopt a critical political economy perspective on the transformation toward net zero (Newell, 2019) to transcend the overwhelmingly technological and economic focus of many academic and policy debates on CDR. Through this, we particularly seek to foreground diverging interests and strategies of different business sectors as well as related lines of conflicts as CDR technologies evolve from contested renderings in climate models (Beck and Mahony, 2018) toward an essential component of climate policies in the EU (Geden and Schenuit, 2020). Specifically, we asked how the main EU-level trade associations of these sectors position themselves toward the nexus of residual emissions and CDR, and what function CDR performs in their respective sector-specific visions to reach net zero. Regarding particular functions of CDR, we wanted to find out whether CDR is envisioned as part of the sector-specific decarbonization paths at all and, if so, what emissions CDR is supposed to compensate for. We also investigated whether these trade associations claim residual emissions for their sectors beyond 2050, how they justify these claims and whether they quantify residual emissions. Our focus is on whether these actors claim residual emissions in the sense that they do not compensate residual emissions in "their" respective value chains, which would

1 Following Smith et al. (2022, p. 2) "CDR methods remove CO_2 from the atmosphere and permanently store it in geological, terrestrial, or ocean reservoirs, or in specific products. CDR methods produce negative emissions, whereby the total quantity of atmospheric CO_2 removed and permanently stored is greater than the total quantity of GHGs emitted to the atmosphere." Carbon Capture and Storage (CCS) involves capturing CO_2 from industrial point sources and storing it permanently in geological reservoirs, thereby reducing CO_2 emissions. Carbon Capture and Utilization (CCU) in turn refers to a process in which CO_2 is captured from an industrial point source or ambient air and then utilized in, or as, a product (Smith et al., 2022).

require negative emissions in other economic sectors. Through this analysis we contribute to the nascent debate on the politics of residual emissions and potential distributional conflicts between sectors, specifically regarding the issue what and whose needs and interests are reflected in the construction of projected residual emissions (Lund et al., 2023).

In the following section we develop our analytical perspective based on approaches from critical political economy. Section 3 outlines our methodological approach. In Section 4 we briefly reconstruct how the net zero target for 2050 came about in the EU and situate more recent, particularly CDR-related EU climate policy initiatives in this context. Subsequently, Section 5 delves into the sector specific strategies to achieve net zero, presenting the core results from our analysis. In Section 6 we discuss our main findings regarding the implications for wider discussions on the integration of CDR into climate policy and the politics of net zero more broadly. Section 7 outlines areas for further investigation.

A critical political economy perspective on CDR

As environmental crisis deepen, a broad field of research has been established around the terms transition and transformation[2] in recent decades (Köhler et al., 2019; Scoones et al., 2020). In this context, our study is specifically based on strands of critical political economy to conceptualize socio-technical change as a contested political process in which various actors with their respective interests and values struggle with each other or may form coalitions (Newell, 2019). While the study of interest conflict and coalition building for (or against) climate policy measures is not reserved to critical political economy approaches (Sabel and Victor, 2022), this lens allows us to understand competing interests and conflicts between actors and social forces as rooted in (although not directly determined by) social relations of production and the specific position they occupy in a given (capitalist) mode of production (Brand et al., 2022). Accordingly, there are not only competing and antagonistic interests between social classes, e.g., capital and labor, but also within capital. Capital is fractionalized along different bases of accumulation (e.g., fossil fuel extraction or deployment of renewables), and the related accumulation strategies are always contingent upon a specific spatial and temporal context and require a strategic orientation and political safeguarding by the state (Jessop, 1990; on the notion of capital fractions cf. Overbeek and van der Pijl, 1993).

Against this background, and despite the historical reliance of capitalism on fossil energy (Malm, 2016), Newell and Paterson (2010) emphasize that capitalism does have a certain capacity for change, and that both actors and governance regimes can change their orientation. At the same time, processes of low-carbon transition and transformation are inherently political, specifically regarding contentious issues as to "what is to be transformed, who is to do the transforming" and to what extent disruptive processes of change as opposed to incremental shifts are required to drastically reduce GHG emissions (Scoones et al., 2015, p. 1–2). This warrants particular attention as to which actors and social forces attempt to drive and shape social and economic change under capitalism in certain historical directions (Brand, 2016).

Such a perspective allows us to go beyond superficial assertions about 'green growth' and 'win-win solutions' in order to delve into the underlying conflicts and compromises associated with the process of fundamentally reshaping an economy and the power relations embedded in it in the process of 'deep' decarbonization (Newell, 2015, p. 70–71). This not only implies an analysis of struggles between incumbent actors seeking to preserve the status quo of a fossil fuel-based energy system and social forces trying to advance low-carbon transformation, breaking up fossil path dependencies which have been described as a 'carbon lock-in' (Unruh, 2000; Asayama, 2021). It also reveals how different actors advocate and promote diverging transition pathways based on different sets of low-carbon or 'net zero' technologies which benefit or disadvantage various capital fractions differently, based on their current accumulation strategy, but also the energy sources and feedstock they depend on (e.g., centralized nuclear vs. decentralized renewable energy) (Rosenbloom et al., 2018).

Against this background, we assume that different coalitions of capital fractions and other actors may form around the promotion of different pathways, giving rise to specific fault lines in the politics of low-carbon transformation and decarbonization. Such fault lines become specifically apparent at critical junctures or branching points leading to different pathways of transformative change (Newell, 2015). In these conflicts, visions and expectations of pathways and technologies, sustained by specific sociotechnical imaginaries—i.e., collectively held visions of the future, underpinned by interrelated ideas of future society and technological progress (Jasanoff and Kim, 2009)—as well as technological discourses and technology myths (Peeters et al., 2016), motivate real policy and investment decision, but also inaction (cf. Beckert, 2016). Such visions and expectations often rely on highly optimistic and uncertain assumptions regarding future technology development. Yet, even though highly uncertain, they are often (unintentionally) held or (intentionally) constructed and advanced because they serve specific purposes (Peeters et al., 2016), particularly by promising technological "fixes" to climate change and the ecological contradictions of capitalism more generally. Building on Harvey's (2006) concept of spatiotemporal fixes we understand technological fixes in the double sense of providing a temporary solution to (ecological) contradictions of capitalisms, while at the same time fixing capital in the form of investment in new infrastructure, machinery, built environment, etc. (cf. Markusson et al., 2017; Carton, 2019). We reveal how visions and expectations of CDR technologies reshape different capital fractions' vision of low-carbon transition pathways. Specifically, we are interested in whether the assumption

2 The terms transition and transformation are used distinctively in transition research and political economy. In transition research, transformation denotes a particular type of transition (among substitution, transformation, reconfiguration and de-alignment and re-alignment; Köhler et al., 2019, p. 5). By contrast, in political economy the term transformation often refers to sweeping and disruptive reconfigurations of the entire socio-economic system, while transitions are confined to changes within individual socio-technical systems (Newell, 2015; Scoones et al., 2020). In this paper, we follow the use of the terms in the political economy literature.

of future large-scale availability of CDR technologies allows stakeholders to envision pathways toward net zero greenhouse gas emissions compatible with partly maintaining emission-intensive accumulation strategies.

Methods

To investigate these questions empirically, we focus on four sectors which are considered to account for most residual emissions in relevant IEA and IPCC scenarios—cement, steel, aviation, and the chemical industry—as well as the oil and gas industry as highly emission-intensive incumbent industries (see Section 1). Our approach to approximate the interests and strategies pursued by these capital fractions is based on analyzing publicly available statements and position papers of the major European branch-level trade associations. The scientific literature on lobbying activities in the EU has highlighted that many large companies in the EU chose to establish their own lobbying capacity in Brussels and increasingly rely on specialized service providers such as law firms, public affairs agencies and think tanks to influence the policy agenda in the 1990's and 2000's. Nonetheless, trade associations have remained key actors in business interest organization, intermediation and assertion in the EU (Eising, 2007; Coen and Richardson, 2011). As Fagan-Watson et al. (2015) point out, many companies consider trade associations lobbying advantageous over direct lobbying by individual firms because policymakers tend to regard their perspectives as more representative of the industry as a whole. To maintain this specific advantage, trade associations need to constantly aggregate and mediate diverse positions and interests and to articulate branch-level compromises, which makes them a particularly interesting entry point for our study.

However, the fact that trade associations typically articulate and advocate lowest common denominator compromises also implies that by focusing on their positions, we cannot account for the heterogeneity, internal conflicts and different strategic approaches of their members. Individual companies may substantially deviate from the positions adopted by their respective trade associations, and such differences may even lead companies to leave trade associations and possibly also found competing ones (Fagan-Watson et al., 2015). While this warrants closer attention to the extent to which major companies in the respective sectors are aligned with the trade associations' positions, we only consider in this analysis whether the major European producers in the respective industries are members of the trade associations (directly or indirectly through respective national trade associations) and whether there are alternative, competing trade associations in the industry, i.e., to what extent the trade association is indeed dominant in the industry. Assessing the exact extent to which trade associations are representing the entire industry (e.g., in terms of proportion of sector turnover or the percentage of members over the total number of companies in the industry) is complicated by the fact that trade associations typically do not make such data available publicly, as this would potentially contradict their claim to represent the entire industry.

Trade associations employ a variety of tools and strategies to exert policy influence, ranging from organizing events with policymakers and technical policy experts, briefing policymakers on specific (technical) subjects, and launching policy initiatives within the EU institutions, to press work, ad campaigns and the publication of position papers. Focusing on publicly available statements and position papers therefore only partly reflects the activities, strategies, and prioritizations of the associations' lobbying activities. Nonetheless, following Tilsted et al. (2022), we consider these documents particularly relevant because they can be read as attempts to maintain legitimacy, especially from the position of actors facing increasing pressure to reduce their GHG emissions. Against this background, these documents serve as a means to preserve the credibility of these actors, helping to demonstrate their commitment to sustainable practices and their ability to adapt to evolving environmental challenges. Additionally, these documents act as tools for interest mediation within the sectors causing and being affected by climate change. These documents both reflect the results of and facilitate the discussion and negotiations between different stakeholders within the respective industries and between the industry and other stakeholders.

Our focus of analysis is on net-zero or decarbonization roadmaps of the selected associations to work out how the associations present their contribution to the EU's net-zero target.[3] We specifically analyze the extent to which the associations claim residual emissions for their sector, and which approaches to emissions reduction and CDR are envisioned. To extend and refine this analysis, we use publicly available statements and position papers from the selected associations. Our investigation focused on two areas: First, position papers that directly relate to CDR, i.e., statements on the Commission's communication on Sustainable Carbon Cycles (which was published in December 2021) and the EU Carbon Removal Certification Framework (CRCF; which is currently under negotiations; see Section 4 for more details). Second, since not all associations positioned themselves on these policies (see Table 1), we expanded our focus and took into account the statements on the Net Zero Industry Act (NZIA), which was published in March 2023. Since the NZIA is particularly relevant for CCS and CCU applications, the statements by the trade associations provide insights on the positions toward important adjacent infrastructures for CDR (see Section 4 for more details). Besides statements on these three policy initiatives, we selectively considered further statements or position papers which allow us to analyze the trade associations' stance on CDR and adjacent infrastructures, as well as on EU climate policy initiatives more generally to contextualize our findings in the discussion.[4] We

3 To systematically asses these documents we relied on qualitative content analysis. Taking into account the political circumstances on which these documents were produced, the documents were analyzed according to a three-step process of summarization, explication and structuring. In the summarization, the core statements were first compiled inductively in order to gain an overview of the material and to sort it. Subsequently, unclear passages and statements were decoded in the explication by adding further documents—the analysis and collection of documents thus took place in parallel. In the final step, the material sorted and explicated in this way was coded and structured according to deductive categories based on the research question (Zhang and Wildemuth, 2009).

4 In order to find the relevant documents of the analyzed trade associations, we made a web search on their homepages. The documents we analyzed are listed in the references together with the net zero roadmaps under A4E, Cefic, Cembureau, Eurofer, Eurogas, and FuelsEurope.

TABLE 1 Positioning of key trade associations.

		Cement (Cembureau)	Steel (Eurofer)	Chemical (Cefic)	Aviation (A4E)	Fuel industry (FuelsEurope)	Gas (Eurogas)
Carbon dioxide removal	Carbon Removal Certification Framework	Yes	No	Yes	No	No	Yes
	Sustainable Carbon Cycles	Yes	No	Yes	No	No	Yes
Adjacent infrastructures	Net Zero Industry Act	Yes	Yes	Yes	Yes	Yes	Yes

Source: author's elaboration.

analyze the positions of the oil and gas industry separately, even though oil and gas are often treated as one sector (cf. Green et al., 2022). The central reason for this is that there are two trade associations in the EU polity, FuelsEurope and Eurogas, which are composed of different constituencies, although there is a significant overlap (for more details on membership see Sections 5.5 and 5.6). What further motivates this analytical distinction is the fact that oil and gas occupy different roles in current politics of low-carbon transformation processes. Petrol has increasingly come under pressure as the central fuel for private transport due to the rise of e-mobility and policies to phase out internal combustion engines in the EU (Haas and Sander, 2020). At the same time, the gas sector successfully managed to promote gas as a low-carbon alternative to oil, particularly in domestic heating, and to portray its grid system as an essential component of the hydrogen transition (Ohlendorf et al., 2023).

The political economy of climate neutrality in the EU

According to its self-image, the EU has established itself as a leader in global climate policy, aiming to become the world's first "climate-neutral" continent (Oberthür and Dupont, 2021; Tobin et al., 2023), and the "myth of a green Europe" (Lenschow and Sprungk, 2010) has been a long-standing driving force of the European integration process. The reality is much more ambivalent, however (Plehwe et al., forthcoming): Overall emissions declined by about 37.6% between 2005 and 2022 in the sectors currently covered by the so-called flagship of European climate policy, the European Union Emissions Trading Scheme (EU ETS) introduced in 2005 (Bayer and Aklin, 2020)—power and heat generation, civil aviation within the EU, as well as energy-intensive industry including oil refineries, steel, cement, lime, and chemicals (European Environment Agency, 2023). However, the emission trends across sectors are not uniform (e.g., emissions from aviation grew substantially between 2013 and 2019) and the price for CO_2 emissions remained extremely low for more than a decade (Gerlagh et al., 2022)—below even highly conservative estimates of prices required for stringent mitigation (Pindyck, 2019). This was particularly due to numerous loopholes, an over-allocation of certificates and the free allocation of certificates that were created under pressure from industrial lobbies (Plehwe et al., forthcoming). It is only since 2019 that prices for emission certificates have reached a level from which positive mitigation incentives could emanate. The large energy companies were not only successful in lobbying for an EU ETS that largely corresponds to their interests but have also succeeded together with their political allies, such as conservative think tanks or parties, in slowing down the transition to renewable energies (Haas, 2019). In addition to a general narrowing of the sustainability discourse to the aspect of decarbonization (Morata and Solorio Sandoval, 2013; Eckert, 2023) and the decline of investment in renewables due to austerity policies in the aftermath in the Eurozone crisis, the abolition of feed-in tariff systems and the massive expansion of influence on green trade associations by large incumbent energy companies delayed the energy transition (Haas, 2019).

While these examples illustrate that already the decarbonization of the energy sector has been highly contested, EU climate policy has entered a new phase of development with the European Green Deal (EGD) and its goal to achieve climate neutrality by 2050 (European Commission, 2019). In this net-zero phase of EU climate policy the questions of how to mitigate hard to abate emissions, particularly those that cannot be abated through electrification and decarbonization of the energy system, and how to compensate for residual emission through CDR are increasingly entering the political arena and can be expected to be at least as contested as previous issues of EU climate policy. The EGDs climate neutrality goal is based on different scenarios toward climate neutrality developed in the Commission's Clean Planet for All communication (European Commission, 2018a). In addition to the climate neutrality goal, the EGD raised the emission reduction target for 2030 from 40% to a net emission reduction of 55% compared to 1990 [and more recently to 57% as part of the revision of the land use change and forestry (LULUCF) regulation]. Furthermore, emission trading underwent significant reform with maritime transport being included into EU ETS, the creation of a separate EU ETS for buildings, road transport and fuels and measures to reduce the number of allocations more quickly to raise carbon prices in the ETS (Oberthür and von Homeyer, 2023). Fundamentally, the EGD, advocated by the European Commission (2019, p. 2) as the EU's "new growth strategy," relies on the EU's dominant climate policy paradigm that low-carbon technologies will foster emission reductions while at the same time stimulating green growth, based on the assumption that GDP growth can be progressively decoupled from GHG emissions and resource use (Brad and Schneider, 2023, p. 5).

The EGD's emission reduction targets and the extensive revisions of existing environmental and climate policy initiatives indicate EGD's level of ambition to achieve climate neutrality.

However, a key question that has remained largely unanswered is how CDR will be integrated into EU climate policy and its three main pillars—the EU ETS, the LULUCF regulation and the Effort Sharing Regulation—in particular (Schenuit and Geden, 2022). The EU ETS has so far been kept separate from CDR,[5] even though there are different proposals as well as initiatives to integrate CDR into emission trading (cf. Brad and Schneider, 2023), e.g., managed by a carbon central bank (Rickels et al., 2022). The second pillar, the LULUCF regulation, by contrast, already regulates removals in the land use and forestry sector, aiming to compensate accounted emissions from land use "by at least an equivalent amount of accounted removals" in the sector until 2025 ("no-debit rule") and to reach a net removal of 310Mt CO_2 by 2030 (European Commission, 2023a). CDR is also relevant for the third pillar, the Effort Sharing Regulation, which determines the distribution of emission reductions between Member States in sectors not covered by the ETS, in so far as removals from the LULUCF sector can balance emissions from ESR sectors up to 280Mt CO_2eq (Savaresi et al., 2020). What has remained open so far, however, are crucial questions regarding the future role of CDR in EU climate policy: how many residual emissions will be emitted in 2050? Which economic sectors, industries and individual companies will emit how many (residual) emissions? How will the residual emissions be distributed among economic sectors and industries? Who is responsible for achieving the CDR targets? What incentive structures will be created for CDR? Which CDR technologies will be utilized? All these questions will shape future EU climate policy or are currently already—at least implicitly—under negotiation (Geden and Schenuit, 2020).

The most explicit initiatives to address the role of CDR in future EU climate policy are the communication on Sustainable Carbon Cycles (European Commission, 2021a) presented in December 2021 and the ongoing negotiations on a CRCF. The NZIA, which mainly focuses on the EU's competitiveness in "net zero" technologies is also relevant due to its specific emphasis on scaling-up CCS technologies and storage capacity in the EU as an adjacent infrastructure for BECCS and DACCS. The communication on Sustainable Carbon Cycles represents the first comprehensive effort by the Commission to initiate and shape the policy debate on the integration of CDR into EU climate policy, as it recognizes that "conventional" mitigation methods based on emission reductions are not sufficient to limit global warming to 1.5°C. Consequently, the communication sets specific targets, focussing not only on increasing the EU's land sink by 42 Mt of CO_2 by 2030 through "carbon farming" activities (as part of 310Mt CO_2 emission reduction goal under the LULUCF regulation), but also pursues the goal that another 5 Mt of CO_2 "should be annually removed from the atmosphere and permanently stored" through CDR technologies such as BECCS and DACCS (European Commission, 2021a, p. 9, 17).

The CRCF, in turn, aims to provide a consistent and transparent approach to defining, quantifying, accounting, verifying and monitoring carbon removals to make sure that CDR providers actually extract and durably store CO_2 and are held liable in the event of reversals (i.e., if CO_2 is released from storage; McLaren, 2020; Dahm, 2022). A key challenge in this respect is the differentiation of CDR from various methods of CCU, particularly regarding the issue of permanency, as in most cases CCU merely represents a delay of emissions [as the CO_2 stored in the product is usually (re-)emitted after the end of the utilization period] so that no (net-)negative emissions are achieved beyond temporary storage (Smith et al., 2022; Schenuit et al., 2023). The relevance of the NZIA for the politics of CDR and residual emissions predominantly lies in the fact that it establishes for the first time a specific CO_2 injection capacity target of 50 Mt per year by 2030. While this storage capacity target is intended to facilitate the emergence of a CCS value chain in the EU, CCS related transport and storage infrastructure is also necessary for engineered CDR methods such as BECCS or DACCS which can be shared or clustered with CCS (cf. Maher, 2018). The NZIA also explicitly holds the oil and gas industry responsible for exploring and developing the required storage sites based on its "assets, skills and knowledge" (European Commission, 2023b, p. 21).

Analysis: visions of EU's trade associations for net zero

In the following, we zoom-in on the positions of cement, steel, aviation, and the chemical industry as well as the oil and gas industry. Based on the methodological considerations described in Section 3, we proceed as follows: First, we introduce the relevance of each sector in terms of its share of total GHG emissions in the EU (based on the annual EU greenhouse gas inventory[6]) and the specific challenges in decarbonizing these sectors as well as the main trade association of these sectors in the EU. We then turn to the analysis of their net zero or decarbonization roadmaps and related position papers regarding CDR and the NZIA and highlight their main policy demands. Table 2 provides an overview of the main features of key trade associations' net zero or decarbonization visions.

Cement

According to the annual EU greenhouse gas inventory (European Environment Agency, 2021), cement production accounted for 78 Mt CO_2 emissions in 2019 or 1.9% of total EU GHG emissions (4,067 Mt CO_2-eq), with Germany (17%),

5 Unlike CDR, the recent EU ETS revision [Directive (EU) 2023/959] includes a reference to CCU, stipulating that emission allowances no longer need to be surrendered if emissions are "captured and utilized in such a way that they have become permanently chemically bound in a product so that they do not enter the atmosphere under normal use" (paragraph 3b).

6 For cement production emissions we used category 2.A.1, for steel 1.A.2.a and 2.C.1, for chemicals 1.A.2 c and 2.B, and for aviation 1.A.3. as well as data provided in the annual EU greenhouse gas inventory on international aviation. The share of sector emissions in total emissions was calculated using total EU GHG emissions excluding LULUCF as well as emissions from international aviation and international maritime transport, as reported by the European Environment Agency GHG inventory under the UNFCCC.

TABLE 2 Overview of key trade associations' net zero visions.

	Cement	Steel	Chemical	Aviation	(Fossil) fuel industry	Gas**
Main EU-level trade association	Cembureau	Eurofer	Cefic	Airlines for Europe (A4E)	Fuels Europe	Eurogas
Has net zero/decarbonization roadmap?	Yes "Cement the European Green Deal. Reaching climate neutrality along the cement and concrete value chain by 2050" (2020)	Has a low-carbon roadmap "Low Carbon Roadmap. Pathways to a CO_2-neutral European steel industry" (2019)	Has scenario models "iC 2050 Project Report. Shining a light on the EU27 chemical sector's journey toward climate neutrality" (2021)	Yes "Destination 2050—A route to net zero European aviation" (2021)	Yes "European Carbon Neutrality: The Importance of Gas" (2020)	Has decarbonization scenario "Clean Fuels for All. EU refining industry proposes a potential pathway to climate neutrality by 2050" (2020)
Has a net zero target?	Yes (2050, carbon neutrality)	No	Yes	Yes	Yes (2050, carbon neutrality)	Yes ("soon after 2045,"* carbon neutrality)
Claims residual emissions in 2050 to be compensated outside the sector (% of total projected economy wide residual emissions by 2050 under the EU's 1.5TECH scenario*)?	No	Yes, 15–255 Mt CO_2, depending on scenario (2.5–42.4%)	Unclear if remaining emissions between 68 and 111 Mt CO_2 (11.3–18.4)—depending on scenario—will be compensated entirely by negative emissions generated within the chemical industry	Yes, 22 Mt CO_2 (3.7%)	No	No (but only 89% decarbonized if negative emissions from biomethane are not considered)
Considers CDR?	Yes (BECCS, enhanced recarbonation through concrete)	No	Yes (BECCS, DACCS)	Yes (BECCS, DACCS)	Yes (BECCS)	Yes (BECCS)
Considers CCU?	Yes (mentions synthetic fuel production)	Yes	Yes (circular carbon feedstocks)	Not explicitly, but Sustainable Aviation Fuels may comprise CCU.	Yes (as part of e-fuel production)	Yes

*Own calculation based on the European Commission (2018b) indicative scenario, Annex 7.7.

**This target is not contained in the decarbonization scenario but communicated on the association's website: https://www.eurogas.org/our-priorities/, accessed 18 October 2023.

Source: author's elaboration.

10.3389/fclim.2023.1268736

Spain (11.6%), and Italy (10.1%) being the member states with the highest emissions. Compared to 1990, CO_2 emissions from cement production decreased by 24.1% in the EU. However, these numbers exclude energy related emissions. Therefore, verified emissions from cement production under the EU ETS, which also cover emissions from the combustion of fossil fuels in the sector (European Environment Agency, 2021, p. 36–37), are significantly higher, i.e., 113 Mt CO_2 or 2.7% of total EU GHG emissions in 2019.[7] Some of the emissions from the sector are inherent to the cement production process and therefore classified as "hard to abate" (Marmier, 2023). Particularly the heating of limestone to make clinker through a chemical reaction produces CO_2 emissions which are impossible to abate through electrification and renewable energy sources (Fennell et al., 2022; Marmier, 2023, p. 5). This process referred to as calcination accounts for 60–65% of current cement manufacturing emissions according to Cembureau, the EU-level trade association of the cement industry (Cembureau, 2020, p. 15), with the remaining emissions resulting from the combustion of fossil fuels in the heating processes. Cembureau acts as the umbrella organization for currently 23 national cement industry associations in the EU and beyond (Norway, Switzerland and the United Kingdom). Cembureau is highly inclusive in its role as the main branch association: the EU's largest cement producers according to production capacity in the EU such as HeidelbergCement, Holcim, Buzzi Unicem and CRH are all members of Cembureau.

While Cembureau foresees only limited reduction potentials regarding these process-related emissions in the production of clinker (e.g., through thermal efficiency and use of alternative raw materials), the industry nonetheless aims to reach net zero emissions across the cement value chain by 2050. The main share of the emission reductions required for this is to be achieved through Carbon Capture Utilization and Storage (CCUS), which is supposed to decarbonize roughly 42% of CO_2 emissions per ton cement vs. 1990 emission levels (Cembureau, 2020, 2022a). Further emission reductions are to be attained through the use of alternative and biomass fuels, thermal efficiency, the use of decarbonated raw materials and clinker substitution (as part of alternative cement chemistries) and carbon neutral transport.

While Cembureau does not explicitly claim residual emissions, they assume in their net zero roadmap calculations that process emissions will continue to be emitted beyond 2050. As a result, CDR forms an integral part of its net zero vision, namely two specific CDR techniques: First, implementing capture and storage of biogenic CO_2 from sustainable sources (e.g., biomass waste) in cement plants in the process of combusting biomass-based fuels in the heating process, i.e., BECCS (Cembureau, 2023a). Secondly, by removing carbon through a process called carbonation, i.e., the absorption of CO_2 in concrete and cement. This is a process that already occurs naturally but which Cembureau is seeking to improve in terms of absorption capacity and would like to have recognized as a carbon sink, also reflected in national emission inventories (Cembureau, 2021a, 2023a). Importantly, apart from a 2030 interim target, the roadmap does not contain any details regarding the timing of mitigation efforts as well as the level of emissions and removals in 2050, as the calculations only refer to the output per ton of cement, not to absolute production volumes.

From this, Cembureau derives specific political demands regarding various CDR-related policies. First, it advocates for the rapid roll-out of a pipeline infrastructure to facilitate the transport of CO_2 to storage sites (in case of CCS) or downstream usage (in case of CCU), given that many cement production sites are not located within large industrial clusters (Cembureau, 2020, 2023b, p. 19; Schenuit et al., 2023, p. 3). It also welcomes EU 2030 target for CO_2 injection capacity put forward in the NZIA (Cembureau, 2023b). In case that CO_2 is captured and then transferred to a storage site or used in a product, the association urges the Commission to allow the capturing installation (i.e., the cement producer) "to deduct the CO_2 from its emissions" (Cembureau, 2021a, p. 2). Second—and relatedly—as production sites are decentralized and many of them landlocked, i.e., remote from offshore CO_2 storage sites, the trade association—similar to the chemical industry (see below)—heavily promotes CCU, particularly the production of synthetic fuels (Cembureau, 2022b, 2023b). It opposes a phase-out of industrial CO_2 resulting from CCU as a feedstock for the production of synthetic fuels as stipulated by the Commission's Delegated Act on the greenhouse gas saving criteria for renewable liquid and gaseous fuels of non-biological origin (RFNBOs; European Commission, 2006). In this context, Cembureau also takes a critical stance toward DACCS as a forecasted alternative source of CO_2 for RFNBOs replacing industrial CO_2 from CCU, highlighting unknown deployment capacity beyond 2040, especially regarding the high quantities of zero carbon electricity required (Cembureau, 2022a). With regard to the CRCF, the association demands that concrete carbonation is considered as a form of CCU and thus as carbon removal (when it arises from carbon-neutral cement production) under the EU CRCF (Cembureau, 2023a).[8] Cembureau also demands that carbon removal certificates under the CRCF should be tradeable and exchangeable in the context of the EU ETS (Cembureau, 2023a). This step would benefit the cement industry not only as a supplier of industrial CO_2 for CCU, but also as operator with significant demand for emission allowances under the EU ETS whose gradual tightening would be alleviated regarding price developments if carbon removal certificates were eligible to enter the market. At the same time, implementing these two key demands put forward by Cembureau regarding the CRCF—considering carbon storage in long-lasting products as a removal and making removal credits tradable in the EU ETS—would arguably exacerbate the main concerns regarding the CRCF put forward by environmental NGOs such as Carbon Market Watch: the inclusion of non-permanent removals into the scheme and the use of removal certificates as well as the possibility to sell removal certificates to companies wishing

7 Even these figures, however, are an underestimate of total CO_2 emissions from the sector as verified emissions under the EU ETS include only "installations with production capacity exceeding 500 tons per day or in other furnaces with capacity exceeding 50 tons per day" (European Environment Agency, 2021, p. 36–37).

8 Recognizing carbon removal from carbonation which is already occurring naturally today would of course violate the additionality principle which the Commission's CRCF proposal proposes as a key quality criterion for removals (European Commission, 2022, p. 7).

to delay and offset their emission reductions (cf. Carbon Market Watch, 2022; Brad and Schneider, 2023).

Steel

CO_2 emissions from the production of iron and steel amounted to 157 Mt in 2019 or 3.8% of total GHG emissions in the EU, with emissions down 44.4% compared to 1990 levels (European Environment Agency, 2021). Germany stands out as the EU's member state with the highest share of emissions from the sector (34.2%), followed at a great margin by France (10.6%) and Austria (7.7%; European Environment Agency, 2021). The main EU level trade association of steel industry, Eurofer, represents 14 national steel trade associations, including all main steel producing countries in the EU (Somers, 2022). The main steel producing companies in the EU, such as according to the Joint Research Center of the European Commission (Somers, 2022, p. 41), ArcelorMittal, Thyssenkrupp, Tata Steel, Voestalpine, SSAB and Salzgitter, are also direct members of Eurofer (Eurofer, 2023a).

The production of steel is not only highly energy-intensive, but also—and crucially—the two currently dominant steelmaking routes rely on fossil inputs (mainly coal-based coke and natural gas) for chemical reactions and heating to convert raw materials to iron and iron to steel, implying substantial process-related CO_2 emissions (from the steel making process itself, but also in the process of heating coal to produce coke). In the first production route, the so-called blast furnace—basic oxygen furnace (BF-BOF) procedure (accounting for almost 60% of total steel production in the EU in 2020, cf. Somers, 2022, p. 11), coal and coke are used with a blast furnace to produce hot metal from iron ore. Additional emissions result from the combustion of fossil energy carriers to heat the blast furnace and the basic oxygen furnace as well as from reducing the carbon content of metal to generate steel in the basic oxygen furnace. In the second route, based on an electric arc furnace, steel is produced either from recycled steel scrap or in combination with a process called direct reduction, where natural gas or coal are used to generate reducing agents to produce sponge iron from iron ore (cf. Kim et al., 2022). The two main decarbonization options for the coal-based BF-BOF route are either the direct reduction of iron ore to iron using hydrogen as a reduction agent (depending on the availability of large amounts of 'green' or 'low carbon' hydrogen) or an electrolytical reduction process relying solely on electricity (but not expected to be deployable at scale before 2040; Somers, 2022, p. 22–32). In addition, CCS and CCU are also considered, mainly to retrofit the BF-BOF production process, but also for direct reduction production approach based on natural gas (Somers, 2022, p. 27–30). High capital costs and long investment cycles are considered a particular challenge in decarbonizing the steel industry (Kim et al., 2022).

In 2019 Eurofer presented its "low carbon roadmap" which contains emission reduction targets by 30% by 2030 and by 80–95% by 2050 compared to 1990 levels (Eurofer, 2019, p. 6). Actual emission reduction potentials within this range, the association argues, mainly depend on technology development (including CCS and CCU) and on whether sufficiently large quantities of entirely CO_2 free energy in the form of electricity and hydrogen will be available in 2050. The latter factor, Eurofer asserts, largely lies outside of the control of the sector (Eurofer, 2019, p. 5, 9). Correspondingly, the association outlines not only one decarbonization pathway but six different scenarios, ranging from "business as usual," "ongoing retrofit," and "current projects with low CO_2-energy" to more ambitious scenarios, i.e., full deployment of low-emission technologies with low CO_2-energy (80% emission reduction by 2050 compared to 1990), "current projects with CO_2-free energy" (85% reduction) and full deployment of low-emission technologies with CO_2-free energy (95% reduction). Notably, Eurofer does not assert to reach net zero by 2050 and does not refer to any form of CDR in its decarbonization strategy, thereby implicitly claiming residual emissions in 2050 and beyond which will need to be compensated by deployment outside of the sector. In addition, while the most ambitious decarbonization scenario aims to get at least close to net zero with a 95% emission reduction compared to 1990, the other scenarios would imply substantial amounts of residual emissions. In the "ongoing retrofit" scenario, which merely projects a 15% emissions reduction compared to 1990 levels, residual emissions would amount even up to 255 Mt CO_2 emissions in 2050 (Eurofer, 2019, p. 5). This would equal 42.4% of total economy wide residual emissions anticipated in the European Commission's indicative 1.5TECH scenario to reach net zero by 2050, and more than twice as many emissions as envisaged for the entire industrial sector in this scenario (European Commission, 2018b, Annex 7.7.). Against this background, Eurofer specifically justifies and highlights its sector's role for decarbonization, arguing that the "foundations of the Net zero Age are made of steel, from wind turbines to electric vehicles" which it does not see adequately reflected in the NZIA (Eurofer, 2023b).

Corresponding to the fact that CDR is entirely missing from the European steel industry's decarbonization perspectives, Eurofer has not yet engaged (at least publicly) with the integration of CDR into EU climate policy. The trade association neither commented on to the Sustainable Carbon Cycles communication nor to the CRCF (see Table 1), focusing instead mainly on the EU's proposals for a Carbon Border Adjustment Mechanism (CBAM; European Commission, 2021b) given the particular importance of this policy for the sector. Moreover, and in line with the main pillars of its decarbonization scenarios, the association advocates for the expansion of renewable energy and hydrogen production—partly also with support from green trade associations (cf. Eurofer, 2022)—as well as for improving access, deployment and infrastructure development for CCUS (Eurofer, 2023b). Eurofer's strong emphasis on the issue of the availability of renewable energy and "green" "CO_2-free" hydrogen arguably also foreshadows future conflicts over the prioritization of these renewable energy inputs, given that there will be huge demand from the steel industry against limited supply.

Chemical industry

The chemical industry emitted 133 Mt CO_2-eq or 3.3% of total EU GHG emissions, down 59% compared to 1990 levels (European Environment Agency, 2021). However, these numbers underestimate actual emissions from the sector, as Germany reports its emissions from the chemical industry under a different category (other manufacturing and construction activities, cf. European Environment Agency, 2021, p. 161). As a feedstock industry, chemicals play a significant role in overall economic development. Cefic is the umbrella organization of the European chemical industry. Members include all major European chemical companies such as BASF or Bayer, but also bp, ExxonMobil Chemical Europe, Shell Chemicals and the fertilizer producer Yara. In addition to very large and medium-sized corporations, all major national umbrella organizations of the chemical industry are also members of Cefic. As the chemical industry encompasses many different production processes, there are many overlaps with other associations, but Cefic is the central interest group for the chemical industry in the EU. While it is supportive of the EU's net zero target by 2050, the chemical industry has a special role in that it will continue to rely on carbon as a feedstock beyond 2050. Against this background, Cefic argues that the political debate should be less about decarbonization and more about a carbon cycle economy: "Establishing sustainable and climate-resilient carbon cycles is, in our view, a more efficient approach to climate mitigation than an approach that is essentially geared toward 'decarbonization,' which may result in the wrong diagnosis and thus will lead to suboptimal solutions. In fact, carbon is an essential element in organic compounds: it is not possible to reduce the carbon density of our products and we will remain strongly reliant on carbon as a source of feedstock" (Cefic, 2023a, p. 1).

Accordingly, Cefic emphasizes that it will be extremely costly and nearly impossible to reduce the sector's emissions to zero by 2050: "Certain sources of GHG emissions emitted by our plants will remain extremely costly or even impossible to abate—at least by 2050, and therefore need to be removed/compensated elsewhere in the chemical industry or the economy, necessitating exploiting cross-sectoral synergies, industrial symbiosis and long-term carbon storage solutions" (Cefic, 2023a, p. 2). Unlike most other associations, Cefic has not published a decarbonization roadmap. However, with the help of the business consultancy and accounting firm Deloitte, it developed four scenarios toward climate neutrality: "high electrification," "fostering circularity," "sustainable biomass," and "CO_2 capture" (Cefic, 2021, p. 6). The scenario analyses show that there are many different production processes in the chemical industry for which several different approaches to reducing emissions are conceivable. The umbrella organization acknowledges that there will be some need for CDR. Depending on the scenario the remaining emissions within the sector are between 68 and 111 Mt CO_2 by 2050 (Cefic, 2021, p. 107), which would amount to 11.3–18.4% of total residual emissions anticipated in the European Commission's indicative 1.5TECH scenario and 61.9–101% of residual emissions projected for the entire industrial sector under this secnario (European Commission, 2018b, Annex 7.7). It remains unclear whether the necessary negative emissions are to be realized entirely within the chemical industry. In its Fact Sheet on restoring sustainable carbon cycles, Cefic claims that the chemical industry can contribute to CDR by storing biogenic or air-extracted CO_2 (DAC) either in products (CCU) or underground (DACCS/BECCS; Cefic, 2023a, p. 4). In the case of CCU, however, it is very controversial whether and to what extent this can be evaluated as a removal, because in most cases the carbon bound in products is released after a certain time. Against this background, it appears that the chemical industry has an interest in CCU being classified as a removal. This is also reflected in its statement on the CRCF. The association argues that the term "carbon storage in products" is not appropriate, but pleads for the term "carbon removal products" (Cefic, 2023a, p. 14)—a notion that presumably shall open marketing opportunities for several products.

Cefic has formulated a strong critique of the NZIA, pointing to tensions between different industries in the process of reaching the net zero goal. The umbrella organization argues that the NZIA is actually a Net Zero Technology Act that bypasses the feedstock industries, to some extent similar to the criticism of the NZIA put forward by Eurofer. Cefic specifically criticizes that many components of technologies defined as priorities are based on chemicals and materials produced by the chemical industry. In this respect, unlike other trade associations, Cefic refers to the NZIA's goal to enhance the EU's strategic autonomy to argue that this goal would be undermined if it doesn't cover the full industrial value chain of strategic net zero technologies.[9] Against this background, CEFIC demands that the chemical industry should also receive the benefits (subsidies, accelerated planning) that the NZIA only envisions to provide for a few downstream industries (Cefic, 2023b).

Aviation

CO_2 emissions from the aviation sector in the EU amount to 187.76 Mt or 4.6% of total EU GHG emissions if data on domestic aviation (i.e., within member states) and on international aviation is summed up (European Environment Agency, 2021). The central lobbying association of the aviation industry in the EU is Airlines for Europe (A4E), in which 16 airlines (including all major European airlines such as AirFrance, KLM, easyjet, Lufthansa, and Ryanair) as well as the major manufacturers Airbus and Boeing are represented. Despite enormous progress in efficiency, greenhouse gas emissions have increased significantly since 1990 because of rapid growth in air traffic. While other areas of the mobility sector can be electrified relatively well, A4E emphasizes that this is not or only possible to a limited extent in air transport due to battery weights (A4E, 2021, p. 32). In this respect, the key challenge for the aviation sector is to find other decarbonization options.

In 2021, A4E, together with the associations CANSO (Civil Air Navigation Services Organization), ERA (European Regions Airline Association), Airports Council International-EUROPE (ACI), and Aerospace and Defense Industries Association of Europe (ASD) presented a net zero scenario until 2050 in line with the EU's goal of net zero CO_2 emissions by 2050. The Netherlands Aerospace

9 While this argument could also be put forward by other downstream industries (e.g., steel and cement), the broad spatial dispersion of steel and cement production across the globe makes it more difficult for these industries to claim that maintaining domestic production is crucial to prevent geopolitical vulnerabilities.

Center (NLR) and SEO Amsterdam Economics supported the trade associations in the development of the scenario study. The scenario includes air traffic within the EU and outgoing flights [specifically: the EU, the UK, and the European Free Trade Association (EFTA)]. To reach the net zero target in air traffic by the year 2050 is essentially based on four building blocks: "1. Aircraft and engine technology," "2. Air traffic management and aircraft operations," "3. Sustainable Aviation Fuels," and "4. Smart economic measures" (A4E, 2021, p. i). About 92% of the greenhouse gas emission reductions refer to the first three pillars. In addition to efficiency improvements, the use of hydrogen, the introduction of (hybrid-)electric aircraft, synthetic fuels and agrofuels are supposed to play a key role in decarbonising aviation. Nevertheless, the aviation industry assumes that it will still be using fuels from fossil sources in 2050, about 17% of the total amount of kerosene used by 2050 (A4E, 2021, p. v). Therefore, the decarbonization scenario assumes residual emissions of 22 $MtCO_2$, i.e., 3.7% of total residual emissions anticipated in the European Commission's 1.5TECH scenario and 25.7% of residual emissions earmarked for the transport sector in this scenario. These residual emissions shall be compensated by means of "smart economic measures," i.e., CDR. The sector only reaches net zero by "realizing out-of-sector carbon removals" (A4E, 2021, p. 150). However, the scenario analysis is based on rather optimistic assessments regarding technological innovation and progress, specifically with respect to "breakthrough" or "disruptive technologies" to net zero. Most importantly, the scenario assumes that between 2030 and 2050, the use of sustainable aviation fuels (SAF) will increase from 3 to 32 Mt. In this respect, it is uncertain whether climate-neutral air traffic in 2050 will actually be possible with CDR on the scale of 22 Mt per year.

Regarding CDR deployment options, the net zero study refers to DACCS, but remains rather general on how to scale up DACCS (or other CDR options) to the required deployment levels. This contrasts with A4E's recognition that the short-term possibilities to mitigate aviation emissions are limited as "the lion's share of emissions can only be abated from the mid-2030's onwards" (A4E, 2022, p. 2). At the global level, and in cooperation with CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), the growth in aviation emissions shall be neutralized through certificate trading. Regarding the Fit for 55 Package, A4E has clearly positioned itself against, for example, abolishing the kerosene tax exemption or restricting the free allocation of emission certificates. In this respect, A4E defends the existing regulatory framework and calls for both research funding and subsidies for the market ramp-up of new technologies. It is noteworthy that A4E contradicts the European Commission regarding the cost development of SAFs and accordingly calls for subsidies to compensate for high SAF costs: "A4E does not share the optimistic price projections of the European Commission's Impact Assessment. The cost to produce SAFs will remain multiple times the price of conventional jet fuel until 2030 and will remain higher than that of alternative fuels used in other transport modes. In absence of an orchestrated support strategy, the increased cost of SAFs will lead to the closure of routes and may put individual airlines in financial difficulty" (A4E, 2022, p. 4). This indicates that the decarbonization pathway is full of uncertainties. The simplest way to avoid emissions, reducing air traffic, is strongly opposed by A4E, as the association argues that offsetting "is the sole way to tackle global CO_2 emissions from aviation today" (A4E, 2022, p. 6).

(Fossil) fuel refining industry

Also core EU trade associations of "fossil capital" have embraced net zero emission targets. FuelsEurope, a division of the European Petroleum Refiners Association whose membership encompasses all 40 companies which operate petroleum refineries in the European Economic Area in 2019 (European Environment Agency, 2023), including the major European (and other multinational) oil and gas companies such as BP, Eni, Equinor, OMV, Shell, TotalEnergies, or ExxonMobil, published a proposal for a "Potential Pathway to Climate Neutrality by 2050" in 2020 (FuelsEurope, 2020a). The pathway is based on so called "clean fuels" or "low-carbon liquid fuels" for road, maritime and air transport. It assumes an increased uptake of hydrotreated vegetable oils and of lignocellulosic residues and waste as feedstock as well as a massive increase in the use of e-fuels, i.e., synthetic fuels based on carbon dioxide or carbon monoxide combined with "clean" hydrogen to achieve net zero in road transport (as well as a 50% CO_2 emission reduction in the aviation and maritime sector). Together, the production of these fuels, denoted by the trade association as low-carbon liquid fuels, could reach up to 150 Mt by 2050, with the lion share coming from lignocellulosic residues and waste as well as e-fuels (in roughly equal proportions).

However, as the projected uptake of low-carbon liquid fuels use still relies on blending these fuels with conventional fossil fuels (FuelsEurope, 2020b, p. 19), the pathway to net zero in road transport ultimately relies on CDR technologies, namely BECCS, to achieve net zero emissions in 2050. This is mentioned in an asterisk to the claim of reducing CO_2 emissions in road transport by 100% by 2050, but not further specified in any way. On the contrary, in an FAQ document accompanying the road map, FuelsEurope argues that it is impossible to specify the amount of low-carbon liquid fuels in relation to conventional fossil fuels used in 2050, which indicates a high level of uncertainty regarding the trade association's claim to reach net zero by 2050 by way of compensating (an unspecified amount of) residual emissions through BECCS.

While we did not find any statements of FuelsEurope on the Sustainably Carbon Cycle communication and on the CRCF, the trade association's position toward NZIA reveals its emerging approach to CDR (FuelsEurope, 2023). Here FuelsEurope pursued the goal to broaden the definition of sustainable alternative fuels to include not only SAFs and bunker fuels (for shipping) but also "low-carbon fuels for road transport and chemical products" (FuelsEurope, 2023). It also welcomed the NZIA's strong emphasis on CCS, highlighting the "carbon abatement potential [of] combining CCS solutions with biomass feedstocks in bioenergy (BECCS)" (FuelsEurope, 2023, p. 2). However, FuelsEurope urged to include in the NZIA's focus on CCS as a strategic net zero technology the relevant transport and storage infrastructures (which are largely operated by the oil and gas industry), not least as a way of "reducing stranded asset risk" (FuelsEurope, 2023, p. 3).

Gas

Like FuelsEurope, Eurogas, the main trade association of the European gas industry, has put forward a pathway to carbon neutrality in 2050, based on a study conducted by Norwegian registrar and consultancy DNV GL (2020). Eurogas represents different national associations of the gas industry (including the German gas and hydrogen industry association Zukunft Gas, Francegaz, and Italgas) as well as more than 70 companies. Among them are major oil and gas companies which are also members of FuelsEurope (Eni, Equinor, Shell, and TotalEnergies), but also energy suppliers (such as the Italian A2A, the German RWE, or the French Engie) and distribution network operators (such as the Austrian Wiener Netze or the French GRDF). The membership structure is both heterogenous (in that it covers companies with significantly different bases of accumulation, i.e., production of natural gas but also energy and heating provision more generally) and—compared to the other trade associations investigated here—less encompassing. Besides Eurogas, there are two further trade associations articulating positions of the European gas industry: Gas Infrastructure Europe (GIE), which represents the European gas transmission system operators, the LNG terminal operators and the gas storage system operators, as well as Gas for Climate. While there is some overlapping membership between Eurogas and GIE (for instance RWE and Uniper), the main functional difference between the two associations is that Eurogas represents companies producing and/or supplying natural gas to end users, while members of GIE are responsible for supra-regional transmission systems, storage, and LNG terminals. Gas for Climate is an association representing 11 gas infrastructure and transport companies (10 of which are also members of GIE) as well as three biogas trade associations (among them the European Biogas Association which, in turn, also counts oil and gas companies such as Eni, Shell or TotalEnergies among its members, i.e., companies which also hold membership with Eurogas). While GIE has neither come forward with a decarbonization or net roadmap nor positioned itself independently to the CRCF, the SCC communication or the NZIA,[10] Gas for Climate developed a decarbonization roadmap which fundamentally differs from the one put forward by Eurogas (Gas for Climate, 2020). Even though Gas for Climate did not position itself to the CDR-related EU policies investigated here, its alternative roadmap arguably weakens the claim of Eurogas to speak for the entire industry.

The decarbonization scenario promoted by Eurogas (DNV-G, 2020) is set up in juxtaposition to the European Commission's 1.5. TECH scenario to reach net zero by 2050—notably the Commission's scenario which is already significantly dependent on BECCS and DACCS as compared to the alternative 1.5 LIFE scenario with a stronger emphasis on lifestyle-based mitigation options (as well as ecosystem-based sinks; European Commission, 2018b). The Commission's 1.5 TECH scenario projects a considerable absolute decline in gaseous energy supply by 2050 (by more than 20% compared to 2015 levels) and a substitution of natural gas with so called carbon free gases (e-gas, biogas, and waste gas) and hydrogen by over 50% (European Commission, 2018b, p. 85). The decarbonization scenario put forward by Eurogas, by contrast, foresees an absolute *increase* of gaseous energy supply in 2050 by 18%, with the majority (55%) still based on natural gas (Eurogas, 2020, p. 6). Eurogas asserts that this scenario is consistent with an 89% emission reduction in the gaseous energy supply chain (heavily reliant on CCS) and can even be considered net zero ("fully decarbonized") if negative emissions from biomethane in power generation (i.e., BECCS) are accounted for (DNV-G, 2020, p. 21, 33). By contrast, while the alternative net zero pathway advocated by Gas for Climate similarly emphasizes the important role of gas (and hydrogen) transport infrastructure, the key difference to the Eurogas scenario is that it envisions an absolute phase out of natural gas by 2050,[11] its substitution with biomethane and hydrogen, and an absolute *decline* in gaseous energy supply (by 37.1%; Gas for Climate, 2020, p. 3–9).

The main argument put forward by Eurogas in favor of its decarbonization pathway (as opposed to the Commission's 1.5 TECH scenario) is cost-efficiency. Eurogas claims that its scenario would allow the EU to reach net zero using to a large extent existing infrastructure. The EU could thus save €4,1 trillion until 2050 for infrastructure investment, particularly in highly intricate areas such as the electrification of heating, where Eurogas considers the continued use of gaseous energy a cost-efficient decarbonization option for the building sector. Along these lines, Eurogas maintains that "[e]lectrification makes sense, but only up to a point" (Eurogas, 2020, p. 3). The main infrastructure investment needs in the Eurogas scenario therefore do not stem from the transition to renewable energy as well as related grid systems and electrification processes, but from retrofitting existing and building new transport networks for hydrogen[12] (DNV-G, 2020, p. 2).

Due to the all-encompassing role of CCS in its decarbonization scenario, Eurogas is highly supportive of the NZIA's strong focus on CCS (Eurogas, 2023a, p. 1). It sees the CO_2 injection capacity targets formulated in the NZIA (50 Mt per year by 2030) broadly in line with its own study estimates (54 Mt by 2030) but urges to fully consider not only CO_2 storage capacity in the EU but also on the territory of the European Economic Area (i.e., Norway; Eurogas, 2023b, p. 2). In a similar vein, Eurogas uses the debate about carbon removal triggered by the CRCF to further promote transport and storage infrastructure as well as capture technology for CCUS which, as Eurogas asserts, "would enable and enhance the deployment of certain technology-based carbon removal solutions (e.g., BECCS, DACCS)" in the future (Eurogas, 2023b, p. 1). At the same time, Eurogas also advocates to increase the tradability of CDR certificates, particularly through their integration into the EU ETS. While Eurogas justifies this position by stressing that it would

10 GIE did, however, support a joint letter calling for the recognition of CCU as a strategic net zero technology in the NZIA (see also Section 6; Cefic, 2023).

11 However, Gas for Climate foresees a continued role for natural gas in the production of blue hydrogen (Cefic, 2023).

12 Crucially, however, what is not taken into account in the Eurogas scenario, however, is that over a longer averaging period (e.g., until 2100), renewable energy sources (and related electrification processes) may become more cost-efficient, as they are characterized by relatively high upfront investment costs and lower operating costs (IEA, 2021b,c, p. 163–168).

"enhance the business case" for CDR (Eurogas, 2023b, p. 2), such a step of establishing "some level of equivalence between ETS CO_2 equivalent quotas and carbon removal certificates" (Eurogas, 2023b, p. 3) would arguably be highly prone to mitigation deterrence as it would create strong incentives to substitute emission reductions in the gas industry by purchasing removal credits if carbon removal certificates are cheaper than emission allowances.

Discussion

Based on the analysis and comparison of the roadmaps and policy papers of EU level trade associations representing sectors considered to account for a large share of residual emissions as well as associations representing the incumbent fuel industry, we can draw five findings. First, all capital fractions project largely "conservative" accumulation strategies into the future, insofar as changes merely relate to technological innovations, whereas absolute reduction of production quantities as a crucial mitigation option is absent from the low carbon or net zero roadmaps (except for the Gas for Climate scenario). For instance, Eurofer, projects an increase in crude steel production from 166 Mt (in 2015) to 200 Mt in 2050, Airlines for Europe (A4E) assumes an annual passenger growth rate of 1.4% until 2050, and Eurogas estimates an increase of gaseous energy supply (including hydrogen and biomethane, but mostly natural gas) by 18% compared to 2017 levels. This is in line with the EU's dominant climate policy paradigm based on the notion that decarbonization and GDP growth can be reconciled through decoupling, but at odds with recent debates which stress the importance of absolute reductions in production and consumption for effective mitigation (e.g., within consumption and production corridors or by focusing on demand-side measures; c.f. Creutzig et al., 2018; Fuchs, 2021; Bärnthaler and Gough, 2023). We can therefore observe a parallel between climate mitigation scenarios which treat GDP growth as "an unquestioned norm" (Hickel et al., 2021, p. 766) and the fact that all low carbon or net zero roadmaps put forward by the investigated trade associations project sector-specific growth trajectories (regardless of their respective role in low-carbon transitions). At the same time, growth in some sectors may be more reconcilable with (and indeed required for) stringent mitigation efforts than in others: While some proportion of the production of steel and cement is critical for the infrastructures anticipated to underpin net zero (even if this may not necessarily require overall growth in these sectors; Wang et al., 2023), others—especially aviation—may need to substantially contract, particularly given the technological obstacles to the decarbonization of the sector as highlighted by A4E (see Section 5.4).

Second, however, none of the trade associations explicitly opposes the EU's net zero target. All associations have developed decarbonization or net zero roadmaps, and five out of six have committed to net zero (carbon neutrality) targets, the achievement of which depends on CDR technologies (see Table 2). At the same time, on a more general level, a cursory look at positions adopted by these associations toward other EU climate legislations reveals opposition against individual policies that aim to reach climate neutrality in the EU. One example is the opposition of A4E against ending the kerosene tax exemption (A4E, 2022, p. 7). FuelsEurope's attempts to undermine the planned phase out of internal combustion engines in new cars after 2035 (FuelsEurope, 2022). Also, all of the associations analyzed, except Eurogas, spoke out against the expiry of free allowances as part of the recent EU ETS reform (A4E, 2021; Cembureau, 2021b; Eurofer, 2021; FuelsEurope, n.d.), even though these are hardly justifiable as a safeguard against carbon leakage protection with the CBAM entering into force. There is a tension between the sectors' commitment to the long-term net zero target and the opposition on behalf of individual sectors to take decisive steps toward this target in the short- and medium-term. This indicates that despite rhetorical commitment to decarbonization or net zero targets, there are strong continuities regarding climate policy opposition by emission intensive sectors in the EU (Plehwe et al., forthcoming).

Third, and relatedly, our findings support research highlighting the problematic ambiguities of net zero targets (McLaren and Markusson, 2020; Armstrong and McLaren, 2022). The ambiguities of net zero target framings enable emission intensive sectors to resolve the tension between long-term ambition and short-term opposition in climate policy, as many of the net zero roadmaps investigated fail to define a clear timing of mitigation efforts as well as the relation of emissions and removals over time and levels of residual emissions when net zero is achieved. As shown in Table 2, most trade associations do not make any efforts to explicitly estimate the level of residual emissions or provide only very large ranges for future residual emissions which will need to be compensated by negative emissions, let alone the timing for scaling negative emissions before the net zero year (and corresponding timing for emission reductions). While CCUS is constructed as the key technology that allows the trade associations under investigation (except for aviation, which has no prospect for using CCS) to assert that deep emission reductions in their sectors can be achieved, it is ultimately CDR technologies which bring the pathways of Cembureau, Cefic, A4E, FuelsEurope, and Eurogas on a net zero trajectory by filling the remaining, largely unspecified emission reduction gaps. Resolving the tension between long-term ambition and short-term opposition therefore (over)relies on promises of technological innovation, even though it is highly uncertain whether the CDR technologies mentioned in the roadmaps (mainly BECCS and DACCS) can be scaled up in a sustainable and socially just manner (Dooley and Kartha, 2018; Larkin et al., 2018; Creutzig et al., 2021). Thus, even though the sociotechnical imaginaries produced by these roadmaps mostly revolve around CCUS and other sector-specific technological promises (e.g., SAFs or green hydrogen in the case of steel), the roadmaps' consistency with net zero targets is heavily reliant on optimistic technological expectations—if not myths (Peeters et al., 2016)—regarding future CDR technology viability and deployment. CDR technologies can therefore be considered to act as techno-fixes in that they resolve the contradiction between maintaining (parts of) emission-intensive accumulation strategies and climate change mitigation (even though they do not—at least not yet—facilitate the fixing of major capital investment in new infrastructure, machinery and built environment). Up to this point, our findings confirm other studies (McLaren and Markusson, 2020) that net zero framings enable—and are enabled by—techno-fix thinking regarding CDR technologies.

Fourthly, however, the roadmaps and policy papers investigated do not simply reflect a uniform techno-fix thinking based on highly optimistic expectations regarding future technology breakthroughs.[13] We also found pessimistic views regarding specific technological pathways, suggesting that techno-optimism and -pessimism depend on respective economic interests and accumulation strategies For instance, A4E questions the optimistic projections regarding the price development of SAFs of the European Commission—even though SAFs are at the heart of its decarbonization pathway—in order to underline the need for subsidies for the sector (Section 5.4). While A4E is optimistic about the future viability of large-scale deployment of DACCS, Cembureau takes a critical perspective on future potentials of DACCS (particularly in terms of energy requirements) in order to assert that industrial CO_2 from CCU (e.g., derived from cement production) should continue to be allowed as a feedstock for renewable liquid and gaseous fuels of non-biological origin (RFNBOs) beyond 2040 (Section 5.1). Eurogas, in turn, is pessimistic regarding the economic viability of end-use electrification, particularly in the area of heating—a stance adopted to promote natural gas combined with CCS as the allegedly cost-efficient alternative for decarbonizing the building sector (Section 5.6). By contrast, the alternative decarbonization pathways articulated by Gas for Climate eliminates natural gas from EU energy supply. This supports our theoretical assumption that different capital fractions (or coalitions of them) promote different transition and decarbonization pathways, relying on different sets of technologies and sociotechnical imaginaries. While fossil capital foresees only a limited role of electrification and renewable energy sources in housing and transport and advocates for a continued role for fossil infrastructures and—in part—also fossil fuel extraction and production in the transition to net zero, the steel industry (and to some extent also the chemical industry) emphasize the importance of electrification and the rapid expansion of renewable energies. The key role of hydrogen both in the decarbonization scenario of Eurofer and A4E as well as in the net zero roadmaps of FuelsEurope (as a feedstock for e-fuels) and of Eurogas also foreshadows future conflicts of prioritized use which already pervade current hydrogen politics (Ohlendorf et al., 2023). Moreover, the participation of some major gas infrastructure providers in Gas for Climate indicates emerging splits within fossil capital particularly regarding the questions to what extent and which elements of carbon lock-in should be discontinued (e.g., natural gas production) to preserve others (e.g., pipelines for biogas and green hydrogen transport) in face of mounting political pressure. What all associations except A4E converge on, however, is a strong focus on CCUS and strong confidence in building a massive CCUS infrastructure—as a way to deal with process-related emissions (Cembureau, Eurofer), as a way to promote its products as a form of carbon storage or removal (Cefic) and as a way to abate emissions from the combustion of fossil fuels (Eurogas, FuelsEurope). This convergence is also evident from the fact that these associations signed a joint letter demanding that, besides CCS, CCU should also be recognized as a "strategic net-zero technology" under the NZIA (Cefic, 2023).

Fifth and finally, we find diverging approaches among the sectors regarding residual emissions, even as the extent of residual emissions and how to address them generally remains imprecise in the roadmaps. Steel is arguably unique in that Eurofer has not committed itself to a net zero target, thus acknowledging their inability to become fully decarbonized by 2050 and explicitly claiming residual emissions which need to be compensated outside the sector. This is coupled with an attempt to generate legitimacy for continued emissions, e.g., when Eurofer emphasizes the particular importance of steel for the transition toward a decarbonized economy (Section 5.2). A4E also admits that reaching net zero hinges on CDR to be realized outside of the aviation sector (Section 5.4). By contrast, the cement industry as well as the oil and gas industry do not claim any residual emissions which need to be compensated outside of the sector, arguing that they can achieve net zero based on CDR occurring within the sectors' value chains. We understand this position of the oil and gas industry as indicative that fossil capital is in a much weaker position than sectors required for the energy transition (e.g., steel) to legitimately demand residual emission to be compensated outside the sector, given growing political pressure to decarbonize or phase out fossil fuels entirely (Kenner and Heede, 2021; Green et al., 2022). The chemical industry is a special case in this regard as it does not specify whether compensation for its residual emissions via CDR will take place entirely within the sector.

On a more general level, we observe that, similar to countries' long-term climate strategies (Buck et al., 2023), key questions regarding residual emissions—their extent and how to deal with them—remain underexposed in the associations' roadmaps. The cement as well as the oil and gas industry do not make any attempts to quantify the extent of residual emissions in their sector. Steel, aviation and the chemical industry provide estimates, but partly on a very wide range (steel), partly without defining where in the economy (i.e., inside or outside of the sector) negative emissions are to be produced (chemicals), and in all cases (steel, aviation, and chemicals) without clarifying to what extent they take the responsibility for the scaling of CDR technologies required to balance "their" residual emissions. We interpret this as a consequence of the emergence of net zero as the new organizing principle of climate policy, which has led many trade associations to adopt net zero targets without being able (or willing) to specify the extent of residual emissions and/or how they are to be compensated. This is problematic in that it obscures pending conflicts over the distribution of residual emissions across sectors as well as over the responsibility for delivering negative emissions (e.g., by heavily investing into the scale-up of CDR technologies). There is thus an incongruity between the key role that CDR technologies play in most of the roadmaps to actually achieve net zero and the sectors' lacking interest in actually implementing and scaling these technologies and, in part, engaging with key CDR policies (see Table 1). Interestingly, this also holds for the fossil industry which can be considered to have an interest in CDR to "moderate the devaluation of fossil fuel assets" (Carton et al., 2023, p. 9) and to demobilize attempts to unlock carbon lock-in (cf. Gunderson et al., 2019; Pradhan et al., 2021). While authors have highlighted the possibility for the oil and gas industry to position

13 We are highly thankful to the anonymous reviewer 1 for drawing our attention to this important point (as well as to many other critical issues).

itself as a carbon disposal industry for CDR in other economic sectors (Hastings and Smith, 2020), we did not find any indication for this in our data. This suggests that CDR performs an abstract function to align emission-intensive accumulation strategies with net zero in long-term scenario projections, but not—at least not yet—in the actual accumulation strategies of these sectors, where CCUS (and related risks of diversion of capture carbon into short-term utilization, cf. McLaren, 2020) plays a much larger role. Rather on the contrary, Eurogas appears to see the CDR debate mainly as an opportunity to promote infrastructure development for CCS (Section 5.6).

Conclusion

We investigated how the main EU trade associations of sectors considered to account for a large amount of residual emissions by 2050 as well as how the oil and gas industry position themselves toward the nexus of residual emissions and CDR. Furthermore, we analyzed what function CDR performs in their sector-specific visions of decarbonization or transition toward net zero. We find that none of the associations openly opposes the EU's climate neutrality goal and five out of six associations have committed to net zero targets. In these five associations' roadmaps to reach net zero, CDR technologies—BECCS and DACCS—are essential to balance residual emissions. However, the main focus of these roadmaps lies on other technological promises, namely CCUS as well as sector-specific ones (e.g., SAFs for aviation or green hydrogen in the case of steel). Correspondingly, the extent of residual emissions and how to balance them through CDR technologies remain largely imprecise. Besides concerns over mitigation deterrence through unwarranted expectations in CDR, these ambiguities regarding residual emissions and CDR embedded in the net zero target framing conceal pending conflicts concerning how residual emissions will be distributed among sectors and which sectors should be accountable for advancing negative emissions. These conflicts are set to intersect with other lines of conflict regarding different transition and decarbonization pathways promoted by different capital fractions or coalitions of them (e.g., regarding the role of electrification and continued use of fossil fuels).

Our analysis also reveals a variety of questions to be addressed in future research. First, as trade associations typically advocate lowest common denominator positions, the degree to which individual dominant companies in the respective sectors align with or deviate from the positions of the trade associations, i.e., the question of intra-sector differences and conflicts, deserves closer attention. Second, the extent to which the associations' roadmaps concur with recent scientific evidence on the feasibility of different technological decarbonization options would need to be investigated systematically. Third, to complement our investigation, further research on the role of CDR and residual emissions in net zero pathways promoted by dominant actors in agriculture and shipping is required. The main political challenge emerging from our analysis is not predominantly that trade associations are advancing large and unsubstantiated claims on residual emissions. Rather, current imprecisions regarding residual emissions and CDR in corporate decarbonization or net zero roadmaps may propagate and reflect misconceptions about the necessity of deep emission cuts and related disruptive, transformative change—and forestall the necessary societal debate about legitimate claims on and distribution of residual emissions.

Data availability statement

The primary data that support the findings of this study are derived from resources available in the public domain. URLs to the original source are provided in the reference list. Further inquiries can be directed to the corresponding author.

Author contributions

AB: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. TH: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. ES: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

Publisher's note

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Blurring societal acceptance by lack of knowledge—insights from a German coastal population study on blue carbon

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Within the context of climate change, coastal vegetated ecosystems have the capacity for long-term carbon storage. Blue carbon refers to such carbon trapped in the oceans and coastal shelf seas. These ecosystems are under anthropogenic pressure and, to help these ecosystems to thrive and realize their carbon storage potentials, interventions require acceptance from society, in general, and adjacent coastal communities, in particular. Through a random street survey along the German coasts in 2022, quantitative and qualitative data were collected from more than 200 participants. A questionnaire comprising 50 open and closed questions was designed to assess the status quo of German coastal residents' norms and values concerning blue carbon ecosystems. Focus was put on nature conservation and climate change perceptions. The survey results reveal that most residents along the German coast valued nature conservation while idealizing nature that is seen as "untouched" by humans. Responses regarding active interventions to improve coastal ecosystem services were diverse. Blue carbon strategies are likely to operate within this area of tension. Most respondents were aware of climate change as a threat to their home region and were in favor of an increase in action against climate change there. The respondents were familiar with CO_2 reduction and avoidance strategies. However, they were less aware of measures to remove atmospheric CO_2 and the potential of storing CO_2 in ecosystems beyond afforestation measures. Due to a lack of knowledge, no consolidated public opinions on blue carbon in coastal vegetated ecosystems could be identified, blurring societal acceptance of blue carbon strategies. While these ecosystems are particularly vulnerable to human disturbance, long-term carbon storage is essential for blue carbon. Therefore, the individual acceptance of interventions from people living in close proximity to intervention sites is key for sustained success. The present article concludes that there are possibilities to co-create knowledge and acceptance as prerequisites for blue carbon interventions to possibly become efficacious.

KEYWORDS

carbon dioxide removal, climate action knowledge, coastal vegetated ecosystems, perception, Germany, Baltic Sea, North Sea

1 Introduction

At the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris in 2015, the global community agreed on limiting global warming to 2°C, preferably 1.5°C above pre-industrial levels. While the identification of a common goal is a big step toward climate action, practical solutions to achieve this goal have not yet been applied sufficiently (IPCC, 2023). A transition toward a fossil-free society, a prerequisite to reaching the Paris Agreement, does not only require new technologies and their deployment but also needs to consider questions on energy production and consumption with their related impacts on the social and physical environment (Feola, 2015; Boudet, 2019). Involving societal actors across scales in the discussions and decisions on solutions is key. Public perceptions and responses can facilitate or hamper climate action as demonstrated, for example, by the resistance against the wind energy industry (Rand and Hoen, 2017). For an understanding of how public opinions and preferences are shaped in the climate change discourse, knowledge of climate change and its communication is key (Fløttum and Gjerstad, 2017). The presence or absence of potential gains and losses, risks, uncertainties, or moral implications in the communicated 'story' helps to explain the success of climate action or resistance against it. New technologies are more easily accepted if they can be associated with known processes. In this case here, however, the new processes are associated with negative experiences, such as fracking (Cox et al., 2022; Westlake et al., 2023) or quests for final storage sites (Braun, 2017; Arning et al., 2019), even if they have little in common technically. This then has a negative effect on the acceptance of the new approaches.

Mainstream political and public discourses on climate action in the 1990s to early 2000s focused on mitigation (reducing emissions). In the late 2000s, adaptation was discussed at a similar rate, as efforts to reduce anthropogenic carbon dioxide (CO_2) did not halt or reverse the global trend of rising emissions and negative climate change impacts became increasingly evident (Görg, 2011; Mercer et al., 2011). Around 2010, as an urgent need to take climate actions to avoid a climate crisis became more prominent, large-scale engineering techniques entered the discourses (Mercer et al., 2011; Oschlies and Klepper, 2017). In light of the Paris Agreement, the Intergovernmental Panel on Climate Change (IPCC) developed recommendations to stay within the agreed 1.5°C to 2°C range. These pathways endeavor to reach net zero emissions by 2050, which includes the utilization of 'negative emissions' or 'carbon dioxide removal' (CDR) to offset hard-to-abate emissions. CDR corresponds to the capture and long-term storage of atmospheric CO_2 and has become part of the discourse (IPCC, 2018). As of today, the need for measures beyond mitigation and adaptation seems indisputable to keep climate change within the range of the Paris Agreement (Gattuso et al., 2018; IPCC, 2018; Carton et al., 2020). However, local to global levels of societal knowledge and acceptance of CDR options are under-researched.

The terms 'climate engineering' or 'geoengineering' can serve as umbrella terms for large-scale engineering techniques, including solar radiation management (SRM) techniques, which aim to lower the global temperature by, e.g., increasing the reflection of sunlight via the injection of sulfate aerosols into the stratosphere. SRM carries potential environmental and social risks (Shepherd, 2009; Ricke et al., 2010). Public and political resistance focused on SRM, and in the public perception, SRM and climate engineering became synonyms (Mercer et al., 2011; Merk et al., 2019). CDR techniques can also be seen as examples of climate engineering but have been less discussed in public. Both options might produce undesired side effects, which "may raise severe ethical, legal, and governance issues" (Oschlies and Klepper, 2017: 128). Within scientific discourses, attempts were made to place CDR in opposition to SRM and climate engineering, arguing that CDR addresses the causes of climate change (anthropogenic CO_2) rather than merely addressing the symptoms (global warming) (Kiehl, 2006; Schellnhuber, 2011). Based on the experiences with SRM, an expectation of public opposition to CDR seems plausible. However, a conclusion that excludes the public from such discourses appears to be premature (Merk et al., 2019). Marginalizing or depoliticizing the discussions on the potential impacts of CDR options on society by only focusing on sociotechnical aspects, in fact, delays the decarbonization of society (Low and Boettcher, 2020). Furthermore, controversy, exchange, and forming of opinions are a means to encourage deliberation and, with this normalization process (Hansson et al., 2022), potentially contribute to accelerating climate action.

Marine CDR options are a relatively new field within the context of CDR, including ocean alkalinization, enhancements of the physical and biological pumps, the utilization of storage sites below seafloors, and blue carbon (Gattuso et al., 2018). Blue carbon refers to atmospheric carbon trapped in the oceans and coastal shelf seas and has been included in IPCC reports since 2019 (IPCC, 2019; Hilmi et al., 2021). As coastal vegetated ecosystems (CVEs), such as mangroves, macroalgae, seagrass meadows, or salt marshes, capture more than half the CO_2 the oceans sequester, they play a critical role within the blue carbon discourse. Management activities of these ecosystems imply interferences with existing CVEs and connect social and ecological systems; therefore, these activities have social, ecological, and spatial impacts that affect adjacent communities. As the carbon captured in CDR projects has to be stored for centuries for such projects to be impactful, societal acceptance is vital. While land-based options are under great pressure from competing land uses (e.g., for afforestation, food, fodder, and biofuels), some suggest that marine nature-based CDR options might be under less pressure (Gattuso et al., 2018). While opposition against SRM and climate engineering is based on attitudes that nature should not be manipulated in such ways (Mercer et al., 2011), few technology-based blue carbon measures are thought to have more positive side effects than negative ones (Hilmi et al., 2021). Blue carbon can be perceived as an ally to create synergies with nature conservation. With the need for sustained climate action at hand, the Federal Government of Germany recently installed an "Action Plan on Nature-based Solutions for Climate and Biodiversity" (BMUV, 2023), aiming to link climate action and nature conservation and taking blue carbon activities into account. Thus, perceptions of German coastal communities on potential blue carbon interventions are highly relevant. However, previous studies on public perception focused on comparing different climate engineering or CDR options, but to the best of our knowledge, blue carbon has not been included in Germany (Merk et al., 2019, 2023) or elsewhere (Corner and Pidgeon, 2015; Carlisle et al., 2020). Furthermore, studies explicitly focusing on coastal residents' realms and their perceptions of marine CDR are missing.

The objective of this article is to analyze coastal residents' perceptions of blue carbon, taking German coastal communities as a case study, to understand drivers of public acceptance and identify barriers and enablers for implementing blue carbon. The identification of people's values and their knowledge of CVEs, climate change, and blue carbon is a prerequisite. Therefore, first, we present a climate research understanding of blue carbon before further discussing the links between values, knowledge, and societal acceptance. Then, we introduce our survey design and present our results. We identify a lack of basic knowledge regarding CDR and blue carbon in German coastal societies. Accordingly, public opinions have not yet been formed. In consequence, we recommend more public discussion on (marine) CDR and discuss strategies to co-produce climate action knowledge based on shared values to accelerate the forming of opinions, to start and settle controversies, and finally, to be able to decide if or under which circumstances blue carbon interventions might become legitimate climate action options.

2 Coastal vegetated ecosystems, blue carbon, and the German coasts

The IPCC defines that "[a]ll biologically-driven carbon fluxes and storage in marine systems that are amenable to management can be considered as blue carbon. Coastal blue carbon focuses on rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses. These ecosystems have high carbon burial rates on a per unit area basis and accumulate carbon in their soils and sediments" (IPCC, 2019: 680). Blue carbon interventions are measures along the coasts to enhance the potential of CVEs to store carbon. According to the level of intervention, these measures range from protection and conservation to the expansion of areas within or beyond former sizes and the creation of new habitats. As the shape and the scale of interventions are hardly discussed in the literature, global storage potentials are difficult to determine. According to one prominent recent study, the absolute storage potential of CVEs per year might be <2% of current emissions (Hilmi et al., 2021). Nevertheless, CDR technologies such as blue carbon can support compensation for hard-to-abate emissions (Paltsev et al., 2021).

Mangroves grow in tropical or subtropical climates and, similar to salt marshes, thrive in intertidal zones. Most seagrass species prefer shallow waters below tides but can also be exposed to tides. Macroalgae, also referred to as kelp or seaweed, grow best on solid rocks outside of tidal exposures but still need sufficient sunlight. All CVEs have socio-ecological benefits for the local communities. Specifically, mangroves, seagrass meadows, and kelp forests are areas used by fisheries as they serve as nursery habitats for valuable fish and other marine species. Salt marshes are used for pastures and tourism (Friess et al., 2020). As all CVEs protect against coastal erosion and sea level rise by accumulating sediments or slowing down wave energy, they also provide benefits for climate change adaptation (Hilmi et al., 2021). Additionally, CVEs contribute to the health, recreation, and sense of belonging of people (Conroy, 2023). Potential negative impacts on socio-ecological systems include seagrass as breeding grounds for disease carriers (Govers et al., 2017), harmful algae blooms (Gobler et al., 2017), or beach grooming related to increased flotsam.

Due to climate change, coastal development and construction, marine pollution, agriculture and aquaculture, bottom trawling and overfishing, and other intensive landscape and seascape uses, all blue carbon ecosystems suffer (Hilmi et al., 2021). In the last three decades, the global area of mangroves has shrunk to 1.04 million ha from 14.8 million ha (FAO, 2020). Seagrass meadows cover a known area of 1.2 million ha. The exact magnitude of its area loss is still uncertain but is estimated to be 34% in the past 50 years (Telesca et al., 2015). Global figures on macroalgae are rare; an analysis by Krumhansl et al. (2016) concluded a loss of 38% in the last five decades. Salt marshes have shrunk to half their historical size during the last century (Giuliani and Bellucci, 2019). Conservation activities might not only serve CDR intentions but also reduce emissions because "[i]f degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the atmosphere" (IPCC, 2019: 680).

German coastal waters, from a geopolitical and ecological point of view, encompass coastal areas of the North Sea and Baltic Sea that are in mutual contact with the open sea and are administered under German legislation. The main habitat of kelp in Germany is around the North Sea island of Heligoland. Since 1989, no significant long-term trends in the standing stock have been reported along the mainland shores (Drent et al., 2017). Salt marshes dominate the German North Sea coast, "semi-natural systems that have been constructed for means of land reclamation via conversion of tidal-flat ecosystems during the late 19th and early 20th century" (Mueller et al., 2019: 2). In the present times, they also have other socioeconomic benefits for local communities, including tourism, as a source of feed or fuel, and even for the provision of medicinal remedies (Friess et al., 2020). Their extent of approximately 22,000 ha has been rather stable over the last decades (Esselink et al., 2017). Seagrass meadows in the German shelf sea are traditionally common, but their mapping is classified as incomplete (Röschel et al., 2022). Seagrass coverage seems to have heavily declined along the North Sea coast of Lower Saxony by more than 75% in recent years, from 37.6 km^2 in 2013 to 8.6 km^2 in 2019 (Küfog and Steuwer, 2020) but remain stable along the North Sea coast of Schleswig-Holstein (Dolch et al., 2017). While the reasons for these diverging trends are unknown, eutrophication, hydrodynamics, and ocean warming are commonly discussed as threats (Dolch et al., 2017; Küfog and Steuwer, 2020). The Baltic Sea coast of Germany is home to lush seagrass meadows, which cover a total area of approximately 285 km^2 in up to 8 m depth (Stevenson et al., 2022), but long-term studies to detect trends are absent (Schubert et al., 2015). The uses of seagrass as an environmentally friendly insulating material, a sustainable raw material for packaging material, or a soil conditioner in fields have only recently gained new appeal. The estimated seagrass meadow colonization potential off the coasts of Schleswig-Holstein alone is 450 km^2 (Röschel et al., 2022). However, to what extent the current forms of usage interfere with long-term CO_2 sequestration goals is a societal conflict of interest and a matter of negotiation that needs to be resolved.

In addition to the potential benefits for nature, climate, and eventually humans, marine CDR in general and blue carbon in particular can also be instrumentalized against climate action. The effectiveness, permanence of storage, cost-effectiveness, and governability of most marine CDR approaches, including blue carbon, are abundant with uncertainties (Gattuso et al., 2021; Williamson and Gattuso, 2022). Overselling CDR by building unrealistic expectations has the potential to slow or stop political action and industrial transition (Low and Boettcher, 2020; Boettcher et al., 2021). However, within the academic debates on blue carbon, conserving, restoring, and enhancing coastal vegetation are seen as low-regret measures, providing hardly any disadvantages (Gattuso et al., 2021).

3 Knowledge, values, and acceptance

For collective climate action, social learning creates knowledge of what to do, how to do, and why to do it (Pelling et al., 2008; Berkhout, 2012; Goldberg et al., 2020). Social institutions carry out actions as routines, which are understood as efficient and appropriate procedures when facing conventional or unconventional situations (Berkhout, 2012). Learning is needed to develop routines and adjust them when adapting to socioecological changes (Pelling et al., 2008). With that in mind, we will introduce different types of knowledge and their meaning for action. Linking types of knowledge with concepts of societal acceptance, we create a robust understanding of prerequisites for climate action and apply it to blue carbon interventions along the German coasts.

As a first approximation, the rationale for an individual action is based on expected outcomes. Within rational thinking, the expectation of a positive outcome or utility as a motivator for action is based on knowledge (Hawthorne and Stanley, 2008). However, attributions that the outcome is positive or useful are based not only on rational facts but also on individual values and perceptions. Society matters, as values are created, adapted, and persist not only on individual levels but also in greater societal contexts (Lepak et al., 2007). In the context of climate action and broader fields of socio-ecological studies, different knowledge claims with unequal qualities regarding action are common (Lauer, 2017). Formal or scientific knowledge is distinguished from local, traditional, or indigenous knowledge. In the context of dissemination—e.g., via formal or informal education or apprenticeship—distinctions between explicit and implicit or tacit knowledge are common. As explicit knowledge, or simply "information," can be transferred by documents (Gorman, 2002), formal education is linked to formal and scientific knowledge. However, on the one hand, as long as information or bites of information are not embedded in social settings, formal knowledge alone has no depth and does not often lead to action. Implicit or tacit knowledge, on the other hand, is based on experience and unfolds as skills and routines gained by the practical contact with facts or events. Hence, tacit, local knowledge is obtained via action and is more likely to create further action. Depending on the context, local knowledge can be synonymous with practical knowledge or action knowledge. However, in climate change contexts, most people lack adequate experience with ongoing and, even more so, with future changes so that local knowledge and skills' adaptation to future challenges is constrained. In this respect, awareness and suitable action require the application of scientific knowledge and its translation into and merging with local knowledge to generate a new type of knowledge, which then is able to foster climate action (Lauer, 2017; Fink et al., 2021). The type of action knowledge co-produced by researchers, policymakers, practitioners, and members of the wider public alike (Kothari and Wathen, 2017) and needed in a transdisciplinary climate change setting is what we refer to as 'climate action knowledge'.

Value systems are cognitive structures that produce meaning and shape desires within individuals and society. Values serve as standards or criteria to guide action, judgment, and choice, among other things (Rokeach, 2000). Most values are shared within human societies. However, priorities and interests may differ between individuals, societies, and cultures and expressions that similarly depend on context and culture; therefore, values can be conflicting (O'Brien, 2009), but values are also changeable and versatile. Context dependencies and social learning are ways to explain existing dynamics and changes in value systems and subsequent actions from individuals and societies. Eventually, the purpose of values can be framed as "to enjoy a fuller life [and to] make an impact […] theoretical sophistication has to be followed by action" (Prilleltensky, 2001: 760). Action, again, can be associated with individuals as well as society. On the individual level, examples of climate action are shifts to renewable energy or the use of public transport. Social action can, on the one hand, imply individual action as civic engagement, e.g., volunteering in social work. On the other hand, social action is associated with building and executing community development or social movements (Morsillo and Prilleltensky, 2007). On a societal level, the latter can lead to social change, e.g., changing forms of regulation or governance by installing climate laws and climate organizations.

Individual and societal acceptance of any measures is based on expectations of possible outcomes and, therefore, is driven by knowledge and values. Acceptance is an act of giving consent to something, which implies a perception of being beneficial or at least adequate (Cohen et al., 2014). It can be expressed actively by support or engagement and—in case of non-acceptance—by active resistance or by passively fatalistic letting it go. Acceptance is likely to increase with enhanced levels of integration and participation. A low level of participation is a one-way communication providing information, whereas mutual flows of communication and rights in decision-making indicate higher levels of integration. High levels of participation and integration can lead to ownership and identifying actions and outcomes (Kumar, 2002), which, in turn, indicate tacit knowledge and acceptance. Technical and economic feasibilities, which might also affect societal acceptance (Wüstenhagen et al., 2007), are beyond the scope of this article.

For measures with spatial impacts—blue carbon actions imply interferences with socioecological coastal environments—acceptance likely differs between general public opinions and adjacent local communities. On the one hand, the installation of measures can be embraced by the general public and yet fail due to local resistance. The phenomenon of "not in my backyard" (NIMBY, see Van der Horst, 2007) has demonstrated in many instances that even generally accepted measures, once they are to be implemented locally, evoke resistance from the locally affected population as soon as they interfere with a home region. On the other hand, measures that are generally disapproved of can thrive with appropriate incentives in local communities (e.g., job generation), whereas neither the general public nor local communities should be understood as a single homogeneous community of interest. However, local welfare (Cohen et al., 2014), in-depth knowledge, and participation are shown to increase acceptance (Segreto et al., 2020). Overall, for lasting and desirable outcomes and acceptance, the societal embeddedness of these actions in norms and values is crucial (Pelling et al., 2008; Goldberg et al., 2020).

4 Street survey—methods

This study consists of a two-part population survey conducted as a random street survey in open public spaces along the German coasts. In March 2022, 132 local residents were interviewed on both coasts of Schleswig-Holstein, and in July 2022, 90 people participated in the same survey on the coast of Lower Saxony. The participants were between 16 and 88 years of age. Compared to the population of the federal states of Schleswig-Holstein and Lower Saxony, most of the age groups in the survey differed <20% from state averages. Only the 16–25-year-old age group was overrepresented by almost 50%, while the 36–45-year-old age group was underrepresented by 40%. The mean age was 49 years, and 52% of the participants were female, reflecting the states' populations in mean age and gender. Twelve survey locations were chosen to represent the rural and urban coastal populations of Schleswig-Holstein and Lower Saxony as well as the North Sea and Baltic Sea (see Figure 1). Places were selected according to size and infrastructure (more than 1,000 inhabitants and busy public spaces) and represent different administrative districts. Surveys were mainly conducted on the street, in public places, in pedestrian zones, and in front of supermarkets. A question about the place of residence was to be answered with the respective postal code, and an analysis was carried out regarding residency. This information was used to apply a rurality index (Küpper, 2016) to give each place of origin a rurality value based on several indices, such as the density of settlements and the proportion of agriculture and forestry in a municipality or the distance to large centers. At each selected location, 11–24 interviews were conducted. Most of the 222 participants answered all questions, so the sample size is generally between 218 and 222.

The questionnaire included 10 open-ended and 40 closed questions and was structured into four chapters: place attachment and environment, regional climate change, political participation, and sociodemographic data. For the closed questions, the respondents were presented with a Likert scale with options to agree or disagree with given statements using five predefined answers: "yes," "rather yes," "rather no," "no," or "do not know." *Spearman's correlation coefficients* between closed questions were calculated with SPSS. For the interpretation of correlations mentioned in this article, only those correlation coefficients were taken into account, which were statistically significant ($p = 0.01$) and exceeded rather weak relationships ($\rho > 0.2$) (Schober et al., 2018). Open questions provide in-depth insights into people's values, opinions, experiences, and how people draw links between topics.

For each trip, four students were coached, and together with the corresponding author, the mixed-gender group conducted one-on-one surveys. Coaching, taking notes of verbal reactions and non-verbal expressions, and holding reflection sessions twice per day supported the comparability of the survey results independent of the interviewer and interpretations of presented answers. The first question focused on place attachment ("Heimat") and possible threats to it in order to identify values. Then, we asked specific questions about nature and the environment to avoid spillover effects—people's perception of "Heimat" and threats to it should not be biased by the study's focus on nature and climate change. Supported with pictures of the German CVEs (salt marshes, seagrasses, and macroalgae), participants were asked to freely name their associations with these CVEs and to express attitudes in the context of nature conservation topics. In the second part, people could give their views on climate change, negative emission technologies, and the meaning of CVEs in this context. The third part focused on political dimensions; one's willingness to

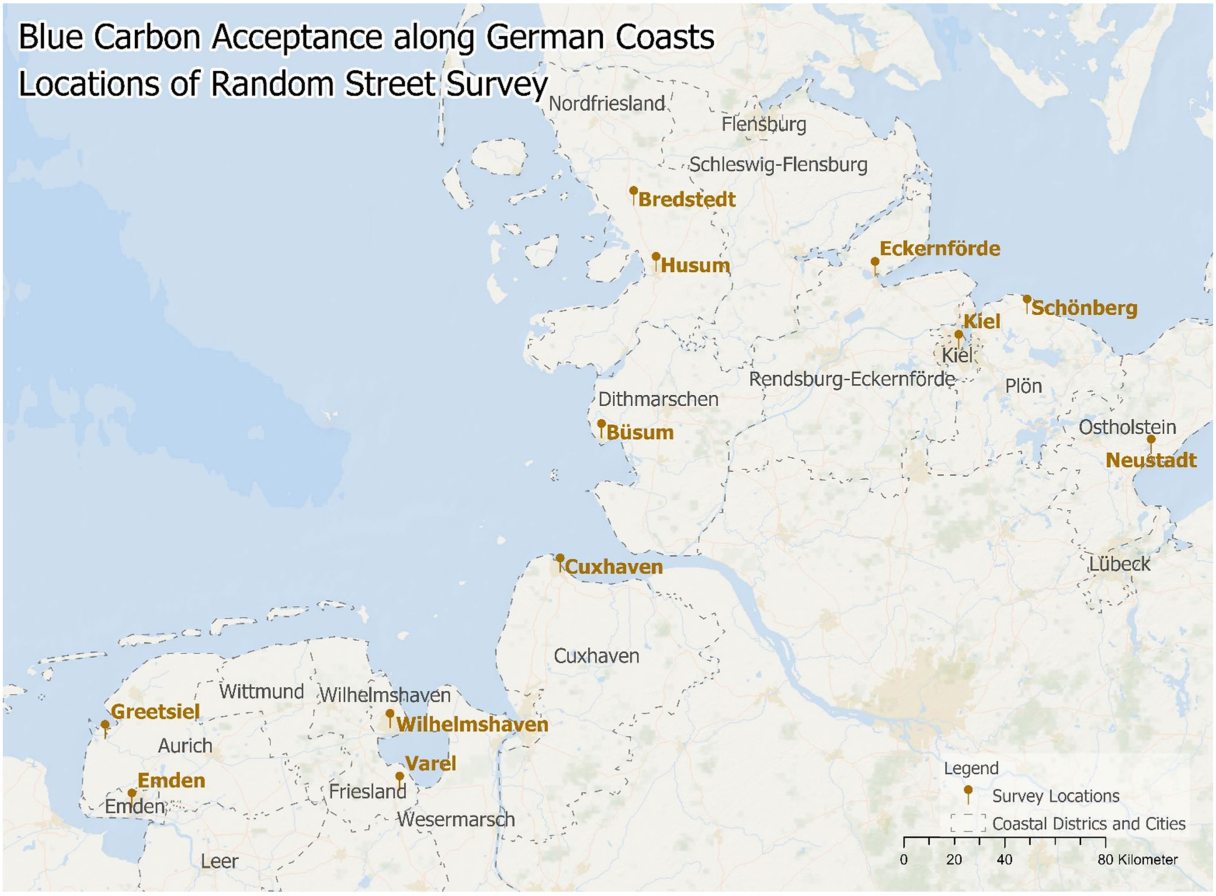

FIGURE 1
Map of survey locations.

voluntarily engage in decision-making processes shaping the region is this article's focal point. The objective was to identify patterns and correlations between local identity, knowledge, and values in the context of potential blue carbon climate interventions.

5 Results

5.1 Values and threats, place attachment, and nature

To set a base on what people value, the first open questions were "What is typical for your home ("Heimat")?" and "What is nature for you?" Both questions were answered by 220 and 221 out of the 222 participants, respectively, and the characteristics respondents refer to when asked about home and nature overlap, as landscape elements and physical environmental features dominated both answers. "Home" was associated with coastal features such as "water," "the sea," "wind," and "air." They not only list such elements but feel attached to them, as this quote exemplifies: "This is where my soul breathes. I cannot live in warm countries. I need wind and I need water." (female, born in 1966). Regarding "nature," the top answer was "forests" (58 times), and most other answers related to the coastal landscape, such as "beach" (25) and "the sea" (24), while five respondents directly mentioned salt marshes. People mentioned qualities (e.g., tranquility and fresh air) 170 times, and people mentioned activities 74 times, which indicates special place attachments. In their own words, nature is "when I go out in the morning at 6 o'clock on the mudflats - there is no one on the way" (female, born 1962), or "when everything can grow wild without intervention" (female, born 1950). While respondents explicitly refer to the absence of civilization 111 times (e.g., untouched, no houses, and no cars), they referred to socio-culturally produced elements, such as meadows (19), gardens (12), dykes (9), or parks (5) as being elements of nature, 83 times. The contradictions in the role of humankind and its activities toward nature (separated vs. forming) seem independent from place, age, or gender.

All 222 participants reacted to the statement "Certain areas should be protected from human utilization," 203 respondents completely agreed, and another 9 people answered, "rather yes" (see Figure 2); and 60% of participants agreed to the statement, "environmental and nature conservation have already had a lot of success in this region." Living along the North Sea or Baltic Sea shows insignificant, negligible correlations, but age positively correlates with seeing success. However, 20% of the respondents being unsure and 20% of them denying success might still be a sign of skepticism (see Figure 2). The statement "My environment is destroyed" invoked mixed reactions with almost as many yes as no answers. Many people reacted emotionally and explained their choice of answer. The younger the respondents were, the more likely they agreed with the statement.

To avoid spillover effects and to ensure an understanding of values, the very broad question "What are threats to the region?" was placed between questions about 'home' and 'nature.' The most feared threat is "flooding" (see Figure 3). Flooding and synonyms thereof were mentioned 60 times (28%). In addition, climate change (28 times) and sea level rise (19 times) were frequent, spontaneous answers, sometimes in direct relation to flooding. Other climate-related hazards were "storm," "wind," "weather," "drought," or "forces of nature" (26 times in total), some of which might also relate to flooding or climate change. While another 59 times nature and environment were in focus, e.g., man-made environmental and sea "pollution" or "environmental destruction," economic and sociodemographic threats moved participants too. A total of 33 individuals (15%) named "tourists" or "tourism" as a threat to the region, and others were concerned about increasing prices in housing and the youth moving out of the region. In Lower Saxony, poverty, unemployment, and dependency on a single company (Volkswagen) are issues of concern.

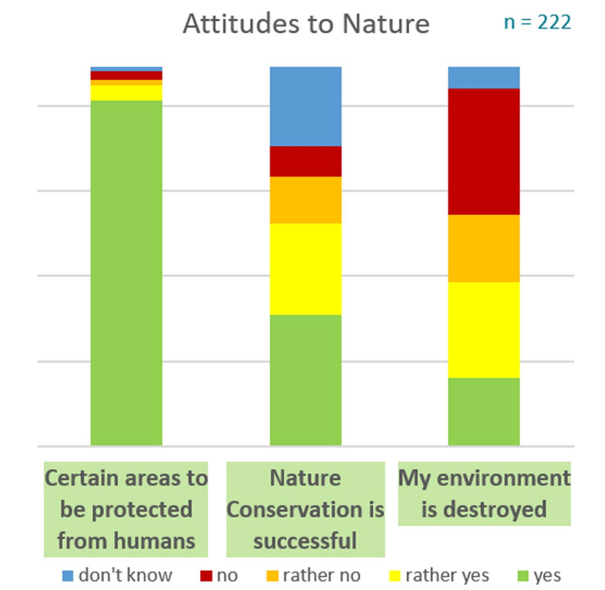

FIGURE 2
Attitudes toward nature.

5.2 Engaging with CVEs

In the second part of the survey, respondents were shown photographs of coastal vegetation depicting salt marshes on the Frisian coast, a seagrass meadow in the Baltic Sea, and macroalgae in the North Sea and were asked 'What is the relevance of marine and coastal plants such as salt marshes, seagrasses, and seaweed to your home?' Participants could associate on a general level and explicitly give statements to the individual ecosystem. Of the 222 participants, a majority of 134 respondents answered with a general association to the shown ecosystems, and only 23 respondents could not give any answer. Specific reactions were reported for salt marshes by 75 respondents, seagrasses by 56 respondents, and macroalgae by 58 respondents. After a first reaction that an association is difficult to give, the ecosystems were judged as generally important. In more detail (see Figure 4), 79 individuals stated that these ecosystems are good for nature, e.g., for animals and biodiversity. Twenty-seven times respondents mentioned other co-benefits such as coastal protection or water quality enhancement. Twenty-three individuals explicitly attached them to their own *Lebenswelt*, and 21 individuals spontaneously stated that they think these ecosystems are worth protecting, for example: "These biotopes are important, vital for survival. Can

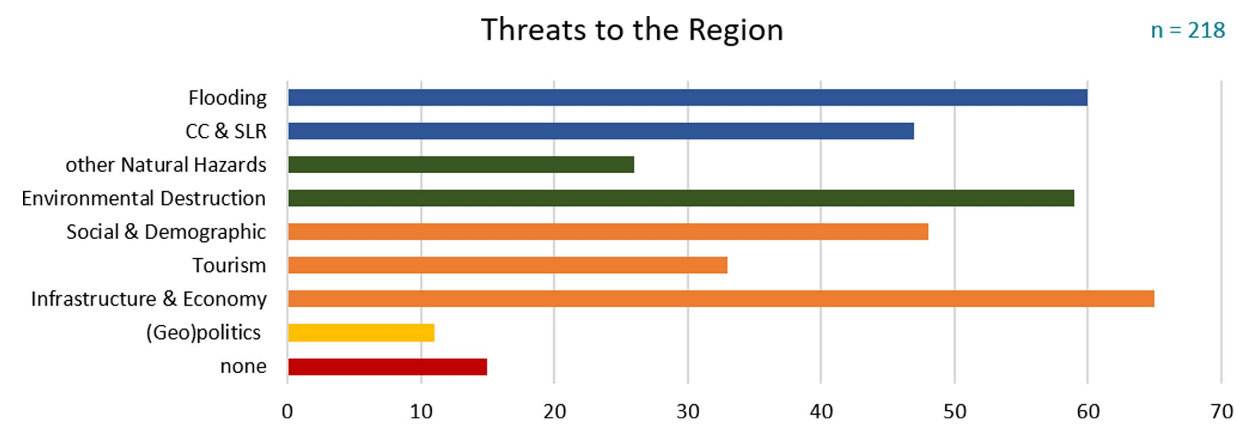

FIGURE 3
Perceived threats to the home region.

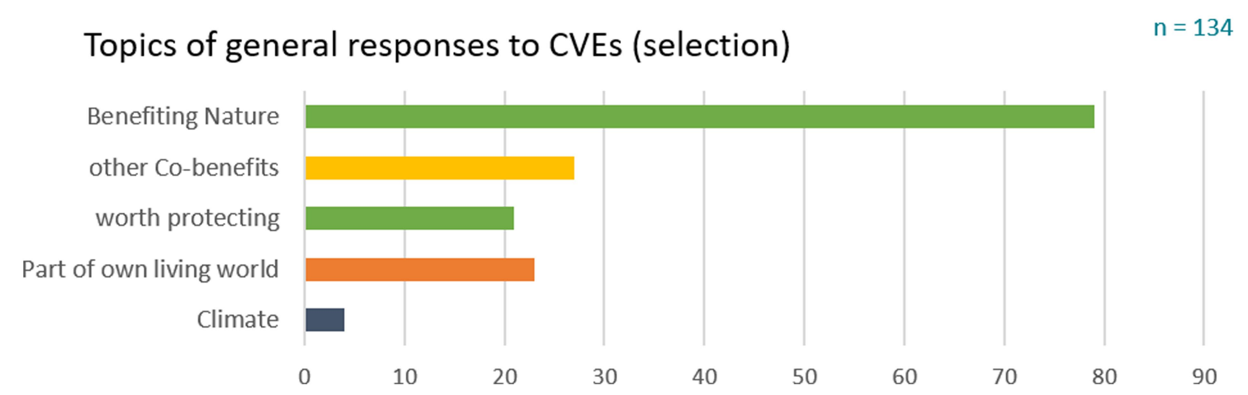

FIGURE 4
General statements on coastal vegetated ecosystems.

we please stop ruining them? That would be great!" (male, born 1987). Four participants attempted to link the ecosystems to climate or climate change, and two had reservations about these ecosystems.

Answers given about the individual ecosystems focus on specific benefits. Salt marshes were connected to a wide variety of benefits. Mostly, they were valued for coastal protection (16 of 75), e.g., "No coastal protection without salt marshes!" (female, born 1940), land reclamation, and birds. Seagrass serves as a vitally important habitat for hatching and breeding fish (21 of 56). Out of 58 respondents, 18 mentioned macroalgae as a food source. However, not every respondent voiced support for macroalgae; 15 respondents raised concerns—mostly seeing them as a sign of environmental pollution, e.g., seeing them as a "danger, grows too much due to pollution" (a man born in 1952).

Following the open statements, participants were asked to assess predefined statements on nature conservation, an active expansion of the previously discussed CVEs, and some co-benefits. Out of the 222 respondents, 169–205 of them answered with a general "yes" to the direct closed questions, if salt marshes, seagrass, or macroalgae are worth conserving. Another 5–13 people chose the answer "rather yes." The conservation of salt marshes and seagrasses is valued more than macroalgae. However, even with macroalgae, only 7% of those with an opinion disagreed or rather disagreed that these ecosystems should be preserved. When asked whether these ecosystems should be actively expanded, 51–56 respondents (approximately 25%) could not answer. Although more than half of the participants agreed, 10–20% rejected such ideas (see Figure 5). Probably, the widespread perception that nature should be "untouched" explains the differences in whether CVEs should only be conserved or also actively expanded (see also Walsh, 2020). When directly asked about coastal protection and improvement of water quality, hardly anyone disagreed (see Figure 6), though individuals sometimes stated that their knowledge on the subject was limited.

Most coastal residents along the German coast have formal and tacit knowledge about different ecosystems. Regarding CVEs, people value all three ecosystems, but they felt most attached to salt marshes and least to macroalgae. Knowledge declines accordingly. Whereas local knowledge of salt marshes is common, as coastal residents actively spend time in these ecosystems, knowledge of seagrass appears more formal and weaker. Opinions on macroalgae differ, as, on the one hand, people appreciate it as food or just as part of nature. On the other hand, people built up tensions associating macroalgae with pollution, a phenomenon which is more common with green-blue algae (cyanobacteria) or microalgae (phytoplankton) in German coastal waters (Gobler et al., 2017; Dai et al., 2023).

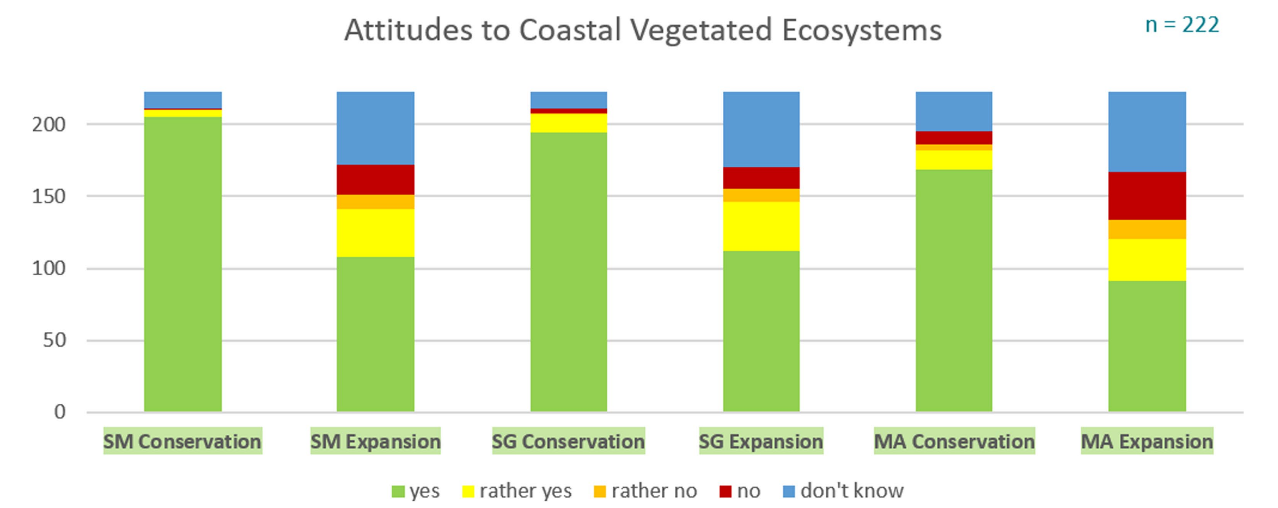

FIGURE 5
Attitudes to CVEs. SM, salt marsh; SG, seagrass; MA, macroalgae.

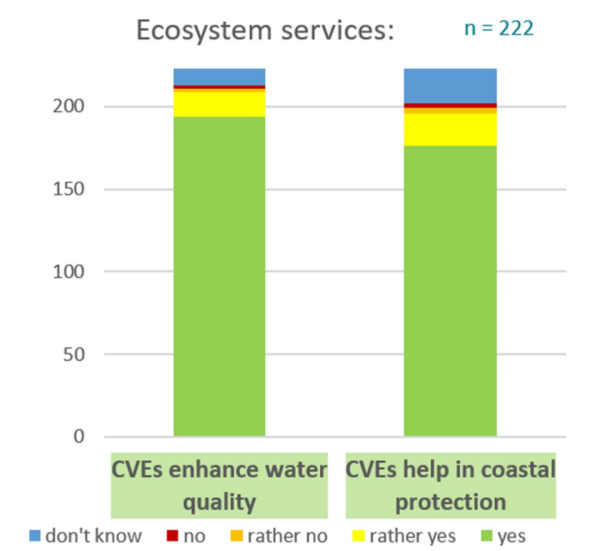

FIGURE 6
Ecosystem services of CVEs.

5.3 Climate action, negative emissions, and potentials for political participation

People along the German coasts are familiar with the term "climate change." Out of 220 participants, 195 confirmed that it is man-made (see Figure 7) and 185 (84%) see climate change as a threat to their home region. The open question on threats to the region (see Figure 3) revealed that the survey participants along the German coasts perceive climate and climate change-related hazards as the most frequent threats. The perception of climate change as a serious threat is consistent, mutually corroborative, and independent of place, age, or gender. With the statement, "In this region, enough is already happening in the fight against climate change," 152 respondents (69%) disagreed, 29 people (13%) were unsure, and 42 respondents (19%) said that their region responds sufficiently toward climate change. These answers point to a general willingness to do more against climate change in their region. Nevertheless, explicit measures might still cause resistance and reveal NIMBY mentalities.

In the next step, a yes/no question was asked: "Do people know ways to extract greenhouse gases like CO_2 out of the atmosphere?" However, 122 of the 222 participants (55%) responded negatively for this aspect. If the participants responded positively, two consecutive open questions followed: First, respondents were asked to give at least one example, and second, respondents were asked to express concerns about this example (see Figure 8). In total, 100 respondents (45%) shared ideas on how this might be done. Therefore, 24 people mentioned activities to reduce emissions but not to remove emissions, such as driving electric cars. The remaining 76 respondents mentioned methods of CO_2 extraction (99 times). Mostly, more nature-based solutions were mentioned (80 times) with a focus on planting trees (47 times). Less frequently, respondents mentioned the rewetting of peatlands (15 times) or CVEs (7 times). Apart from more nature-based solutions, 19 people mentioned technical solutions. Those participants who gave detailed answers were asked about their concerns. Only 7 had related concerns, of which 4 were connected to nature-based solutions and 3 regarded technical solutions. They viewed nature-based solutions as limited and time intensive, and technical solutions as difficult to apply and as potential safety risks. Twelve respondents did not stick to the topic and mentioned concerns against coal plants, fracking, or the production of batteries.

When asked about their contributions to their home ("Heimat"), two-thirds of the respondents viewed themselves as actively engaging in their home region, which is a comparatively high rate of respondents having an answer to the question (see for comparison Ratter and Weig, 2012). Most respondents were engaged in social activities such as caring for the elderly, and a quarter of the respondents voluntarily engaged in keeping their environment clean and unpolluted. Furthermore, 96 respondents organized themselves in clubs mostly regarding sports, allotment gardening, the church, or nature conservation. Half of our respondents agreed with the statement, "I want to be more engaged in decision-making processes," while the

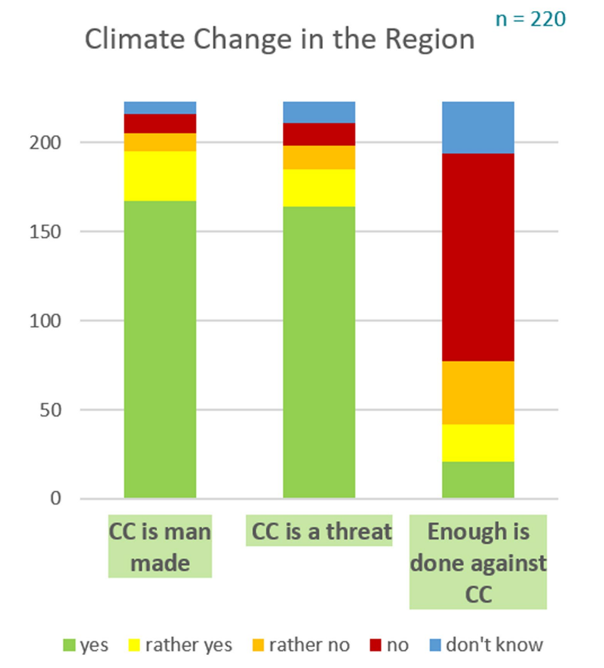

FIGURE 7
Statements on climate change in the region.

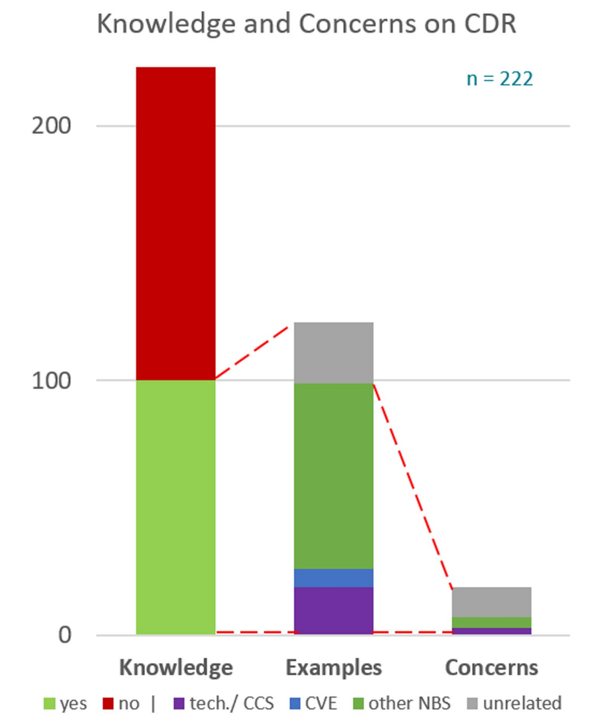

FIGURE 8
Knowledge and concerns on CDR measures (open answers on "Examples" could fit multiple categories).

other half disagreed. The same reactions appeared to the following statement, "I could contribute new ideas in such decision-making processes" (see Figure 9). "Being engaged" and "wanting to be more engaged in decision-making processes" show no significant correlations. Correlations show that the motivation for political engagement decreases with age. As age and having children correlate, parents also show less motivation to participate in decision-making processes. People from Lower Saxony are slightly more willing to engage than people in Schleswig-Holstein.

6 Discussion: blue carbon lack of knowledge along the German coasts

The survey confirmed the results of previous studies on place attachment among German coastal populations. Similar to our findings, related studies have concluded that German coastal residents have had a strong attachment to their coastal environment for decades (Döring and Ratter, 2018; Döring and Ratter, 2021). People feel emotionally attached to their home region and its cultural, socio-economic, and environmental specifics (Ratter and Gee, 2012; Döring and Ratter, 2021). While the installation of national parks along the German North Sea in the 1980s was perceived to be an intervention in the foundation of values on "Heimat" by many and accompanied by massive protests (Walsh, 2020; Döring and Ratter, 2021), the majority of the respondents in this study perceived nature conservation organizations as successful. This aspect supports the concepts of acceptance, values, and perceptions being dynamic (Pelling et al., 2008; O'Brien, 2009; Hansson et al., 2022).

Many respondents were aware of climate change and considered it a threat to their home region. A comparable study conducted 10 years ago revealed similar findings: 33% of the German North Sea Coast population was afraid of storm surges and climate change, with 10% mentioning clear-cut terms like "climate change" or sea level rise (Ratter and Gee, 2012). A comparison indicates persistence in the perception of the threat of flooding and increasing fear of climate change. Our study thereby confirmed the links between knowledge, perception, and action, as most respondents wanted an increase in action against climate change. The respondents were familiar with CO_2 reductions and respective avoidance strategies. However, they were less aware of CDR options. Apart from afforestation, Western populations are not adequately informed about CDR activities, or even about ongoing pilot projects (Carlisle et al., 2020), and German coastal residents are no exception. CVEs are known and valued for enriching biodiversity and coastal protection. Regarding salt marshes, recreational activities and high levels of local, tacit knowledge already seem widespread among German coastal residents. As deeper coastal waters are less accessible, local knowledge of and experiences with seagrass and macroalgae are less intense. CVEs were linked with coastal protection but not with climate action.

On a broad level, interventions in CVEs could gain high levels of acceptance and resistance, depending on the framing and motif for action. In a UK setting, Westlake et al. (2023) detected perception spillover from fracking, which could lead to negative attitudes toward geothermal energy. Our study revealed similar issues, as two participants transferred their concerns against fracking to CDR measures. Nature conservation is a familiar and appreciated motivation; however, interferences with nature due to CDR are unknown. Due to a lack of knowledge, no consolidated public opinions on blue carbon, let alone local blue carbon actions, could be identified, which blurs societal acceptance of blue carbon strategies. The participants in this study showed a willingness to personally

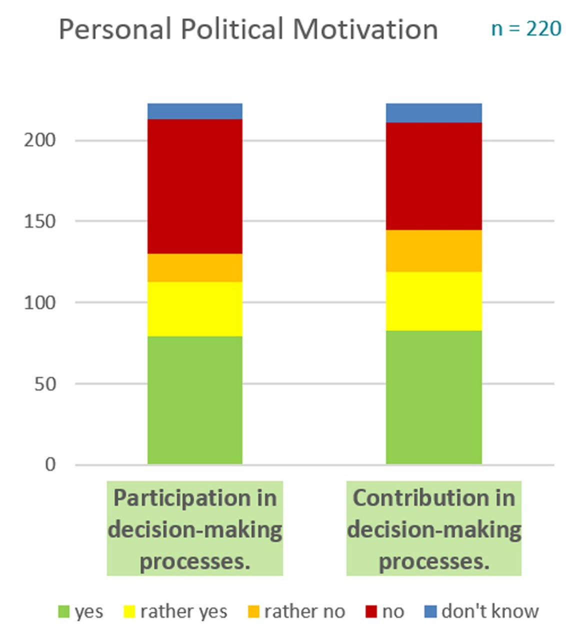

FIGURE 9
Political participation.

engage in shaping their regions, and a comparable survey on perception along the German North Sea coast confirms this result, stating that "70% of the respondents wanted more participation in decision-making processes, in particular where land use, nature conservation and coastal defense are concerned" (Ratter and Gee, 2012: 134). A higher level of publicity on blue carbon strategies and opportunities for participation would be needed to familiarize people with the blue carbon perspective on interventions in CVEs for serving climate action by storing CO_2.

The results of this study may be subject to several limitations. Descriptive statistics alone can only recognize correlations but not causalities. While the sample size allows for statements about respondents from larger regions such as the Baltic Sea compared to the North Sea or Lower Saxony compared to Schleswig-Holstein, statements on a city and district level lack appropriate sample sizes. Surveys were conducted only during the daytime, and it remains unclear to what extent the sample reflects the population concerned. Discussions on nature and perceptions of tourism might also be influenced by seasonality.

7 Combining knowledge, acceptance, and blue carbon toward climate action

Our study highlights the meaning of in-depth knowledge for societal acceptance of blue carbon climate action. As coastal ecosystems are known and valued for several socio-ecological benefits, nature conservation interventions to preserve these ecosystems and their known functions are likely to be highly accepted. Furthermore, people are sensitive to climate change as a threat and accept climate action. However, if people are only familiar with mitigation and adaptation concepts and measures but not with CDR, the latter remains vague and alien. As long as people lack knowledge of CDR, opinions and attitudes on CDR options cannot solidify and may alter, which blurs societal acceptance. Transient knowledge and fugitive acceptance are not a solid base for CDR interventions, which are designed to last for centuries. However, as demonstrated before, knowledge and acceptance are not fixed entities: they are dynamic and can be developed and changed by social learning (Pelling et al., 2008; Berkhout, 2012). How far dissemination of information on CDR and blue carbon will lead to knowledge-based acceptance of interventions, or non-acceptance, or will lead to initial controversies and later normalize to acceptance (Hansson et al., 2022) still remain to be seen. Nevertheless, the spread and growth of knowledge is a prerequisite for and often leads to societal acceptance, but the design and execution of interventions remain crucially decisive (Corner et al., 2012; Mauser et al., 2013).

There is a lack of information on the potential of CDR in general and blue carbon in particular. To counter this, it is necessary not only to provide information but also to transform information into knowledge and routines. Tacit knowledge is constructed through the active involvement of citizens. Experience and identification are links for new knowledge and an increase in acceptance. To generate knowledge on blue carbon, at least two links can serve as entry points to connect formal and local knowledge. First, since nature, nature conservation, and active engagement in these fields are already commonly valued, and CVEs services—such as being beneficial to biodiversity, spawning of fish, water quality, and coastal protection—are popular, blue carbon strategies most likely gain acceptance if framed and communicated as a part of nature conservation and not in opposition to nature conservation. Second, if climate change and, relatedly, flooding are perceived as serious threats, putting the home region at risk, and healthy coastal ecosystems are already acknowledged as stepping stones in climate change adaptation—protecting the coastline from sea level rise, erosion, and flooding—information on blue carbon interventions can connect to these threats and values.

The lack of knowledge this study identified could be an entry point for negative framings hindering acceptance, such as perception spillover from fracking (Westlake et al., 2023) or SRM (Kiehl, 2006; Schellnhuber, 2011). To keep CDR as an option open in order to stay within the range to limit global temperature increases as set by the Paris Agreement, the discourse on the design and contexts of climate change, negative emissions, and climate action as a conducive environment to introduce blue carbon projects is crucial and needs intense dialogue and participation in decision-making processes. Trustful and transparent dialogue, in combination with participation in practice, leads to experience and a co-creation of knowledge, combining local and scientific knowledge and, hence, producing climate action knowledge (Kothari and Wathen, 2017; Lauer, 2017; Fink et al., 2021). High levels of transparency, access to and participation in decision-making processes, and government accountability lead to increased knowledge and acceptance of ecosystem co-design interventions (Zimmer et al., 2022). Earlier studies on societal acceptance of renewable energy projects have shown that societal interests and objectives are changeable and that trust, accountability, and the feeling of being taken seriously are crucial for the acceptance and engagement of the local and regional population (Segreto et al., 2020), especially if potential (blue carbon) implementers are perceived as outsiders. This approach is more difficult in deeper waters beyond the concrete *Lebenswelt* of local residents, where taking part in blue carbon activities to gain action knowledge is restricted. However, earnest activities on macroalgae and seagrasses can still reach high levels of trust and acceptance if the concepts of co-creation of knowledge and co-design in planning, implementation, and continuation are followed (Mauser et al., 2013; Segreto et al., 2020; Zimmer et al., 2022).

Finally, while many studies foresee public protest against certain CDR technologies (Oschlies and Klepper, 2017; Merk et al., 2023), based on initially increased knowledge (Merk et al., 2019), building up in-depth public knowledge is essential for CDR to gain acceptance and become efficacious. Emerging suspicion based on a lack of knowledge and communication jeopardizes entire projects. Instead, addressing discomfort can catalyze the processes of dealing with difficult experiences in ways that promote learning (Freeth and Caniglia, 2020). Resistance and initial rejections might be part of a process of familiarization and normalization (Hansson et al., 2022). This process can only be initiated by transparency, trust, and open discussions about diverging and common interests, trade-offs, and synergies. Local people's knowledge and acceptance are key to sustainable success in the long-term storage of blue carbon in particularly vulnerable coastal ecosystems.

Data availability statement

The data supporting the results of this study contain information that could compromise the privacy of the research participants. Further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

MF: Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, review & editing. BR: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

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Conflict of interest

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

Publisher's note

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Public engagement and collaboration for carbon dioxide removal: lessons from a project in the Dominican Republic

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Despite an increase in literature on public perceptions of carbon dioxide removal (CDR), there remains a paucity of evidence describing the social and developmental processes involved in the implementation of projects *in-situ*. This research illustrates a case study documenting a planned research project for coastal enhanced weathering—a form of ocean alkalinity enhancement—in a remote, rural area of the Northwestern Dominican Republic, a Small Island Developing State particularly at risk from climate change impacts. This paper is a collaboration between the company responsible for the project (Vesta) and researchers located in the Dominican Republic and the United Kingdom, We draw upon 2 years' worth of surveys, interviews, focus groups, group information sessions, and reflexive documentation by the Dominican Republic researchers, to present a first-hand account of local community responses to the planned research project and to coastal enhanced weathering and climate change more broadly. We discuss themes of climate vulnerability, justice, and adaptive capacity through the lens of the collaborative governance and social diffusion principles that the project was designed with. We also reflect on a program of outreach and participatory activities which was established to support community development in the areas surrounding the field trial site, as informed by exploration of community needs drawn from the research.

KEYWORDS

climate justice, coastal enhanced weathering, environmental justice, negative emissions technologies, ocean-based techniques, responsible innovation, Small Island Developing States (SIDS)

Introduction

Anthropogenic climate change is causing unprecedented alterations to the Earth's climate and is posing a significant threat to ecosystems and human communities worldwide. Numerous studies indicate a >50% chance that global temperatures will reach or surpass 1.5°C between 2021 and 2040, with most scenarios highlighting the need for

Carbon Dioxide Removal (CDR) strategies in addition to emissions reductions (IPCC, 2022, 2023). The results of the Peoples' Climate Vote (United Nations Development Programme, 2021), the world's biggest ever survey of public opinion on climate change, illustrate that urgent climate action has broad support amongst people around the globe, across nationalities, age, gender, and education level, with the most popular policies being conserving forests and land, though little light was shone on the global opinions of proposals for CDR.

Public perception is a critical consideration in the implementation of CDR technologies (Cox et al., 2020; Shrum et al., 2020). However, knowledge and awareness remains low in many countries, and the literature displays a significant lack of evidence from the Global South and a general deficiency of context-specific and site-specific data, especially concerning novel CDR techniques (Smith et al., 2023). Public perception of carbon removal is highly influenced by framing, which means that attention must be paid to the communication strategies used, both in research and implementation. Important frames identified in the literature include the analogies and metaphors used to communicate the technologies, the nature-technology divide in valuing CDR, overestimations of potential emissions-reduction, and communication gaps regarding the social aspects of CDR (Bellamy and Raimi, 2023).

Maher and Symons (2022) provide further context on the global political landscape for CDR, emphasizing the need for governance and accountability mechanisms that respond to social and environmental justice impacts and social appraisal concerns. CDR researchers are increasingly recognizing the significance of environmental and climate justice (Schlosberg and Collins, 2014; Pozo et al., 2020; Batres et al., 2021), yet empirical research on the social and ethical aspects of deploying CDR in the Global South remains scarce (Waller et al., 2023). Inequities embedded in climate change risk highlight the unfairness that those who contribute the least to greenhouse gas emissions often bear the brunt of its consequences. Authors note the "double inequality" where communities contributing least to climate change also have the lowest capacity to resist and recover (Barrett, 2013). Recently, authors have suggested that this is actually a triple injustice, because of injustices and inequities brought about by maladaptive climate mitigation programs (Lehmann and Tittor, 2023). For example, the CDR literature notes the inequities created by bioenergy and afforestation projects, which in the worst cases have resulted in land grabs (Gough et al., 2018; Sovacool et al., 2022); thus there is a real risk that attempts to mitigate the double inequality via CDR projects in climate-vulnerable areas could end up exacerbating the issues they seek to solve. Consequently, justice considerations are crucial in addressing climate change causes and impacts, including the development of innovative technologies and interventions (Batres et al., 2021).

One of the major gaps in our knowledge is how to effectively work with local communities in the implementation of CDR approaches. CDR strategies could have social and economic impacts on local communities; as such, it is critically important to engage and involve local communities in the decision-making process to ensure that their perspectives and concerns are addressed. Effective engagement requires a comprehensive understanding of the social, cultural, and economic contexts of local communities, including their existing practices and habitat use patterns. CDR techniques such as ocean alkalinity enhancement (OAE) involve changes to coastal environments and potentially marine habitats, and therefore it is important to examine interlinkages between these contexts and environmental interactions. Furthermore, it is important to recognize that power imbalances may exist between different stakeholders, and to develop mechanisms for meaningful participation (Stringer et al., 2006; Reed et al., 2009). Likewise, it is important to develop context-specific approaches that consider the unique challenges faced by, for example, Small Island Developing States (SIDS) and build capacity for effective and equitable decision-making processes (Jaschke and Biermann, 2022).

In this respect, collaborative governance may aid in the implementation and growth of effective CDR technologies, by involving the participation of stakeholders and local communities in decision-making processes (Scobie, 2016; Lezaun et al., 2021). However, collaborative governance is often more challenging in the Global South (Scobie, 2018), where governments may lack capacity, civil society organizations may be marginalized, and local communities may have limited resources and opportunities to participate in decision-making processes (Banerjee, 2003; Jaschke and Biermann, 2022). The climate crisis is a crisis of justice as much as it is a crisis related to the biogeochemical environment, and as such, calls for a reframing of climate, and broader environmental justice debates (Sultana, 2021). As a form of environmental justice, climate justice has three components: equitably distributed environmental risk, recognition for people's diverse needs and experiences, and participation in the political processes that create and manage environmental policy (Schlosberg, 2007). Accordingly, distributive justice is concerned with who bears the costs and who enjoys the benefits ("who gets what?"). Procedural justice is concerned with the fairness of processes through which decisions get made ("who gets heard, and how?"). Finally, recognition justice is concerned with the extent to which actors are granted status and legitimacy to take part ("who counts?"; See and Wilmsen, 2022; Sovacool et al., 2022). Localized and collaborative governance aligns with procedural justice, with the intentional inclusion of all stakeholders in decision-making processes (Sovacool and Dworkin, 2015).

Sociotechnical considerations for ocean alkalinity enhancement

This paper documents a community engagement process and the local attitudes toward a planned coastal enhanced weathering (CEW) research project in the Dominican Republic (DR). CEW is a form of ocean alkalinity enhancement (OAE), whereby silicate minerals such as olivine are added to coastal zones to enhance ocean alkalinity (Hartmann et al., 2013). Grinding the minerals into small grain sizes increases their reactive surface area to volume ratio, sequestering atmospheric CO_2 through the generation of alkalinity, with the additional benefit of counteracting local ocean acidification (Meysman and Montserrat, 2017). The company responsible for the project, Vesta, is a Public Benefit Corporation[1] based in San Francisco and nationally registered in the DR, which first started researching CEW as a non-profit in 2019. Although ultimately Vesta did not place any olivine in the coastal environment in the DR (i.e., no field pilot was carried out, explained in more detail in the following section), the organization still engaged in scientific research and collaborations in the DR related to ecotoxicology, ecology, (bio)geochemistry, and social sciences.

While ocean-based CDR techniques propose to offer potential solutions to reducing greenhouse gas concentrations in the atmosphere, they also raise significant social, ethical, and governance challenges (Cox et al., 2021; Bellamy et al., 2022). Currently, our ability to anticipate societal outcomes is constrained by limited understanding of the impacts of OAE on marine ecosystems, as well as challenges establishing monitoring, reporting, and verification (Nawaz et al., 2023a). Cooley et al. (2023) outline the public concerns that would need to be addressed if OAE and other ocean-based CDR approaches were to be deployed at scale, and argue that factors affecting public acceptance include attitudes toward risk in general, beliefs about the ocean, perceptions of OAE techniques as "natural," and trust in the people and institutions managing OAE. Cox et al. (2021) use insights from analogous techniques to argue that ocean-based CDR may encounter heightened risk perceptions amongst members of the public, due to heightened affective responses alongside perceptions of the ocean as an open, interconnected system. Nawaz et al. (2023b) examined public attitudes toward four ocean-based CDR techniques, finding that perceived severity and urgency of climate change predicts greater comfort with all four, while views of marine environments as adaptable, fragile, and manageable vary in predicting both greater and lesser comfort. Their paper also highlights the limitations of generalized survey research and proposes more locally contextualized research, since different projects will have different formulations, associated practices, and life cycles. Finally, Hilser et al. (2023) advocate for the integration of actors from the Global South in CDR innovation, emphasizing that such inclusion would enhance ethical and governance aspects, and suggest that participatory, deliberative, and localized governance approaches in Small Island Developing States (SIDS) can inform strategies for ethical CDR solutions aligned with climate justice principles.

The objectives of the CEW research project as a whole were to identify the prospects and barriers for collaboration, as initiatives shift from ideation to the development of laboratory and field approaches for future pilots of highly novel CDR techniques "on the ground." The importance of participating in inter-organizational knowledge exchange networks that facilitate cross-disciplinary learning is underscored through collaboration in the establishment of adaptive capacities within communities that rely on natural resources. This paper presents the outcomes from a series of public engagement events and activities which were carried out in advance of the planned CEW research project.

1 A Public Benefit Corporation is a for-profit corporate entity which pursues positive impacts to society, workers, the community, and the environment, as part of its legally defined goals.

Dominican Republic—Climate change action in a Small Island Developing State

Since the first Global Conference on Sustainable Development of Small Island Developing States (SIDS) adopted the Barbados Programme of Action (United Nations, 1994), SIDS now comprise 52 small countries and territories in the tropics and low-latitude sub-tropics. While there is much diversity in SIDS' physical and human geographies, the United Nations (2005) describes how all display some level of similarity in terms of sustainable development. SIDS are particularly susceptible to the detrimental effects of climate change, such as sea level rise, hurricanes, and altered rainfall patterns (Nurse et al., 2014). These climate characteristics, combined with the socioeconomic circumstances of SIDS, make them among the most vulnerable nations in the world to climate change (Scandurra et al., 2018). Unfortunately, due to their geographical locations, SIDS will likely continue to experience environmental insecurity as they are at the forefront of climate change effects caused primarily by industrialized countries. Even though SIDS typically contribute <1% of total emissions, they are disproportionately affected by climate change (Kelman and West, 2009). The Caribbean region, comprising 23 SIDS, suffers from a marked asymmetry between contribution to global GHG emissions and climate vulnerability (Bárcena et al., 2020). In 2021 it was hit by a record-breaking 30 tropical storms including six major hurricanes, with 50% of the population (about 100 million people) living within 1.5 km from the coast.

Despite being the most vulnerable in the climate crisis, SIDS have played an essential role in raising awareness about climate change. They have been crucial in urging global leaders to take action to address climate change and were among the first to call for placing climate change on the agenda of the UN Security Council (Mead, 2021). SIDS have been influential in advocating for a stronger response to climate change on a global scale, taking a leading role in highlighting the urgent need for action to protect the environment and those most vulnerable to its consequences. This illustrates how a prevalent focus on "vulnerability" of particular locations or communities can obscure the leadership role they often play in responding to climate threats (Robinson and Wren, 2020; See and Wilmsen, 2022).

The Dominican Republic (DR) is a developing country in the Caribbean, classified as upper-middle income. It is ranked as one of the 10 most vulnerable and exposed areas in the world in relation to climate change effects, particularly extreme temperatures, changes in precipitation patterns, ocean acidification, projected sea level rise, and increases in tropical storm activity (USAID, 2013). The DR has one of the fastest-growing economies in the Latin America and the Caribbean region, and is an active player in the international climate regime. The DR's Nationally Determined Contribution (NDC) commits to a 25% reduction in greenhouse gas emissions by 2030 compared to 2010 levels (Gobierno de la República

Dominicana, 2020). The NDC also stipulates a commitment to a participatory and inclusive process, although specific details and mechanisms are not defined (WWF, 2020). The DR has been working on a Gender and Climate Change Action Plan (UICN, 2018) to enhance climate resilience and address gender inequity by empowering local representatives. Concurrently, its involvement in the Initiative for Climate Action Transparency fosters transparent and participatory climate governance through international collaborations and policy training. Such initiatives respond to global calls for greater transparency, citizen participation and localized, collaborative governance on climate action.

The DR was primarily selected for the CEW trial by Vesta for the following reasons: (1) It offered ideal environmental conditions for olivine dissolution due to year-round, warm seawater temperatures; (2) The sedimentological conditions were optimal for carbon removal, with beaches consisting of silicate-dominant sand comprised of relatively small grain sizes; (3) Olivine is a natural component of numerous regional rock formations in the region, such as the peridotites and gabbros of the Puerto Plata Basement Complex (Huerta et al., 2012); (4) The potential site had conditions favorable to the scientific study of olivine dissolution, consisting of two nearly identical bays experiencing the same oceanographic conditions, with calm waters, favorable for measuring changes in sediment transport and seawater chemistry.

In addition, however, the research project provided a unique opportunity to explore the social and ethical issues surrounding CEW in SIDS, including interrogating whether and how research can support local adaptation through inclusive methods of implementation (Morrow et al., 2020; Lezaun et al., 2021). For any actual olivine field deployment, CEW requires ongoing monitoring as olivine minerals continue to dissolve over time, which, in turn, necessitates a robust program with local, regional, and national communities to ensure ecological safety and efficacy of the project. The history of climate interventions in the Global South clearly identifies issues with capacity-building, including a serious need to learn from the mistakes of the past by implementing genuine co-production processes with local communities and stakeholders (Trisos et al., 2021; See and Wilmsen, 2022; Lehmann and Tittor, 2023). Such processes are especially important when there are still natural and social science knowledge gaps. In addition, documenting and providing a platform for the public to share their opinions on this novel CDR technique may assist in developing political mandates and action on much-needed CDR regulations. It may also help researchers and practitioners to understand the extent to which social and ethical concerns around CDR identified in the Global North, such as mitigation deterrence, are salient in the context of SIDS such as the DR (Markusson et al., 2018).

Methods

Working closely with members of Guzman Abajo and surrounding communities in the DR, Vesta's social science research rests upon two central pillars: (1) investigating awareness about climate change and CEW with olivine through social science research and (2) developing a comprehensive community outreach program together with the community. When conducting scientific research in a coastal SIDS community, the overriding imperative should be to avoid entrenching inequities and to challenge outmoded and unethical research paradigms (Mutua and Swadener, 2004; Healey et al., 2021). A cycle of inclusion, openness and receptivity should be maintained. Social research and engagement at Vesta in the DR were led by a local female leadership team made up of a community engagement manager, a community engagement coordinator, and a senior regional manager.

The research was initially planned to take place before and after Vesta's olivine placement in the area, thus adopting a quasi-experimental approach comparing pre- and post- datasets. However, due to local site conditions identified during the initial phase of the CEW research project, it transpired that the site was likely not conducive for efficient olivine dissolution and therefore not suitable for carbon removal. As such, the field trial was canceled before any olivine was placed, although Vesta continued to conduct ecological and biogeochemical laboratory studies in the region. The decision to discontinue the localized field research led to a modification of the social science research to a cross-sectional design, which involved collecting data from specific representative community groups affected by or influential to the CEW research in the area. Ethical approval for this project was supported by the University of Exeter's ethics committee, in accordance with the Economic and Social Research Council guidelines. Consent forms which outlined the ethics, safety, rights, and safeguards of agreeing to the research were read aloud then signed by all participants in Spanish. Monetary remuneration was not provided for participants to prevent potential biases, perceptions of unfairness, and undue influence, with alternative non-monetary incentives such as traditional hamper gifts and equipment for their community groups offered to ensure fair and voluntary participation. It is worth noting that one group that did not respond to inclusion in the research were cattle ranchers due to their reluctance to partake in the questionnaire because of bad past experiences with questionnaires and land issues in general.

Socio-demographic and attitudinal baseline surveys

An initial baseline survey used semi-structured interview questionnaires with participants drawn from a non-probability sample of the local population identified through a chain referral method (Bryman, 2021).This involved selecting individuals as key informants referred to by local representatives and based upon criteria discussed with the community leaders (gatekeepers) representing the key target groups within the local community (Newing, 2010). Questionnaires were conducted in a remote rural area of the DR, Northwest of Puerto Plata, in the Guzman Abajo neighborhood. Participants ($N = 42$) were qualitatively interviewed whilst interviewers filled out paper and electronic questionnaires (see Supplementary material) to assess the socio-demographic and situational profiles of the local communities, and the current knowledge, attitudes, and behaviors toward the project and toward climate change. The common messages and narratives were captured through transcribed audio recordings and in daily field notes accompanying the open-ended questions of the interviews, which were used to complement stripe coding

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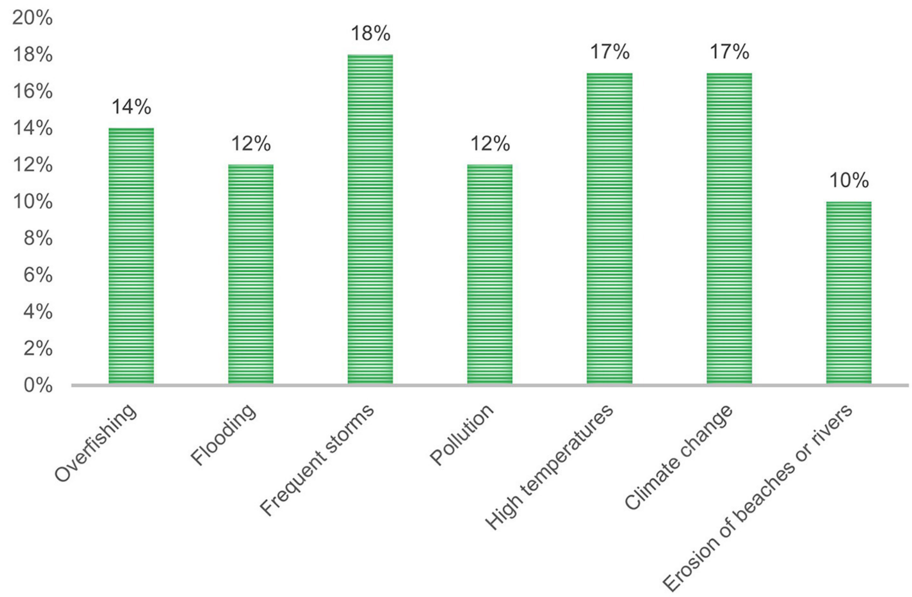

FIGURE 1
Percentage of survey respondents (n = 42) who reported "worrying" or "very worrying" levels of concern for environmental impacts that affect their quality of life.

using NVivo software (V12) to identify trends and patterns from the dialogue.

Community working groups

Local community members affected by and influential to the project must be listened to, understood, and involved in decision-making processes through regular and structured outreach and engagement activities (Jacobson et al., 2015). An initial stakeholder mapping exercise identified appropriate groups to engage and their respective relationship to the project. The deliberative and inclusive process involved grouping stakeholders in terms of specific dimensions related to the management and engagement with local resources (for example, influence, power, and importance), through open discussion and collective, formal ranking exercises (Govan et al., 2013). The identified groups consisted of a women's collective, fisherman's group, beach guardians (stewards from Chiquita and Los Cocos beaches), local government representatives (Municipal District), educational and religious leaders, a handicraft group, a cattle rancher group, and the neighborhood council.

After the initial baseline surveys were conducted, the second research phase involved focus groups involving these key groups, facilitated by Vesta staff and community members. Six focus group sessions were held in the DR throughout 2021 and 2022. The groups involved discussions with between 10 and 12 individuals about the project's development, encouraged feedback on any insights or queries from the broader cross-sections of the communities, and included topics about climate change, socio-cultural significance of the coastal habitat, perceptions of (and engagement with) the CEW project, and other themes which were requested by the community representatives. These meetings aimed to understand the communal processing of notions and social constructs to generate meaning (Morgan and Morgan, 1997), and are regarded as a powerful method to provide rich understandings of certain social issues and socially constructed discourses (Agar and MacDonald, 2008).

To address the unique concerns of all representatives of the local communities, the focus groups were established as working groups, encouraging members to review the information they were receiving, voice concerns, ask questions and make suggestions. Insights from the groups were communicated back to the management team to review recommendations and adapt approaches accordingly through a reflexive process. A continuous feedback loop was ensured by responses being reviewed by the project team and responses were again relayed to the working groups at follow up- sessions, where appropriate inviting input from stakeholder representatives relevant to the query or concern were raised. The project team thoroughly examined the responses and subsequently relayed them back to the working groups during follow-up sessions whilst actively seeking input from relevant stakeholder representatives. By adapting the communication approach and fostering direct interactions, the team established meaningful relationships and received valuable feedback, which significantly contributed to the overall development of the project and aligned with the principles of collaborative governance of the technology as it developed via the CEW research.

Qualitative interviews

Immediately following each focus group session, qualitative interviews were held with a chain referral sample of representatives from each of the local targeted community groups (N =

10). These interviews aimed to understand the stories and personal perspectives that underpin the responses to the baseline questionnaires and focus groups. The interviews were almost exclusively participant-led and included only a few guiding questions. Thematic focus guided discussions, providing a framework while participants had significant control in shaping the discourse within those boundaries. Specifically, the role of the interviewer is acknowledged as influential in initially shaping the interview dynamics by guiding the general setting, introducing follow-up questions, and utilizing non-verbal gestures to facilitate a responsive and open dialogue with participants. Interviews continued until no new or significantly relevant data or patterns emerged, or the category became well-developed and validated (Strauss and Corbin, 1998). Ten community members from the stakeholder groups were interviewed to understand in more detail their respective backgrounds, context, ideas, perspectives, motivations, life stories and perceptions of the environment and climate change concepts. The qualitative interviews also served as an opportunity to understand the realities of climate change impacts already experienced within the community and their mandatory adaptations to them in order to sustain their livelihoods.

The research design and implementation were iteratively shaped through ongoing collaboration between researchers and community members. Survey questions were revised in consultation with local leaders and key informants, with particular focus on ensuring cultural relevance. Working groups were formed based on stakeholder input, actively involving community representatives in project decision-making. Focus group themes were determined collaboratively, aligning discussions with community priorities identified in baseline survey interviews.

Qualitative data from the information sessions, focus groups and qualitative interviews were collected using note taking during the sessions. This included systematically written, typed, filmed, recorded, and photographed material all taken with consent. This was analyzed alongside daily field notes taken by Vesta's DR researchers. Qualitative data was analyzed using NVivo (V12) to identify common themes. Daily notes were recorded and written down by hand, then written "up" and eventually "out" (Madden, 2010) and synchronized into NVivo, importing all notes directly into the system to be immediately available for exploration, with insight into relationships between the research themes and guiding concepts (Flick, 2009). Comparative analyses were performed through framework matrix coding queries, comparing coding at nodes for sub-groups, following Applied Thematic Analysis (ATA) processes, a type of inductive analysis of qualitative data (Guest et al., 2013). Notable benefits of ATA as a pragmatic approach are that it is well-suited to medium to large data sets, the interpretation is supported by the data and it can be used to study topics other than the individual experience (Guest et al., 2011).

Results

Socio-demographic and attitudinal baseline survey results

In the baseline survey, the median age range for responses was 46–55, with a 50:50 representation of male and female respondents ($N = 42$), and a wide range of main income sources from construction to education, with fishing representing the most common main income source ($N = 8$). All respondents stated that they had observed changes in climatic conditions over time. Direct resource users, such as farmers and fishermen, were more likely to report feeling the impacts of these changes on their livelihoods than non-direct resource users. Those with more supportive attitudes (pleased/very pleased) toward Vesta tended to be from older (72%) male (56%) participants, with higher-than-average education for the sample (high school or above; 61%).

Seventy-six percent of respondents had heard about climate change, and all participants expressed concerns about the potential future impacts of climate change. Climate change, frequent storms and high temperatures were the top three environmental impacts reported to affect respondents' quality of life (Figure 1). When asked to what extent they felt climate change threatens their personal health and safety, 19% replied it was threatening, and 40% very threatening—this proportion increased to 57% within the lowest income bracket. Seventy-one percent however, were unaware of the effect of greenhouse gases, ocean acidification, CEW, or principles of climate justice. The study found that people surveyed have the highest confidence in their friends, family, and community members when it comes to addressing climate change, while having the least confidence in government officials or private sector entities that come to the area (Figure 2). Television was the most common source of information about climate change, at 60% of responses, and only five respondents were aware of any government initiative for climate adaptation in the DR, citing tree planning, protection from Saharan dust storms and renewable energies. Interestingly, only one-third of survey respondents stated that they believe climate change to be caused by human activity, although 98% believe that atmospheric temperature has increased in the DR.

Among those who were aware of private sector initiatives for climate change adaptation, multiple references were made of the local Guzmancitos 48.3 MW wind power project, the largest of its kind in Central America, located in the Puerto Plata Province. This project is run by Poseidon Renewable Energies with ∼30 turbines provided by Vestas Wind Systems, which with the similar name to Vesta resulted in some confusion with the community. Following this, when asked about confidence levels for governance of CDR, over a third of responses (35%) were confident in foreign entities, while almost half (48%) expressed a lack of confidence in government initiatives. Follow up questions inquired if the community benefited from the presence of foreign entities in the area: responses were not explicit in answering if they were beneficial and typically focused on job opportunities or the ongoing expectation of economic gain for the community due to the presence of the local wind power project (82%).

Less than a fifth (19%) of those surveyed knew about Vesta previously, with only three respondents having knowledge of the project's intentions, and when asked about their attitude toward the presence of Vesta in the area, respondents either replied as indifferent (57%), pleased (29%) or very pleased (14%), with no-one reporting displeasure. Only 14% of female respondents (from total $N = 21$) had knowledge of Vesta prior the survey, compared to 43% of male respondents (from total $N = 21$), who responded with varying levels of knowledge about Vesta's intentions, ranging from no knowledge through to an understanding of the project representing some form of

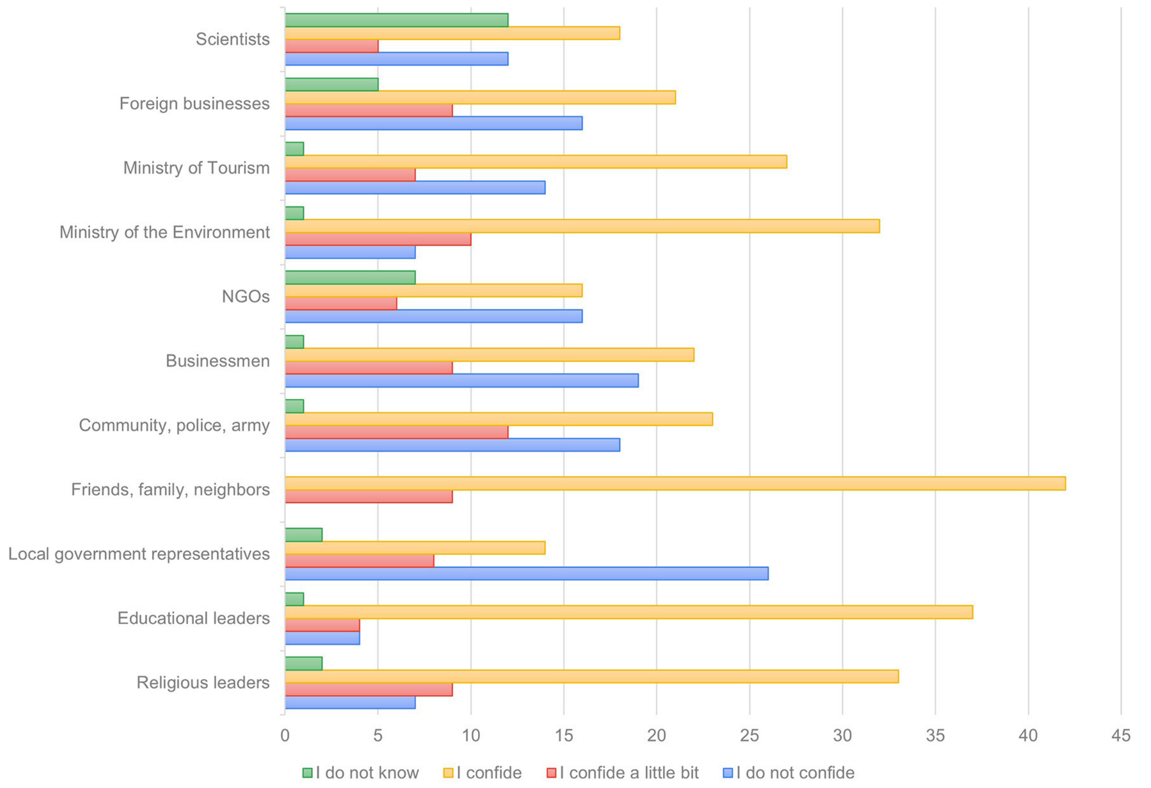

FIGURE 2
Respondents' levels of confidence in various key stakeholders relevant to collaborative governance of carbon dioxide removal in Dominican Republic.

environmental initiative. Male respondents were generally more pleased about the presence of Vesta in the area (48% pleased or very pleased), whereas female respondents were more likely to be indifferent (63%). Specific concerns raised by participants included the presence of scientists and film crews, and the taking of sediment, seagrass, and marine life samples. In general, participants were interested in the project and wanted to know more, with 95% opting to continue receiving information on a weekly basis.

Focus group and qualitative interview results

The following section presents pooled findings from the six focus group sessions and 10 qualitative interviews. Thematic areas were extracted from the transcripts and the accompanying daily consolidated notes and coded accordingly across seven main themes (Table 1), which were then utilized as a node structure for the coding of all transcripts and daily consolidated notes.

Socio-demographic-cultural and structural

Many community members said that they have been unable to sustain themselves by pastoral or horticultural agriculture practices, as is traditional in the area. The research revealed a decline or diversification in livelihoods, with participants reporting that 10 years ago there were 15–20 fishermen in Guzman Abajo and now there are only 6–7 regular fishermen. The fishermen and other members of community groups interviewed reported declines in fish and in biodiversity in general. Socio-demographic considerations of income levels, occupation types, and access to resources appeared to influence the community members' views and openness for participation in the project. Those with lower incomes may see the project as a potential economic opportunity, offering employment or economic growth in the community, while individuals in climate-sensitive sectors, like agriculture or fishing, seem to view the project as a means to address challenges brought about by changing climate conditions. Access to resources, such as land or water, may also influence views, as those with limited access might perceive the project as a way to mitigate vulnerabilities. Cultural factors, including community relationships with the environment and historical practices, could shape openness to the project, with traditions influencing attitudes toward environmental initiatives. Historical experiences, particularly with prior sustainable projects, may impact receptiveness, with positive past experiences fostering support and negative experiences leading to skepticism or resistance. Furthermore, we observed that variations in educational backgrounds influenced the level of comprehension among community members regarding the ecological and climate implications of the initiatives. It is important to note that effective communication strategies play a crucial role in fostering mutual understanding between project stakeholders, and that any lack of understanding may be attributed to both the participants and the project's communication approach.

TABLE 1 Thematic areas emergent from applied thematic analysis of qualitative trends within focus group and qualitative interview results.

Order	Name of theme	Details
1	Socio-demographic-cultural and structural	Age, gender, social norms, cultural influence, and perceived behavioral control
2	Climate change perception, impacts and sources of influence	Understanding and perceptions of climate change and presumed impacts, divine/anthropogenic sources of influence
3	Vulnerability and adaptive capacity, and intended personal legacy	Sense of being exposed to impacts of climate change and ability to adapt at local/global levels
4	Responsibility for environment and community	Sense of their role as contributing to the climate crisis and ways to remediate
5	Trust and expectations in the project	Including the project legacy, stated needs and aspirations of community
6	Knowledge, attitudes, beliefs	Toward climate change, and understanding of Vesta's aims and main activities
7	Governance and inclusion	Participative governance, steering committee, regulations, inclusion within the process

Gender dynamics may have played a role in the public perceptions shared within the sessions, with women having distinct viewpoints possibly due to their often more direct engagement with community activities such as the handicrafts and women's community groups. Consistent with the survey results reported above, women were less familiar with Vesta beforehand. It was shared, and observed directly, that men in the community generally exhibited more positive attitudes toward Vesta's presence, while younger women tended more toward indifference. Overcoming cultural biases, particularly toward the women on the project's community engagement team from outside the community, was seen by participants as a mutually rewarding experience that fostered trust. Notably, the empowerment felt by women in the community was evident through an upcycling textile workshop co-created with Vesta's support, identified by the community as an appropriate means of pursuing sustainable livelihoods, addressing the impact of climate change on traditional income sources. Focus groups also discussed structural factors, including existing social hierarchies and decision-making processes, dissecting who held authority in the community, which could impact the acceptance and implementation of CEW in the area. Conversations revealed how power dynamics and influence among different groups within the community could significantly shape perceptions. The identification of key community stakeholders though these discussions, including local government representatives, community leaders, and influential groups, helped to provide further insights into the potential drivers or barriers influencing openness to embracing innovative environmental initiatives, as shared in this paper.

Climate change perception

All focus group and interview respondents said that they noticed changes in weather and ecosystem conditions, many of whom were gravely concerned about the impacts of such: "*Everything has changed. There are no fish anymore. I ask myself if the end of the world is near*" Sandy Vasquez, member of the Beach Guardian group. Direct resource users felt that these changes directly affected their work and all shared apprehensions about the worsening effects of climate change in the future: "*Climate change and increasing heat has caused more Sargasso [a type of brown, floating algae] than before. Biodiversity has also been damaged drastically and there is noticeably less coral cover in the last 10 years along the coastline*," Raul Vasquez, member of the fisherman's group.

Eight out of the 10 interviewees expressed belief in anthropogenic climate change. that said, some interviewees also expressed belief in natural or divine forces causing such impacts:

> "*I think that we must be ok with what is happening. These are God's things. We must be ok with what God does. This is what we tell ourselves every day. If it is not raining, we must be ok with it because God knows. These are the words we tell each other*" Diogenes Holguín, Community Leader, and appointed Mayor of Guzmán Abajo.

Specific localized effects were also made apparent: "*Yes, a lot of it is man-made. Look at that project as I told you [referring to the turbines]. What a mess those people have made. That also contributes to climate change. Man has a lot of influence on climate change even if you don't believe it*" Luis Humberto Vasquez, Neighborhood Council vice president. Indeed, experiences with prior sustainable projects influenced receptiveness to community development initiatives, particularly the negative reactions to the Guzmancito wind power project.

Vulnerability and adaptive capacity

Vulnerability aspects identified included geographical location (e.g., coastal areas prone to sea-level rise and storms), economic dependence on climate-sensitive sectors (e.g., agriculture, fisheries), limited access to resources, and inadequate infrastructure. Those who are more vulnerable may see CDR as a potential avenue to address these challenges. A majority of the community members interviewed in Guzman Abajo have had to look for alternative sources of income due to climate change.

> "*I am worried because everything is disappearing in the ocean. Before you could eat fish daily but now you can't, it's very difficult*" Erizelda Vásquez, Leader of the Women's Group.

Only two respondents have been able to subsist with their original source of income—one young fisherman and an elderly man receiving tourism revenue at the beach. Most interviewees had to supplement their income from agriculture with other activities because of prolonged drought. *"Before there were many trees and there were a lot of hills, that's why I think that before it rained a lot. But not now- now they have deforested a lot… When the dry season comes, the farm crops and grass dies due to lack of water. This is very sad."* Sandy Vasquez, Beach Guardian group.

Most expressed that the community lacks the capacity or resources to deal with climate change effects, though there was an indication of faith in the resilience of the community regarding some of the impacts. Some have dug wells to access water because of the drought, but there remains insufficient water availability and funding for adequate infrastructure. One participant believed that the community has been able to deal with climate change effects and has become more resilient by working together and finding alternative sources of income as a community, for example a tourist stand catering to cruise ship tourists that go on safaris or carry out other tourism activities in the area. Another perceived climate change to be the long-term effect of industrialization, expressing that there is little choice but to adapt: "*We are living the effects of climate change and try to live and survive however we can*" Dulce Vásquez, Women's Group.

Dust was reported as a major issue in their community and largely attributed to the activities of the wind project. Participants felt that such projects should have more environmental responsibility to the local area:

> "*You know the trees and the hills that these people have destroyed! This is bad for the environment, because it is not going to rain, because if they are cutting down the few trees that exist, where is a cloud going to form and how is the rain going to fall? So that is harmful to the environment, very harmful*" Luis Humberto Vasquez, Neighborhood Council vice president.

Trust and expectations in the project

Many participants expressed distrust and lack of reliance on the government: "*Guzmán Abajo does not have a godfather and godmother, the government does not help us*," Member of fishermen's group. However, most respondents stated that they had no personal issues with the Vesta project being conducted in the area, and additionally perceived the other community members to be supportive and with little in the way of concerns, skepticism or objections about the project's impacts: "*I am happy because we are helping the world and doing things that we did not know about. We have not even started with the deployment of olivine and everything is going very well. God is in the sky and will help us*" Diogenes Holguín, Community Leader and appointed mayor of Guzmán Abajo. Diogenes changed his mind about climate change during the project through continuous focus groups and information sessions and is now convinced that it is anthropogenic.

Most respondents were keen to learn more about the science and any opportunities to be involved that may emerge. All asserted a desire to receive more information about climate change and to be able to explain the concepts to others in the community. They all stated their interest in becoming ambassadors for Vesta (a role including carrying an identity for the project and active participation at outreach events) and supported the idea to implement a climate change module into secondary school curriculums such as in Cambiaso, which was then carried out by the community engagement team as stated.

There were clearly expectations from those who participated in the research and who had been involved in the program, in terms of the benefits that the program has the potential to bring to the community, and possibly a sense in the progress emergent from the developmental support for the area: "*I thought that in 10 years the community would be worse, but now with all these projects that are coming I see how everything is progressing*" Erizelda Vasquez, Member of the Neighborhood Council and leader of the Women's Group.

Suggestions were made for the project team to distribute summary information sheets to raise awareness and access to information regarding the project and climate change after the suggestions were made during the focus group sessions and interviews. This was then carried out in the second information session for community members to refer to at any time in their households to help cement the abstract concepts about Vesta, climate change, CDR, CEW and olivine.

> "*Anything they need from us, we will support them. If they need men, by the time they put the olivine we will be there*" German, Neighborhood Council.

> "*We are happy that you are coming to the community and teaching us all these climate change concepts and about your project. It is important to us and without you we would not learn them because no one comes around to teach us or explain*" Diogenes Holguín, Community Leader, and appointed mayor of Guzmán Abajo.

Knowledge, attitudes, and beliefs

Similar to the survey, the majority expressed cautious support for the Vesta project, although some also voiced skepticism regarding the project's potential ability to assist them in establishing sustainable livelihoods. The women's group conveyed a desire for a community engagement program to assist with this. Two participants expressed discomfort at the lack of monetary remuneration.

Community perceptions of CDR initiatives were influenced by awareness of climate change and its mitigation, as well as by potential economic benefits through job creation and sustainable practices. Beliefs about the ocean and perceptions of naturalness in the techniques and those managing the technologies were discussed as important considerations. This was closely aligned with concerns about environmental impacts on water, biodiversity, and health, and considerations of cultural and ancestral ties. Apprehensions emerged concerning potential disruptions that might arise due to large-scale CDR undertakings, particularly among those heavily reliant on natural resources for sustenance (e.g., fishermen and farmers). While most expressed support or indifference to potential negative impacts from the project, the potential repercussions on water availability, biodiversity, and traditional land and coastal utilization emerged as sources of worry. Participants shared cultural values of environmental stewardship, concerns about the social and economic equity implications of environment and development projects, and a desire for inclusive and transparent decision-making processes that consider community needs and aspirations while ensuring effective mitigation of carbon emissions.

Overall however, a substantial portion of the research participants displayed a marked enthusiasm for climate impact mitigation endeavors. The project was also perceived by many participants as a potential economic prospect for the community, with the notion of engaging in government or foreign projects for sustainable marine management being viewed as a means to generate employment opportunities and invigorate local economies. Some expressed pride that unique research that could influence climate change on a global level was to take place on their local beaches. Many had read up on Vesta's operations via social media and had observed CDR initiatives on the television and internet, and there was general enthusiasm to learn more about the program:

> "*Of course, when someone like you shows up, we are very grateful because we learn and also have the desire to learn. People ask if you are coming and so when they find out… everyone goes! Because they go to learn about things they have never heard about. There are people here that want to learn. Everyone that came here today has a desire to learn and to listen to what you are saying*" Diogenes Holguín, Community Leader, and appointed mayor of Guzmán Abajo.

Collaborative governance and inclusion

Participants of the focus groups expressed enthusiasm in being involved in the governance of the CEW technique, and widespread openness for inclusion. The aim of the social science framework for action includes creating a platform where community members feel free and open to comment on Vesta's work, provide input into approaches and voice any concerns. The project team fed back recommendations and key info from the working groups to Vesta management to review research recommendations and adapt accordingly, in addition to the participation and training of local ambassadors. While acknowledging the potential bias in the correlation between those supporting training and those interested in project association, this approach received support and appreciation from prominent community leaders.

There was also some indication of the presence of the project fostering positive cohesion within the community:

> "*The lack of connection within the community members causes sadness. This is changing with your presence and the community feels more connected. Your communication with everyone is causing things to change*" Diogenes Holguín, Community Leader and appointed mayor of Guzmán Abajo.

While appreciation for the working groups was regularly expressed, establishing genuine inclusivity in decision-making across various layers of the governance structure, notably within the steering committee, presented considerable challenges, mainly due to logistical constraints, communication issues, and time availability. The dissemination of project objectives both on and off site was challenging due to the community's remote location, and the limited educational background of its members. A sustained commitment was required to foster transparent dialogue with community representatives and individuals who raised queries or apprehensions. Regular follow up from the Vesta team endeavored to prevent community members feeling marginalized, particularly during periods of dissent related to political affiliation and national elections which caused at times an unsettled atmosphere within the community, and instances of discomfort expressed at the lack of monetary remuneration. These instances of dissent highlighted the importance of not only recognizing the external factors influencing community dynamics but also the necessity of developing strategies to navigate these challenges. This underscores the project's commitment to a continuous improvement process, demonstrating the resilience and adaptability required for effective community engagement in diverse and dynamic settings. However, such efforts were complicated by disruptions due to the COVID-19 pandemic, cultural nuances such as punctuality, community bereavements and attendant rituals, and also the challenging climatic conditions and dusty environment in the region. Furthermore, the remote field setting meant a 4-h round trip to the site for field operations, constraining the regularity of site visits.

The participants relayed their desires for localized governance and inclusion in CDR initiatives in the DR. For them, this encompassed aspirations for the following: active involvement in decision-making processes; access to comprehensive project information; assurance of economic growth through job opportunities; environmental safeguards; equitable distribution of benefits; preservation of cultural values; empowerment in monitoring and evaluation; and educational programs. Addressing these desires became essential conditions for fostering trust, collaboration, and effective implementation of CDR initiatives in the region.

Discussion

This paper contributes to a body of research on public perceptions of CDR, which is thus far entirely lacking in perspectives from SIDS, despite their place at the forefront of both climate impacts and climate action. Our research responds to increasing calls to utilize place-based research to investigate local perspectives on OAE (Nawaz et al., 2023a) particularly in the Global South (Sovacool, 2023). Pouponneau (2023) highlights the marginalization of SIDS in academic literature, particularly regarding blue economy initiatives. SIDS are often treated as a homogeneous group without recognizing their diversity. Furthermore, the lack of representation and knowledge production by and with SIDS leads to their general invisibility in scholarly works. This reveals an ongoing inequity between countries with and without research capacity, echoing calls for more vigorous research within SIDS and a broader recognition of the diversity of SIDS perspectives (Benzaken et al., 2022). We argue that collaborative governance should be implemented across communities to support

OAE in the DR. This involves engaging with local stakeholders, including fisherfolk and community leaders, to design and implement OAE projects that meet both environmental and social goals. The goal is for the communities to be able to identify and address potential challenges and leverage points for participation, to ensure the project benefits are shared equitably (Morrow et al., 2020; Batres et al., 2021). While challenging and still in its infancy, this approach recognizes the importance of local knowledge and engagement in designing effective solutions that benefit both the environment and the people who depend on it (cf. Robinson and Wren, 2020; Waring et al., 2023).

According to Haas et al. (2023), a general lack of inclusion in ocean governance can be attributed to existing power structures and the exercise of power within forums aimed at promoting inclusion and cooperation. Indeed, the climate justice literature points out that governance dynamics in the Caribbean must be understood through the history of exploitation, resource extraction, and economic marginalization, which continues to impact climate responses (Smith and Rhiney, 2016). Avoiding consideration of the underlying political economy tends to obscure important questions about the social justice implications of inequality (Popke et al., 2016). There is a growing body of literature showing how adaptation and mitigation programs may actually exacerbate inequalities, because such programs are often deeply political and are subverted by the powerful, including powerful members of the community itself (Barrett, 2013; Andersen et al., 2016; See and Wilmsen, 2022). In this project, we attempted to embed principles of collaborative governance and participatory justice, as outlined in the preceding sections. Yet there are inherent limitations to the extent to which a single project can tackle or overcome embedded injustices and inequalities in access to power and resources. It is important to consider the structural context, a crucial fourth dimension of climate justice, in addition to procedural, distributional and recognition aspects (See and Wilmsen, 2022). Despite a participatory and collaborative approach on the ground, the project did not attempt to tackle such structural issues. Social systems also involve structures and processes which are shaped by privilege and uneven power relations, and these affect the way in which individuals can respond (Baptiste and Rhiney, 2016). In this study, powerful actors within the community emerged as a prominent voice in the community engagement and in our results section above—for example, Diogenes Holguín, the Mayor of Guzman Abajo. We attempted to mitigate this, for example by setting up a women's group and promoting transparency in communication and governance structures (cf. Waring et al., 2023); however, it is important to recognize that the collaborative governance approach of this project may have inadvertently acted to drown out other voices, including those which project staff were not even aware of, revealing a possible underlying tension between objectives of collaborative governance and climate justice (see also Riggs et al., 2021; Ng et al., 2023). Overall, the project going forward will need to recognize that one project cannot overcome centuries of power imbalance, and to be aware of our role in potentially perpetuating such imbalances.

By giving the community a means and a right to contest the project, we attempted to mitigate the triple injustice identified by Lehmann and Tittor (2023) using a collaborative governance approach. In addition, the triple injustice has a major distributional aspect, because communities often bear the impacts of climate mitigation projects whilst the profits accrue to foreign or multinational entities. Therefore, going forward there will be a need to reflect on the way in which any financial benefits (for instance, carbon credits) are distributed, and to embed principles of procedural and recognition justice in how such decisions are made. Although such distributional issues did not emerge as a strong theme in the analysis, community members did voice some anticipation that the project would create jobs in the local area, due to confusion with the wind farm project with a similar name, and therefore there is a risk that distributional misgivings could emerge if expectations are not met or managed (cf. Ng et al., 2023). In addition, two participants expressed discomfort at the lack of monetary remuneration for involvement in the project going forward; this decision made by Vesta could have created barriers to participation amongst those in need of an income for their time, although the reflexive handling of dissent played a crucial role in the project's overall responsiveness and adaptability to the dynamic nature of the community context.

Key findings from this study include an increasing concern about localized climate change effects, livelihood stability, and poverty cycle dynamics. Identified risks involve concerns over unintended ecological impacts, clashes with present land applications, uncertainties about the efficacy and economic feasibility of untested technologies, and implications for social fairness. Several of these are in line with broader concerns about CDR and weathering techniques which are highlighted by global experts (Sovacool et al., 2022), with specific local concerns relating to the disruption which is already occurring to traditional uses of land and sources of income. Yet participants in both the interviews and focus groups also generally showed strong support for the project's aims, and toward global responses to climate change, despite limited awareness of the anthropogenic origins of climate change and a prevailing belief in natural or divine causes.

Environmental education was highlighted as a key component to fostering widespread community support and participation in CEW development. Our results suggest that there is a need for awareness-raising campaigns and education initiatives to improve understanding and knowledge about climate change and its impacts, particularly in rural locations (Kabisch et al., 2017). Of course, this should not be undertaken with instrumental goals in mind: increased knowledge about climate change should be viewed as a fundamental good in its own right, contributing toward community empowerment, rather than as an attempt to make communities more favorable toward climate interventions. Our results also indicate the importance of building trust and collaboration with local communities and establishing strong partnerships to address climate change effectively, as well as transparency and participation in the governance of CDR technologies at multiple levels wherever feasible (Spalding et al., 2023). An essential aspect of this process involves second-order reflexivity, as highlighted by Schuurbiers (2011), whereby the underlying value systems and theories influencing CDR governance are subject to critical examination. It is crucial to define and tackle context-specific challenges related to CDR approaches, ensuring that responsibilities and burdens are distributed fairly, with a strong focus on community involvement in decision-making, as emphasized by Batres et al. (2021).

We found that participants most positive toward CDR were typically older, male, and high-income or high education, in common with studies from other parts of the world (e.g., Bellamy, 2022). However, all types of participants expressed a strong desire to support initiatives that may provide both local and global resilience in the face of climate change. This finding is supported by studies which have indicated how under worsening climate impacts, public attitudes increasingly favor climate action (Nawaz et al., 2023b; Nayna Schwerdtle et al., 2023), and that communities vulnerable to climate impacts may be more supportive of novel interventions such as CDR (Sugiyama et al., 2020). Intended personal legacies shared by community members involved in this study revealed their desires to leave a positive mark on their community and the environment for future generations. This could be driven by a commitment to uphold traditional values, a wish to be remembered as proactive environmental stewards, or a deep-seated sense of duty toward the wellbeing of their community; the intertwining of these notions of responsibility and legacy may plausibly influence community members' engagement, support, and perspectives on CDR initiatives. We identified high levels of trust in friends, family, and fellow community members, stemming from the belief that these individuals are deeply invested in the local environment and possess a genuine understanding of the unique challenges faced by their specific community. In contrast, government officials and private sector entities were viewed with skepticism and disillusionment due to past experiences, particularly the local onshore wind project, in a form of attitudinal "spillover" effect (Jaschke and Biermann, 2022; Westlake et al., 2023).

However, once it was understood that the CEW project bore no relation to the wind power developer, these misconceptions faded, with respondents also perceiving other community members to be broadly supportive. This may give an indication of trust in the visibility of the social engagement being carried out, although of course may also reflect a bias of the interview conditions, because the social position of participants may well have shaped their response. Some of the voices expressing considerable positivity about the project may have been due to their desire to be involved in the project going forward, or because they expected future personal or political benefits. Our study participants were largely self-selecting, due to the place-based nature of the study which involved a small, rural community. The limited sample size means that our capacity to make categorical comparisons and generalizations is restricted—in particular, the final in-depth interviews only included 10 respondents, and further research would greatly benefit from including more voices from different segments of the community. The participants' varying educational backgrounds and literacy levels were identified as factors influencing their understanding of climate implications, potentially contributing to decreased engagement among certain community members. It is crucial however, to recognize the significance of local knowledge and ensure that information exchange is a bidirectional process. In addition, fostering genuine inclusivity in decision-making within the steering committee proved challenging, due to logistical constraints, communication issues, and time availability. In future research, an ethnographic approach with ongoing field research on the ground could help to foster trust and improved deliberation (Zandlová and Cada, 2023), although this may be more challenging to resource. Finally, a major challenge was around the interplay of the social science research and the CEW field trial because the olivine placement was ultimately canceled for geophysical reasons. This necessitated a major shift away from a pre/post pseudo-experimental design to a cross-sectional one, illustrating the challenges which can occur with interdisciplinary research on novel techniques "on the ground." Although the eventual research design was not entirely congruent with what had originally been intended, the social science research contributed to an understanding of public perceptions of coastal CDR and novel climate interventions in a remote rural area of the DR.

While the focus of this paper centered on approaches to generate collaborative governance among different communities of stakeholders with an environmental justice lens, we acknowledge that addressing the legal implications of our work is important, particularly since statutes for OAE are still being developed. Please see the following papers for a deeper discussion on governance topics relevant to ocean-based CDR (GESAMP, 2019; Webb, 2020, 2021; Cox et al., 2021; Webb and Silverman-Roati, 2023). So far, the only ocean-based CDR approach that is specifically considered by legal instruments, such as the London Protocol, is ocean iron fertilization with coastal approaches such as CEW generally not being mentioned. Because of this, Vesta needed to assess how to best proceed according to existing local statutes in the DR, and thus engaged with local regulatory authorities that subsequently guided the entire process. As this project was the first of its kind, a bespoke permitting approach needed to be developed by the DR Ministry of Environment, working with a local law firm and climate consultant. During the baseline studies, Vesta hosted an 8-h workshop with the Ministry of Environment and Climate Change Council to introduce information regarding CEW, Carbon Credits frameworks, and Measuring, Reporting, and Verification (MRV) methods. The overall intention was to use the resultant framework, alongside the public engagement and collaborative governance approaches described above, as a foundation for subsequent field pilots. In addition, it could serve as a possible template for any projects by other organizations in the region, and to help inform the broader development of future governance for ocean-based CDR activities in the DR and elsewhere. Taken together, the OAE research and resulting legal and community governance frameworks undertaken by Vesta and local stakeholders serve a significant empirical step toward conducting OAE activities in local jurisdictions, as broader statutes continue to be developed to regulate ocean-based CDR.

Conclusion

The Caribbean faces significant risk from the impacts of climate change, and the Dominican Republic (DR) is one of the most vulnerable countries globally, despite contributing relatively little to global greenhouse gas emissions. Climate justice must be considered when implementing any climate intervention, including both the risks and potential benefits of carbon dioxide removal (CDR), and critically its governance. In this paper, we explore public perceptions and social acceptance of Coastal Enhanced Weathering projects, particularly focusing on the integration of local ownership, participation, and governance. Through a case study in a rural and remote area of the DR, we examine how these elements shape community perspectives. This research contributes to a body of research on public perceptions of CDR, which is thus far entirely lacking in perspectives from Small Island Developing States (SIDS), despite their place at the forefront of both climate impacts and climate action. Community perceptions of CDR initiatives were shaped by people's understanding of climate change and its mitigation, and by perceived economic advantages and employment opportunities in a community which is experiencing rapid changes to local subsistence practices and economies due to climate change. In addition, perceptions were shaped by concerns over environmental effects on water, biodiversity, and health, and the importance of cultural responsibilities to community and to the natural environment. We emphasize the inclusion of vulnerable and relatively uneducated groups in rural and coastal communities who are most vulnerable to climate change, ensuring they can be heard and developing trusting relationships while countering potential negative perception spillover from previous development programs in the area. We emphasize the importance of participatory approaches to societal appraisal and reflect on the potential challenges and opportunities in the establishment of CDR initiatives.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Vesta, with support in development from University of Exeter. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

HH: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. LH: Methodology, Writing – review & editing, Data curation, Investigation, Project administration. CM: Data curation, Investigation, Methodology, Project administration, Writing – review & editing, Conceptualization, Resources, Supervision. AD: Investigation, Methodology, Project administration, Writing – review & editing. EC: Methodology, Writing – review & editing, Supervision, Writing – original draft. MA: Funding acquisition, Resources, Supervision, Writing – review & editing. LW: Conceptualization, Writing – review & editing. NW: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

This research was funded by Vesta. Vesta staff were involved in all aspects of the research, including the conceptualisation and design of the research, writing, review and editing of the manuscript. CM, LH, AD, MA, and NW are employees of Vesta, an international Public Benefit Corporation researching the potential of enhanced weathering experiments in the Dominican Republic, where it is nationally registered as a Dominican Public Benefit Corporation. AD and LH are Dominican and CM currently resides in the Dominican Republic. HH and LW have been contracted to consult on the social science framework for Vesta representing environmental education consultancy Lestari LLP, UK.

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

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2024.1290999/full#supplementary-material

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Scaling carbon removal systems: deploying direct air capture amidst Canada's low-carbon transition

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Carbon dioxide removal (CDR) technologies, such as direct air carbon capture and storage (DACCS), will be critical in limiting the rise of the average global temperature over the next century. Scaling up DACCS technologies requires the support of a complex array of policies and infrastructure across multiple overlapping policy areas, such as climate, energy, technology innovation and resource management. While the literature on DACCS and other CDR technologies acknowledges the path-dependent nature of policy development, it has tended to focus on abstract policy prescriptions that are not rooted in the specific political, social and physical (infrastructural) context of the implementing state. To address this gap, this paper provides a country-level study of the emerging DACCS policy regime in Canada. Drawing on the existing literature that identifies idealized (acontextual) policy objectives that support DACCS development and effective regulation, we identify the actionable policy objectives across six issue domains: general climate mitigation strategies; energy and resource constraints; carbon storage and transport regulation and infrastructure; financing scale-up and supporting innovation; removal and capture technology availability and regulation; and addressing social acceptability and public interest. Using a database of Canadian climate policies (n = 457), we identify policies within the Canadian (federal and provincial) policy environment that map to the idealized policy objectives within each of these domains. This exercise allows us to analyze how key policy objectives for DACCS development are represented within the Canadian system, and enables us to identify potential niches, and landscape influences within the system, as well as gaps and potential barriers to the system transition process. This paper contributes to our understanding of national DACCS policy development by providing a framework for identifying components of the DAC system and linking those components to desired policy outcomes and may provide a basis for future cross-country comparisons of national-level DACCS policy.

KEYWORDS

carbon dioxide removal, direct air capture, negative emissions, climate policy, low-carbon transition, socio-technical system, multi-level perspective

1 Introduction

As countries prepare to meet their Paris Agreement commitments, there is an increasing recognition that carbon dioxide removal technologies will play a central role in limiting the rise of average global temperatures over the next century. Among these technologies, direct air carbon capture and storage (DACCS)[1] has the potential to make a significant contribution to state-level carbon management strategies. The scaling up of DACCS to meaningful levels will require states to develop a complex array of policies across multiple domains to support the infrastructural, technological, environmental and social demands of DACCS deployment. To date, much of the literature that seeks to examine these policy requirements has done so in an abstract manner, with less attention being paid to the existing policy frameworks with specific states. However, it is widely acknowledged that policies supportive of carbon dioxide removal (CDR) will be built on the foundations of existing policies and will be influenced by the structure and content of this policy landscape (Cox and Edwards, 2019; Creutzig et al., 2019; Fajardy et al., 2019; Schenuit et al., 2021; Craik et al., 2022). To address this deficit, this paper provides a country-level study – in this case Canada – that identifies and characterizes the existing policy foundations for developing and deploying DACCS. By mapping out the existing DACCS-relevant policy framework, we can identify policy gaps and better understand the potential trajectories or policy pathways that Canada can pursue in the context of its transition to net-zero emissions.

This study is underlain by several conditions that characterize the DACCS policy environment. Foremost, the policy environment is best understood as part of a complex, dynamic system. DACCS deployment relies on other large sub-systems, particularly non-emitting energy systems, but also large (gigatonne) scale storage, pipelines, and climate mitigation structures, such as carbon pricing (Minx et al., 2018; Erans et al., 2022). Since these systems interact and co-evolve with DACCS, DACCS development and deployment will be structured by policy decisions made in these domains and the relationships and barriers in current policies and infrastructure may enable or impede DACCS-related goals. The long lead times associated with DACCS deployment and related systems place pressure on existing policy frameworks since near-term decisions will have longer term, downstream implications. For example, decisions that Canada makes in the next 5 years regarding energy systems and geological storage may not foreground DACCS, but will nonetheless shape DACCS in the years and decades to come (O'Riordan, 2018; Craik et al., 2022). The embeddedness of DACCS extends to the social and political aspects of the system with implications on the acceptability of the technology, which may be influenced by perceptions of the distribution of future benefits and burdens from DACCS and associated sub-systems.

Since DACCS siting and scale-up are context-specific and have a high potential to be influenced by path dependencies within a system, it is important to conduct country-level case studies to assess the prospective technology development pathways, particularly as states begin to name negative emissions technologies (NETs) in their near and long-term climate mitigation policy plans (Schenuit et al., 2021; IEA, 2022). The existing physical infrastructure (pipeline networks, storage sites, energy, and DAC facilities) and policy infrastructure (regulations, carbon taxes, and other incentives and plans) will direct how states make policy and plans in light of path dependencies because they may impede the availability of alternative options and policy pathways in future decisions (Asayama, 2021).

Canada offers an informative case study for several reasons. Canada has one the highest *per capita* emissions rates globally and is already warming at twice the average global rate (Warren and Lulham, 2021; World Resources Institute, 2021). The Canadian government has set an ambitious mitigation target of reaching net-zero by 2050, and has established a robust policy framework, including an accelerating carbon price in support of this goal (Environment and Climate Change Canada, 2022). Canada, and certain Canadian provinces, have been active in the development and deployment of carbon capture and storage (CCS), and as such have advanced CCS regulatory and policy frameworks (Bankes, 2019). Canada also has a high potential for wealth loss associated with stranded fossil fuel assets over the course of the low carbon transition, which scaling up CCS infrastructure may help to reduce. According to a study by Marcucci et al. (2017), the higher marginal costs associated with producing oil and gas over the next few decades may eliminate the industry in countries like Canada and United States Canada not only needs to decarbonize for climate reasons, decarbonization is also an economic imperative. Finally, Canada has growing technological capacity to research and develop DAC technologies, which include innovation support and financial incentives to pursue DACCS, and has identified DACCS as an important element of future mitigation pathways (Canada Energy Regulator, 2023; Natural Resources Canada, 2023).

To address these conditions and conceptualize DACCS as a coordinated system of technologies and policies integrated within the larger socio-technical system, we adopt the Multi-Level Perspective (MLP) (Geels, 2002, 2004) as a framework for understanding the drivers at play within systems undergoing socio-technical transitions. The MLP is well-suited for the purposes of this study because it provides us with a basis to identify the different components of a socio-technical system and theorize how they interact with one another to shape economic, political, and social outcomes, particularly as they destabilize and restabilize the system in response to internal and external pressures during the transition process.

Our study followed a two-step approach. First, we identified actionable objectives for policy identified in the literature on DACCS and CDR. Then, we applied the objectives to the Canadian policy context by examining a database of 457 federal and provincial climate policies and mapped relevant policies onto 6 domains of policy relevant for supporting DACCS. The goal in this step was to identify where the idealized policy objectives are represented within the Canadian policy landscape. The results provide a picture of the existing DACCS policy environment in Canada, which we then interpret and analyze, drawing on insights from the MLP, but also drawing on the existing DACCS policy literature. In the second stage, our analysis centers on three dimensions of policy analysis: we identify policy gaps, areas where policy needs to be tailored to CDR or extended across the country, and interactions between regime policies and federal and provincial strategies.

1 In this paper we use the acronym "DACCS" to describe the system components as a whole (direct air capture and the transportation and storage of carbon). We use the acronym "DAC" to describe the direct air capture component alone.

The second section of this paper provides the context for the study. We describe the role that DACCS may play in future climate mitigation pathways, and the components of the technology and its system demands, its relationship to the wider physical, economic, social and political components of the socio-technical system in which DACCS is being developed in Canada. The third section of the paper describes the two-step methodology we employ to identify the components and structure of the existing policy framework for DACCS development and deployment in Canada. The results of this study are contained in section 4, which outlines the key findings from our analysis of the DACCS policy framework in Canada. In section five, we return to the MLP to structure our discussion of the broader structural implications of the study. Here we identify those elements of the system that are critical to the scaling-up of DACCS, and the extent to which DACCS has destabilizing and transformative potential. In the final section of the paper, we conclude with a discussion on the potential application of this study approach in other national contexts and situate the study within the existing descriptive and prescriptive literature on DACCS policy formation.

2 Background and approach

2.1 Understanding the DACCS system

DACCS consists of a group of technologies that filter carbon dioxide from the ambient air through various chemical processes, after which captured carbon is either permanently stored in natural geological formations or sold for reuse in industrial activities. DAC, as a process, is energy-intensive, which means that, to be an efficient means of CDR, facilities should use a non-CO_2 emitting energy supply. There are variations of DAC technologies using different forms of chemical processes (solid sorbents and liquid solvents) that have different energy and heat input requirements (Barahimi et al., 2023). Other inputs into the capture process include heat, water and chemical materials (Realmonte et al., 2019). The other central components of the system consist of the geological storage sites or utilization processes and the means to transport the captured carbon to these sites (Nemet et al., 2018; Keleman et al., 2019). Since DACCS does not rely on point source emissions, there is greater flexibility in locating the capture facility close to renewable energy sources or storage sites, potentially reducing the need to transport energy supplies or the captured carbon, or both.

Along with other forms of CDR, the role of DACCS in achieving long-term climate objectives is to offset hard-to-abate emissions and to draw down atmospheric CO_2 to lower the overall concentration of CO_2 to levels consistent with the Paris Agreement targets (IPCC, 2022). Some forms of CDR may act as a substitute for emissions reduction and may be preferred where the costs of CDR are lower than other forms of mitigation. The current estimated cost of DACCS ranges from 250 USD to upwards of 600 USD, though DACCS companies and the Sixth Assessment Report (AR6) expect costs to fall within the next decade (~100–300 USD) as new facilities are built and undertake large-scale removal (IPCC, 2022; Lebling et al., 2022). Relative to the high cost of DACCS, even high abatement costs or carbon prices may not be enough to incentivize purchases of CDR, therefore it is less likely that DACCS will play a significant role in the near term as a substitute to emissions reduction (Chen and Tavoni, 2013; McQueen et al., 2021; Erans et al., 2022). In the long-term CDR needs to be used to deliver net-negative emissions, not just as a means to offset high emissions industries. Despite the high relative costs, there are several characteristics of DACCS that provide advantages over other forms of CDR. Unlike forms of CDR that use biological sequestration, geological storage of CO_2 is stable with high permanence and presents fewer accounting and verification challenges (Beuttler et al., 2019). DACCS has lower land requirements than other forms of CDR, such as bioenergy with carbon capture and storage (BECCS), and may, as a result, place less pressure on agricultural systems (Smith et al., 2016). Some DACCS technologies nevertheless have significant demand for water and the chemicals used in sorbent materials, but its greatest sustainability challenge is the energy required to remove CO_2 from the air, in which the concentration of CO_2 is relatively low (Realmonte et al., 2019).

In AR6, the IPCC identifies the range of cumulative CDR deployment from 2020 to 2,100 within modeled pathways that limit warming to 1.5°C with no or limited overshoot from 20 to 660 $GtCO_2$ (IPCC, 2022). Within that bundle of CDR, the range of cumulative DACCS deployment for 1.5°C and 2°C is 0–310 $GTCO_2$ and 0–250 $GTCO_2$, respectively (IPCC, 2022). Motlaghzadeh et al. (2023), looking more closely at the scenarios within the AR6 database that include DACCS, indicate that annual DACCS deployment in the year 2,100 has significant variation among scenarios, ranging from 0 to 18.9 $GTCO_2$/yr.

The significant uncertainty around the amount of DACCS at both global and national scales is driven by a variety of factors including assumptions regarding broader socio-economic pathways, future cost of DACCS, the degree of temperature overshoot (beyond 1.5° C and 2°C) that would be tolerated, and limits on competing forms of CDR, namely BECCS (Motlaghzadeh et al., 2023). Many national characteristics such as physical suitability (pore space access), availability of low carbon energy, financial and technological capacities and the degree of social and political acceptability of DACCS deployment are not represented in the IPCC scenarios but have been identified as important influences on DACCS development and deployment (Ocean Studies Board and National Research Council, 2015; Buck, 2016; Honegger et al., 2021; Erans et al., 2022; Satterfield et al., 2023).

Recognizing the importance of policy decisions and practices to shape these influences, the existing literature on DACCS policy requirements has focused on interventions that address these key infrastructural, environmental, economic and social conditions (Marcucci et al., 2017; Beuttler et al., 2019; Fajardy et al., 2019; Honegger et al., 2021; Meckling and Biber, 2021). In their article outlining the barriers to CDR, Honegger et al. (2021) claim that the ideal CDR policy mix for overcoming this gap should: "(i) clarify the intended role of CDR, (ii) accelerate innovation to reduce cost barriers, (iii) ensure public participation in the process of mobilizing NETs, (iv) promote long-term, rather than pilot projects for technologies, (v) have robust carbon reporting and accounting procedures, (vi) prevent side effects and maximize the co-benefits of carbon removal" (pp. 5–6). In effect, these recommendations seek to close the current incentive gap by encouraging policymakers to directly support innovation financially and to introduce measures to ensure transparency and diffusion of information on CDR throughout society, thereby reducing uncertainty in the system.

Sovacool et al. (2022), drawing on a large number ($n = 125$) of expert interviews identify a set of 10 DAC-specific policy recommendations. In line with earlier studies, Sovacool et al. emphasize the importance of using DACCS to lower the stock of atmospheric emissions, not as a substitute for reducing emissions and climate adaptation (see also Beuttler et al., 2019; McLaren et al., 2019; Erans et al., 2022), as well as the need to prioritize long term storage and to leverage emerging carbon capture and storage infrastructure. The social dimensions of DACCS have received increasing attention from both instrumental (acceptability) and non-instrumental (justice and legitimacy) perspectives, with recommendations directed toward procedural conditions, such as transparency and stakeholder participation, and substantive outcomes, such as the distribution of benefits and impacts of DACCS (Buck, 2016; Pozo et al., 2020; Sovacool et al., 2022; Satterfield et al., 2023). Overall, the literature underlines the importance of introducing policy instruments to create incentives for investing and scaling up DACCS, such as carbon pricing; decarbonization policy; CDR-specific targets and tax credits; research and development subsidies for NETs and carbon utilization; carbon offset and trading protocols; and clear regulations around carbon storage and transport (Creutzig et al., 2019; Fajardy et al., 2019; McLaren et al., 2019; Honegger et al., 2021; Meckling and Biber, 2021).

Of significance to the current study is that the DACCS policy literature identifies the embeddedness of DACCS systems within a wider system that is itself undergoing a significant low-carbon socio-technical transition. The key physical linkages are between DACCS and the energy system – specifically, the scale-up of non-emitting energy sources – and carbon storage and transportation systems. Likewise, much of the supporting policy environment, such as carbon pricing, innovation support and environmental information and public participation procedures, are part of an existing and evolving policy environment (Cox and Edwards, 2019). While the literature on recommended DACCS policy draws on examples of specific domestic policy instruments, there have been few studies that have sought to identify the elements and contours of domestic DACCS policy frameworks in a comprehensive fashion (but see Schenuit et al., 2021). General, idealized policy recommendations are an important and necessary step in understanding the requirements of the policy framework for DACCS development and deployment, but do not address the social, political and institutional conditions within a specific domestic context.

We share the view of Schenuit et al. (2021) that MLP provides a useful heuristic to structure and make sense of net-zero transitions and the role of CDR policy within those transitions. The MLP distinguishes the three 'levels' that make up the system and determine socio-technical pathways. The first is the existing regime, which encompasses the practices and associated rules that maintain the existing system (Geels, 2011). This includes culture and symbolic meaning, markets and user practice, techno-scientific knowledge, technology, infrastructure, industrial networks and strategic games, and sectoral policy (Geels, 2002). The existing system is subject to destabilization from exogenous "landscape" factors, such as "material and environmental conditions, external agents, [and the] larger socio-cultural context" (Geels, 2004, p. 908). In addition, niche innovations can gain traction and progressively shift, or else radically reconstruct, the architecture of the system, particularly where landscape conditions simultaneously destabilize a regime.

If we accept that DACCS systems will develop, not in isolation, but rather as part of an existing socio-technical system, then a key characteristic of such systems is that they will tend to exhibit high degrees of path dependence (Geels, 2019). Policies that are supportive of DACCS development will be influenced by the existing policy framework, which will reflect the preferences of dominant actors and institutions and will be responsive to the infrastructural and social conditions of the system (Cox and Edwards, 2019). These conditions will be context specific, which indicates the importance of understanding the policy framework at domestic levels since abstract policy recommendations may face "fit" issues within specific domestic contexts (Young, 2002).

In addition to identifying the path dependent nature of dominant technologies and the policies supporting those technologies, MLP provides a theory of change through the incorporation of insights from evolutionary economics that highlight the adaptive, progressive changes in material production and consumption that can align with or impose change on the dominant technological regime. In either case, evolutionary economics understands that successful niche technologies fulfill a functional role within the system by interacting and synergizing with existing technologies and institutions (Boulding, 1991; Geels, 2002; Cecere et al., 2014).

The interdependencies between economic, social and political forces are central to MLP dynamics, and lead to examinations of the way in which these often path dependent interactions result in "lock-in" and more specifically, "carbon lock-in" (Unruh, 2000; Cecere et al., 2014). In this regard, DACCS provides an interesting example, as aspects of DACCS, such as the development of a robust carbon storage and transport infrastructure or the potential role of DACCS as a substitute for emissions reduction, are viewed by many as being supportive of the dominant – fossil-fuel oriented – regime, and as such, may contribute to carbon lock-in (Markusson and Haszeldine, 2009; Shackley and Thompson, 2012; Cairns, 2014). However, DACCS is also a critical component of the transition to net zero (Asayama, 2021). Asayama argues, and we agree, that the dilemma that CDR poses in connection with carbon lock-in is not inherent to the technologies, and can, therefore be shaped through policy choices.

The complex-systems ontology that the MLP adopts is well-suited to an analysis of DACCS' roles in the incumbent (fossil-fueled) or emergent (net-zero) regimes, since MLP favors non-linear, multi-factor causal explanations. DACCS development, because it is so deeply interconnected to other major systems, which interact with one another, is not likely going to be satisfactorily understood with reference to a select number of drivers. This does not, however, suggest that we cannot identify the principal sub-regimes or domains that are relevant to DACCS. Geels notes that "for sustainability transitions, it may be fruitful to pay more attention to multi-regime interactions" (2011, p. 32). In the case of DACCS, its development and deployment will be a product of interactions across energy, climate, and geological storage systems, each of which has constellations of policies that shape both the individual systems and their interactions with one another. In this study, we do not

TABLE 1 DAC projections in Canada.

$MtCO_2$ removed with DAC per year in Canada					
Year	2030	2050	2075	2100	Cumulative DAC by 2100 ($MtCO_2$/yr)
Shared Socio-economic Pathways in a 2°C scenario ($MtCO_2$/yr)					
SSP 1: Sustainability	0.02	0.08	4.30	13.43	430.60
SSP 2: "Middle of the road"	0.01	2.58	64.43	19.00	1945.28
SSP 5: Fossil-Fueled Development	0.51	47.91	283.37	284.15	11774.63
From GCAM 5.3 in Fuhrman et al. (2021)					

precisely specify the boundaries of the broader DACCS system in Canada, which are fluid and imprecise. Instead, we draw on the DACCS policy literature, which identifies a variety of policy domains and policy concerns, to identify the elements of the DACCS system. This approach differs from prior studies on CDR and DACCS policy frameworks, which have tended to look at policies that are explicitly directed to DACCS technologies, whereas our approach is more functionally driven looking at the system elements that will shape DACCS development and deployment, but may address broader system conditions.

2.2 The Canadian context

Canada is certainly not the only country well-positioned to scale up CDR deployment, but its current policies and infrastructure (e.g., available government subsidies and existing carbon storage capacity and regulation) will likely allow it to become an early mover whose deployment strategy other countries may observe and emulate. There is already a maturing DACCS research and development presence in Canada, including an operating demonstration plant that captures 1 tCO_2/day in British Columbia (Carbon Engineering, 2021). The Province of Alberta has several operating commercial-scale CCS projects which contribute a combined capacity of 3.0 MtCO2/year to dedicated storage. Alberta is actively considering proposals to increase its capacity to 56 MtCO2/year, which will make for more efficient use of the province's existing carbon storage and transport infrastructure (Canada Energy Regulator, 2022a).

Canada's emissions are high, both currently and historically. The country's greenhouse gas (GHG) emissions were 670 $MtCO_2$eq in 2021, or approximately 1.5% of global annual emissions, though Canada accounts for only 0.5% of the global population. Canada's existing nationally determined contribution (NDC) is to reduce its emissions 40–45% below 2005 levels by 2030 (to 438 to 401 $MtCO_2$eq) and to achieve net zero emissions by 2050 (Government of Canada, 2021).

The government has acknowledged the importance of CDR in its long term low GHG emissions development strategy (Environment and Climate Change Canada, 2022). In a 2023 analysis by the CER, the (2050) net-zero scenario presented included approximately 150 $MtCO_2$ of negative emissions, including 45 $MtCO_2$ of DAC (Canada Energy Regulator, 2023). This analysis represents, of course, just one possible scenario for DACCS deployment. To provide a better sense of the potential scale for DACCS in Canada under different scenarios, we examined modeling studies that provide regional scale DACCS deployment pathways for a variety of socioeconomic pathways. As indicated in Table 1, derived from the integrated assessment modeling study conducted by Fuhrman et al. (2021), estimates of the cumulative deployment of direct air capture in Canada varies significantly based on scenarios defined by the Shared Socio-Economic Pathways (SSP) framework. This variation spans from 431 Mt. of CO_2 removal in an SSP1 scenario to a substantial 11,775 Mt. of CO_2 removal in an SSP5 world for scenarios aligning with the 2-degree target. The significant variation affirms the high levels of uncertainty at the national level, but suggests that from a planning perspective, there is a need for Canadian policymakers to consider and plan for the development and potential deployment of DACCS, perhaps at very large scales. This is complicated by the fact that DACCS deployment at any level may necessitate cautious or low regret policy steps until greater certainty can be achieved.

3 Methods

3.1 Stage 1: identifying policy objectives

We conducted an integrative review to identify articles related to our thematic areas of interest: CDR and DACCS systems and policy recommendations relevant to their scale up (Braun and Clarke, 2006; Snyder, 2019). Using Google Scholar and the snowballing method, we identified a group of 24 articles (published as of October 2022)[2] published in English after 2015 (Wohlin, 2014). We initially searched for articles that contained the terms "direct air capture," "carbon dioxide removal," or "negative emissions technology" and "policy". Based on this search, we eliminated articles that did not directly address policy and articles that focused on nature-based CDR or making recommendations specific to other NETs. Where possible, we included recommendations from articles that discussed Canada to some extent, though these did supply a more diverse selection of recommendations compared to others in the group. We only included articles that made actionable recommendations or outlined specific objectives of CDR or DAC-focused policy. In this context, "actionable" means that we did not include articles that made general observations about DAC pathways and CDR regime typologies, though many articles that did were still included in the general literature review; however, we did not require articles to identify specific policy instruments. We did not limit our selection to peer-reviewed academic articles because think tank and government reports have put forth

2 Several relevant articles have also been published since we completed data collection, which may be useful in future studies of this kind.

substantial research at this intersection of CDR and policy. Gray literature was therefore included.[3] Although the number of articles is smaller than the sample that might be used in a bibliometric or systematic review, many of the articles reviewed adjacent literature and identified similar objectives, therefore we did not restart or change the parameters of our search to add additional articles after reaching a thematic saturation point in the process of inductive coding (Saunders et al., 2018). Table 2 shows the articles and the criteria based on which they were selected. Manually coding these articles, we extracted 175 policy objectives; that is, specific recommendations regarding desirable policies or policy goals.

After developing the codes, we sorted them into six thematic domains: (1) general environmental policy goals and climate mitigation strategy; (2) energy policy and local resource constraints; (3) carbon transport and storage regulation and infrastructure; (4) financing scale-up and supporting innovation; (5) carbon capture and removal technology availability; and (6) social acceptability and public interest. Within each domain, the policy objectives were ordered in a hierarchical chart. The objectives hierarchy chart allowed us to classify the sub-objectives (or means objectives) that fulfill the more fundamental system objectives indicated by the core organizing domains (Clemens and Reilly, 2014). Subsequently, we removed redundant codes and used those that remained to produce a set of 116 assessment questions representing the objectives and sub-objectives.

3.2 Stage 2: defining the existing Canadian policy framework

The purpose of the second stage of the study was to determine the extent to which the identified policy objectives are represented in the current Canadian policy framework. We drew from the Canadian Climate Institute's climate mitigation policy database, which includes descriptions of all relevant climate and related energy policies at the federal and provincial levels (see Bryan et al., 2022). Since the data collection for the study was completed in the latter half of 2022, there have since been changes in policy and government reports that reflect the pace of change in this arena. The original database itself has also been renamed and reorganized. Their database was suitable for the purposes of this research because it provides detailed descriptions and classifications of a broad spectrum of climate and associated policies at the federal and provincial levels. We collected additional information on non-climate environmental policies not included in the scope of the database, but relevant to the domains. Since our aim was not to conduct a document analysis, we used the descriptions provided within the Climate Institute's database and located Supplementary material where necessary (such as specific policy details or quotations from government materials). The total sample size was 457. We conducted an initial analysis to identify those policies that were relevant to the DACCS policy objectives identified in Stage 1, reducing the sample size to 174 policies.

3 Though number of citations on articles was included in early selection, it was not ultimately relevant because many gray literature sources lacked such numbers and because of the recency of some of the articles (e.g., at the time it was selected, Erans et al., 2022 had 34 citations and now has 182).

TABLE 2 Sources of policy objectives.

Source	A	B	C
Asayama (2021))	✓	✓	–
Beuttler et al. (2019)	✓	✓	–
Cox and Edwards (2019)	✓	✓	–
Craik et al. (2022)	✓	✓	✓
Creutzig et al. (2019)	✓	✓	-
Erans et al. (2022)	✓	✓	–
Fajardy et al. (2019)	✓	✓	–
Fuss et al. (2018)	✓	✓	–
Haszeldine et al. (2018)	✓	✓	–
Hodgson and Hodgson (2022)	✓	✓	✓
Honegger et al. (2021)	✓	✓	–
Larsen et al. (2019)	✓	✓	–
Lehtveer and Emanuelsson (2021)	✓	✓	–
Lomax et al. (2015)	✓	–	–
Marcucci et al. (2017)	✓	✓	–
McLaren et al. (2019)	✓	✓	–
Meckling and Biber (2021)	✓	✓	–
Nemet et al. (2018)	✓	✓	–
Peters and Geden (2017)	✓	–	–
Rueda et al. (2021)	✓	✓	–
Schenuit et al. (2021)	✓	✓	–
Sovacool et al. (2022)	✓	✓	✓
Valiaho (2020)	✓	–	✓
Williams (2022)	✓	✓	–

Column A, Discusses negative emissions, NETs, or CDR policy/includes system relevant insight (including info from the energy sector and CCS development). Column B, Specifically discusses DACCS at some point. Column C, Identifies articles that discuss Canada.

Using the assessment questions developed in Stage 1, we then examined the policy data set to determine whether the policy objectives were met, partially met, or absent (that is where we could not locate a policy that fulfilled the objective in question) within the Canadian policy regime. The policies that fulfilled the criteria were listed, with details of the policy purpose or mechanism where required. We did not place policy examples exclusively in one section or another. Instead, we highlighted the policy aspects that allowed it to meet each objective separately; some policies appear in multiple domains. We also detailed the "MLP level" (niche/regime/landscape) for each policy that fulfilled an objective to provide a more detailed picture of the policy's systemic function within the context of a socio-technical transition. The coded matrix for all 116 questions is included in the Supplementary material.

4 Results and analysis

In sections 4.1–4.6 below, we review and analyze the policy objectives that are present within the Canadian policy framework as well as the policy gaps revealed. We review each domain

TABLE 3 Policy objectives present in Canadian context.

Policy domain	Status of objectives		
	Present	Partially	Absent
Climate mitigation policy (36)	17	13	6
Energy policy and local resource constraints (15)	6	4	5
Carbon transport and storage regulation and infrastructure (14)	3	4	7
Policy for financing scale-up and supporting innovation (18)	12	4	2
Removal/capture technology availability and regulation (19)	5	6	8
Social acceptability and public interest (14)	8	5	1

This table shows how the objectives were assessed for each domain in the Canadian context, while the total objectives in each are listed in the first column. The objectives totaled in columns two through four include higher level and sub-objectives.

separately, with each section beginning with tables that summarize the findings under each domain (see Supplementary materials for disaggregated objectives). The first columns of the tables summarize the key objectives identified for each domain; the second columns identify specific policy instruments (from the Bryan et al., 2022 database); the third columns identify which and how objectives were met; and the fourth columns summarize key gaps in each domain. While the tables in sections 4.1–4.6 provide illustrative examples of the Canadian policy and deployment context, the examples provided in the tables are notexhaustive and do not reflect the complete array of policies analyzed (but which are found in the Supplementary material, along with the complete list of policy objectives and the corresponding policies identified as relevant to them under each domain). Each subsection will expand upon the policy gaps and tailoring needs in the Canadian context, as well as the socio-political dynamic that are not immediately evident in the tables.

A principal goal of this study is to assess the completeness of the objectives within the existing Canadian policy framework. Table 3 below provides a numerical overview of the total number of questions associated with each policy domain, and the policy objectives met, partially or absent for each domain. The results provide a sense of which parts of the DACCS system are more or less complete. Unsurprisingly, the two areas that appear to have policy objectives least represented in the existing policy framework are the two DACCS-specific policy domains addressing removal/capture technology and carbon storage and transportation. Here the policy objectives identified are specific to the technology itself and are less likely to build upon existing policy foundations. Within the storage domain, CCS regulations address many of the technical issues, but these only exist in one or two provincial jurisdictions, and the existing regulations still reflect the limited scale of current carbon storage activities. The more represented areas are those domains that rely more fully on general regulations and policies suitable for DACCS with limited need for adaptation. For example, general public participation processes will be suitable across multiple policy contexts. Table 3 must be read with caution, as a few absent policy objectives may still be highly consequential.

4.1 Climate mitigation policy

Whether the regime has a carbon pricing system is a critical policy for the sociotechnical regime in Canada as a whole, not just the DACCS system. Putting a price on emissions incentivizes abatement itself and the development of innovative technologies to assist abatement (Baranzini et al., 2017; Beuttler et al., 2019; Strefler et al., 2021). Table 4 lists several of the carbon pricing systems in place in Canada, including the federal benchmark that sets the minimum requirements across provinces. Multiple authors observe the centrality of maintaining a stable, long-term carbon pricing system, though most identify it as a necessary but not sufficient condition (Nemet et al., 2018; Cox and Edwards, 2019; Rueda et al., 2021). Although long-term plans for pricing increases have been well established and legislated across Canada, and as such are not identified as a gap in the system, it is important to note that such plans and regulations are politically vulnerable. Carbon pricing remains deeply contested within Canada, with the main opposition party promising to reverse carbon pricing policies (The Globe and Mail, 2023). The instability of a long term carbon price creates greater investment uncertainty for technologies like DACCS, where scaling relies on market-based choices. Without a carbon price, DACCS developers would need to rely solely on government procurement or deployment mandates – though estimates indicate that even the more cost effective end of the DACCS price range (per tonne) will not be comparable to a high national carbon price for at least a decade (Lebling et al., 2022). There are no procurement or deployment mandates for DACCS in Canada. Additionally, maintaining stability in a carbon pricing system is important as internalizing the cost of emissions shifts how society values carbon-intensive production compared to alternatives.

The federal output-based pricing system (OBPS) and the federal fuel charge that create the carbon pricing system in Canada do not apply to every province, as the federal scheme operates as a backstop, and allows provinces to develop equivalent schemes. Several provinces, including Alberta, Saskatchewan, and Ontario, have their own OBPS approved by the federal government, but still have to apply the federal fuel charge. Others, like British Columbia, Quebec, and most maritime provinces, have entirely independent systems; some are cap and trade, and others are tax-based. National policy coherence for climate governance is limited by the distribution of legislative powers between the federal government and provinces. This also results, for example, in inconsistencies between carbon reduction targets and strategies in different provinces. Federal commitments to reduce emissions do not necessarily yield equally robust plans across the country (Fertel et al., 2013).

Commentators have identified the need for government authorities to address removal targets separately from reductions targets within reporting structures (McLaren et al., 2019; Honegger et al., 2021; Schenuit et al., 2021). Currently, the distinction does not exist in Canadian policy, insofar as the regulatory structure treats removal credits in the same manner as reduction credits. Although Canada's carbon offset credit protocol is incomplete under the Greenhouse Gas Offset Credit System, the government has indicated an intention to treat DACCS removals as creditable offsets. In the absence of distinct treatment in offset regimes, removal and reduction credits are effectively fungible, potentially affecting the ability to

TABLE 4 Summary of policy and objectives in climate mitigation policy.

Key objectives	Policy examples	Objectives met	Policy gaps and tailoring needs
• Have a carbon pricing system in place, disclose planned increases and overall long-term climate strategy to reduce uncertainty and align with international targets. Maintain price stability when possible • Establish emissions standards, sector-specific decarbonization objectives, and low-carbon alternatives, especially for high-emissions and HTA industry • Disclose the planned role for CDR and prioritize reduction targets over removal targets (and disaggregate the two) • Maintain robust MRV and carbon offset crediting regulations	Federal: • ECCC and Canada Revenue Agency: Greenhouse Gas Pollution Pricing Act • ECCC: Output-Based Pricing System Regulations • ECCC: Clean Fuel Standard • ECCC: Federal Fuel Charge • 2030 Emissions Reduction Plan • NRCan: National Carbon Management Strategy • Paris Agreement: Canada's Enhanced Nationally Determined Contribution aims for "40–45% reductions below 2005 levels by 2030" • Innovation, Science and Economic Development Canada: Steel project decarbonization investments (hard-to-abate sector) • ECCC: Emissions cap on the oil and gas sector • ECCC & Canada Revenue Agency: Greenhouse Gas Offset Credit System • ECCC: Canadian Net-Zero Emissions Accountability Act • Canada membership in international First Movers Coalition • National Inventory Report methodology Provincial: • Alberta Emission Offset System • Alberta: Technology Innovation and Emissions Reduction (TIER) Regulation • British Columbia: Carbon Tax • Newfoundland and Labrador: Hybrid carbon pricing system • Nova Scotia: Cap-and-trade program • The Management and Reduction of Greenhouse Gasses Regulations; Saskatchewan Fuel Charge • British Columbia: Cement Low Carbon Fuel Program	• Carbon pricing systems and emissions standards are in place at the federal and provincial levels. • Policies prioritize decarbonization and align with international goals and standards. • Government is developing more specific rules for CDR in carbon accounting and MRV.	• Lack of clarity on the planned role of DACCS in meeting Canada's climate goals; policy distinction between reductions and removals (particularly for crediting purposes) • Establishing regional hubs and inter-state cooperation in the transition process.

incentivize high cost carbon removal. It may, however, be desirable to provide further incentive for purchasing removals to enable a commercialization pathway (especially because, for hard-to-abate industries, removals will be more expensive than CCS-based reductions; Rickels et al., 2021). The distinction between types of credits is also necessary to establish standards and offset accounting protocols at the global level (Peters and Geden, 2017). Negative emissions will likely be provided by private firms on a transnational basis, which means that international cooperation will be necessary to avoid double-counting in trade and ensure consistency across national systems. This is a prevailing gap in Canada, but also within the broader system landscape.

4.2 Energy policy and local resource constraints

Table 5 shows select energy decarbonization policies that exist or are in development in Canada. The policy framework for DACCS in Canada must address the strain that the energy and resource intensity of DACCS puts on the energy system, and the potential the DACCS energy demands may conflict with other priorities in the energy transition. Electricity in Canada is largely provided through low-carbon sources with 80% of electricity coming from non-emitting sources, such as hydro and nuclear (Canada Energy Regulator, 2022b). Canada does not have to replace large amounts of fossil fuel generated electricity; additional capacity could be directed to new sources of electricity demand, including DACCS (Wohland et al., 2018; Singh and Colosi, 2022). Since energy policies and infrastructure fall largely under provincial jurisdiction, provincial cooperation to expand non-emitting capacity or direct electricity to negative emission projects would be required. Energy policy planning that accounts for DACCS has been largely exploratory, without explicit policy direction, in part due to the uncertainty associated with DAC scaling. Nevertheless, energy systems will need to expand in lockstep with DACCS to achieve scale in the future (Fuss et al., 2018; Creutzig et al., 2019; Larsen et al., 2019; Lehtveer and Emanuelsson, 2021; Williams, 2022). At present, while the energy and resource demands of a technology like DACCS may be considered in impact assessment processes, such assessments are project-based and would not involve strategic or transition oriented assessment (Nwanekezie et al., 2022). In contrast, United States policy plans have identified the need to coordinate DACCS scale-up with domestic low carbon energy sources (U. S. Department of Energy, 2021). Canadian policy has not yet established guidelines for managing the trade-off between DACCS and the energy-efficiency goals of climate policy. The

TABLE 5 Summary of policy and objectives in energy policy and local resource constraints.

Key objectives	Policy examples	Objectives met	Policy gaps and tailoring needs
• Ensure projects assess the techno-economic feasibility of DACCS deployment within a particular energy system and resource context and increase renewable energy capacity in the system overall • Co-locate projects with non-intermittent renewables or waste heat • Fund transition infrastructure and restrict new fossil fuel energy development (manage industry decline)	Federal: • Impact Assessment Agency of Canada: Impact Assessment Act • NRCan: Strategic Interties Pre-development Program • Canada Energy Regulator Act • NRCan: Expansion of clean electricity • NRCan: Regional Energy and Resources Tables and collaboratively developing carbon management and energy development work plans (Natural Resources Canada, 2023) • NRCan: Establishing Pan-Canadian Grid Council • ECCC: Phase out of coal-fired electricity • NRCan: Smart grids Provincial: • Alberta: Renewable Electricity Act • Alberta: Coal-powered electricity phaseout • Alberta: Oil Sands Emissions Limit Act • British Columbia: Industrial Electrification Rates • British Columbia: CleanBC Program for Industry • Nova Scotia: Emerging Renewable Power • Nova Scotia: Offshore Energy Research Association • Newfoundland and Labrador: Clean technology research and development • Newfoundland and Labrador: Clean Technology Tax Credit • Quebec: Quebec's 2030 Energy Policy	• Funding for clean technology innovation and currently developing more comprehensive national plans and guidelines • Government is funding necessary energy transition infrastructure and improving grid management	• Ensure projects assess the techno-economic feasibility of DACCS deployment within a particular energy system and resource context and increase renewable energy capacity in the system overall • Fossil fuel energy phase-out (particularly in key provinces still reliant on fossil fuel energy)

lack of long-term, coordinated energy planning is a significant deficit.

Many of the policy examples in Table 5 show how governments are targeting emission reduction via electrification and total energy system decarbonization as a regime objective. However, the regional and sectoral distribution of emissions is uneven, with high concentrations of emissions coming from western Canada, as a result of high GHG emissions associated with the oil and gas industry. Table 5 does not reflect the fact that some provinces are further along than others. For example, through the Renewable Electricity Act, Alberta will require 30% of electricity in the province to come from renewables by 2030, in addition to the government's commitment to phase out coal-powered electricity by 2023 and the Oil Sands Emissions Limit Act restriction of GHG emissions above 100 MtCOeq/year. Simultaneously, Alberta has the most fossil fuel intensive electricity production in the country at 90% (54% Natural Gas and 36% Coal and Coke) and the oil and gas sector is a major part of the province's economy, which makes decarbonization a politically contentious prerogative (Canada Energy Regulator, 2022b). Energy infrastructure remains largely a provincial matter, which creates a disjuncture between national climate goals, including DACCS development and jurisdictional responsibilities. The federal government may influence policy direction through fiscal tools, such as subsidies and tax credits, but these may increasingly be at odds with some provincial policies and regulations that are directed toward optimizing fossil fuel extraction.

4.3 Carbon transport and storage regulation and infrastructure

The geology of a region is a landscape condition that, in part, determines where projects can be sited. However, transport infrastructure, technology, and regulations enable particular types of storage. Table 6 shows illustrative provincial and federal carbon storage and transport regulations. Canada has large amounts of accessible geological storage that would be suitable for CO_2 storage, though this potential varies from province to province based on geology (Hares et al., 2022). Alberta, where pore space is abundant relative to most other provinces, has established a clear regulatory regime for CCS (see Bankes, 2008, 2019), and has built supporting transportation and injection infrastructure that optimizes CCS (but not necessarily DACCS) using a hub-based model (Government of Alberta, 2023). As of 2021, Alberta is injecting and storing 3.17 MT CO_2/yr. (CER, 2022). In addition to the Western Canada sedimentary basins, there is further potential CO_2 storage capacity in offshore areas in Atlantic Canada, and transboundary opportunities to transport CO_2 in sedimentary basins located in the Appalachian region of the United States (CCS Knowledge Centre, 2021).

The federal government is in the early stages of clarifying what kinds of storage sites and existing infrastructure can be used to support the scale-up of CDR in the system. There is not enough publicly available information about the federal government's plans to determine what objectives they fulfill – which would enable us to analyze which features may need further improvements to benefit a

TABLE 6 Summary of policy and objectives in carbon transport and storage regulation and infrastructure.

Key objectives	Policy examples	Objectives met	Policy gaps and tailoring needs
• Have a protocol or regulation in place to regulate permanent geological carbon storage that differentiates between types of CO_2 storage and their respective level of security and risks (particularly when issuing offset credits for storage) • Clarify pore space ownership and establish liability (particularly in the case of new offshore developments) • Have guidelines for siting CDR projects proximate to known, accessible storage space; make maps of existing storage publically accessible • Design transport and storage infrastructure networks and repurpose existing infrastructure or shared infrastructure where possible	Federal: • Canadian Environmental Protection Act (CO_2 and other GHGs designated 'toxic substances') • Party to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter • NRCan CanmetENERGY: Canadian CCUS Assessment Framework, open source tool for national carbon management (Natural Resources Canada, 2023) • Geologic Survey of Canada and NRCan CanmetENERGY: compiling data on domestic storage and transport • Department of Finance: Investment tax credit for carbon capture, utilization, and storage (only geological storage and concrete are 'eligible uses' because they are permanent) • CER responsible for regulating cross-border (interprovincial and international) pipeline transport • NRCan cannot issue seabed CO_2 injection licenses under the Federal Real Property and Federal Immovables Act, while ECCC cannot issue permits for seabed CO_2 injection under Canadian Environmental Protection Act (CEPA) (Webb and Gerrard, 2021, iv). Natural Resources Canada (2023) indicates that adding CO_2 to Schedule 5 of the CEPA is in progress Provincial: • British Columbia: Carbon capture and storage regulatory framework • British Columbia: Petroleum and Natural Gas Act: PETROLEUM AND NATURAL GAS STORAGE RESERVOIR REGULATION • British Columbia: Energy Statutes Amendment Act • Alberta: Mines and Minerals Act • Alberta: Carbon Sequestration Tenure Regulation • Alberta: Technology Innovation and Emissions Reduction (TIER) Regulation • Alberta: Alberta Emission Offset System (part of TIER; generates double credits) • Alberta: Alberta Carbon Trunk Line, Quest, and the Alberta Carbon Grid • Saskatchewan: Oil and Gas Conservation Act, O-2	• Provincial policies are beginning to regulate permanent geological carbon storage and differentiate between types of CO_2 storage and their respective level of security and risks. Federal policies have begun to clarify offset crediting protocol • Existing pipeline networks, storage policy/sites, and pore space regulation from oil and gas sector regulation can be reused	• Adapt existing policy to clarify pore space ownership, liability, and overall CO_2 storage regulations in provinces besides BC, AB, & SK (differentiate types of storage and account for CO_2 accordingly) • Federal guidelines for storage, siting projects appropriately, and clarification on existing legislation (i.e., application of CEPA, particularly for offshore capture, storage, and energy generation • Make (CCS) CO_2 transport plans publicly available (in progress)

DACCS system rather than a CCS system. The absence of federal guidelines and incentives to coordinate transport, prioritize secure and permanent storage, and co-locate DAC projects accordingly may inhibit the development of large-scale CDR storage projects (Cox and Edwards, 2019; Craik et al., 2022; Erans et al., 2022). The federal government retains some environmental authority around the regulation of carbon (e.g., via the Canadian Environmental Protection Act [CEPA]), but the regulation of pore space itself falls under provincial jurisdiction. The regulation of geological storage is uneven across regions, with existing frameworks being found in jurisdictions with emerging CCS industries. Other areas with storage potential, notably Atlantic Canada, have not yet taken any concrete actions to develop storage opportunities. The current approach to storage policy reflects the prior interests of oil and gas and other subsurface rights holders, and is rooted in sectoral policy in these areas (Bankes, 2019) – a trajectory that may be followed in other jurisdictions, if and when storage opportunities unfold. The legal issue that arises is how to apply existing laws, where to introduce new amendments and new policies, and whose interests will prevail in the development and allocation of storage opportunities (Cox and Edwards, 2019; Craik et al., 2022). In this latter regard, there is potential for different user groups (EOR, CCS and DACCS) to compete for storage and transport space, but there are no policies in place to address allocation.

The policy objectives identified in this domain emphasized the need for regulations and incentives that support and prioritize the scale-up of CO_2 storage over CO^2 utilization, considering current forms of utilization are generally less permanent or result in rerelease of CO^2 (e.g., beverage carbonation, EOR) (Cox and Edwards, 2019; Fajardy et al., 2019; Meckling and Biber, 2021; Erans et al., 2022). Nevertheless, utilization is an important element of NET developer business models and the commercialization of CO_2 utilization niche innovations will play an important role in securing financing within the system (Mac Dowell et al., 2017; Haszeldine et al., 2018; Nemet et al., 2018). The planned federal investment tax credit for carbon capture and storage will likely introduce some incentives that are

TABLE 7 Summary of policy and objectives in policy for financing scale-up and supporting innovation.

Key objectives	Policy examples	Objectives met	Policy gaps and tailoring needs
• Correct 'market failures' through R&D for low-carbon technology, NETs, and requisite infrastructure • Provide incentives (and other market signals) to reduce investor risk, establish an economy of scale for DACCS, and ultimately bring down cost barriers and improve technology performance • Help establish multiple streams of revenue for developers–not just subsidy (e.g., niche utilization opportunities)	Federal: • NRCan: Energy Innovation Program • ECCC: Low Carbon Economy Fund • Innovation, Science and Economic Development Canada: Net Zero Accelerator • ECCC: Clean Growth Program • Innovation, Science and Economic Development Canada: Clean tech project investment • Innovation, Science and Economic Development Canada: Sustainable Development Technology Canada • Department of Finance: Investment tax credit for carbon capture, utilization, and storage Provincial: • Alberta: CCS investments	• Government incentives are in place to support the research and development of new technologies that will be a part of the transition. • The government is in the process of introducing policies (tax credits, rebates, further incentives) to incorporate DAC and CDR into the climate plan and carbon pricing. Plans aim to help developers secure multiple streams of revenue (government support, private investment, and niche markets).	• Lack of information/ uncertainty surrounding plans, incentives, and other policies related to CDR currently in development (e.g., ITC rules, the sustainability and path-dependencies implied by allowing EOR at scale, flexibility for adapting policy, the extent of government intervention, including government procurement prospects).

directed toward utilization activities, such as using carbon in cementitious material (Department of Finance, 2022).

4.4 Policy for financing scale-up and supporting innovation

Niche technologies can radically change a system and stabilize it amidst landscape changes (Geels, 2004). Moreover, providing financial incentives for investing in and directly funding a niche technology creates a protected market that allows the technology to mature and become more efficient and cheap, grow less dependent on subsidies, and more effectively integrate into the system (Geels and Schot, 2007; Schot and Geels, 2008; Cecere et al., 2014). The government's deployment strategy for CDR seems to focus on creating an environment to foster niche development through subsidies and coordinating infrastructure. Funds for such projects are currently available through a variety of government programs, as listed in Table 7. The Federal Government has recently introduced new funds and incentives to support NETs, CCS, and carbon pipeline infrastructure across the country. Of note, is an investment tax credit (ITC) for CCS development, with a specific DACCS component. The tax credit resembles similar support provided by the United States government for DACCS, although the Canadian amounts provide a lower subsidy (IEA, 2022). The structure of the ITC includes a phase out from 2030 to 2040, indicating an expectation that DACCS would be commercially competitive with other forms of removal within that time frame (Department of Finance, 2022). Through the Energy Innovation Program, the federal government will also invest $319 million over 7 years to the research and development of CCS technologies to lower technology costs. Such funds will also increase the availability and commercial development of CO_2 utilization niches, which would help develop a market for captured carbon. The scale of support in Canada is significantly lower than under recent U.S. legislation, raising potential competitiveness concerns (U. S. Department of Energy, 2021).

There is no indication that the government intends to pay for DACCS directly or act as a primary market by purchasing DACCS credits to offset their emissions, which is a model that some authors explore (Buck, 2019; Honegger et al., 2021; Hodgson and Hodgson, 2022). It is important to clarify whether the government intends to foster the creation of carbon removal markets or treat CDR as a public good because uncertainty in the system may undermine other market signals and incentives that would otherwise aid CDR scale-up. The government's support determines how niche technology developers shape their business models.

Finally, the optimal order and strategy for rolling out financing and innovation policies are still unclear. Meckling and Biber (2021) suggest an "incentives + mandates" policy strategy: mandates because of their lower political cost and incentives due to their demonstrated effectiveness in scaling up other low carbon technologies. Feed-in tariffs, new emissions standards, reverse auctions, and carbon pricing are all options that are likely to help incentivize DACCS (Lackner and Azarabadi, 2021). Subsidies can be controversial, as evidenced by the national backlash against the CCUS ITC (Tuttle, 2022). Subsidies, at least in the near term, are a necessary part of the strategy for CDR at scale because they support the development of niche innovations. The planned reduction of the ITC after 2030 is a reflection of the government's intention for financial support to create a viable niche market that will be able to sustain itself once technologies have reached scale. However, the timeline for reducing high removal costs is a major uncertainty in the current regime.

4.5 Removal and capture technology availability and regulation

There is overlap between the policy objectives in this section and domains addressing innovation financing and broader market structures. Table 8 shows a gap in the policy framework related to DAC specific regulation and overall CDR scale-up (Lomax et al., 2015; Marcucci et al., 2017; Fuss et al., 2018; Haszeldine et al., 2018; Larsen et al., 2019; Honegger et al., 2021). For example, technology mandates in other sectors are a part of the government's climate mitigation strategy at the federal level, both for the market and for the technology the government itself uses (e.g., the Zero

Emission Vehicle Mandate and the Low-Carbon Fuel Procurement Program). A DACCS deployment mandate for the government or the private sector has some analogous programs to build upon, recognizing that DACCS presents some unique challenges (Larsen et al., 2019; Honegger et al., 2021; Erans et al., 2022; Hodgson and Hodgson, 2022; Williams, 2022). Many objectives in this section included longer-term considerations compared to questions about what kind of near-term support the government should provide. This mainly involves introducing new, CDR-specific policy not addressed in other domains (i.e., storage-related tailoring). Canadian policy makers have not identified specific targets for CDR or which types of CDR may play an important role in achieving its net-zero objective. The role that the government needs to take in managing and providing CDR will depend on the degree to which new market mechanisms or mandates related to CDR can provide sufficient social benefit, which are not necessarily reflected in the historical market failures that allowed climate change to progress. It is premature to assess the state of CDR-specific policy in Canada, but the current pattern, as exhibited in CCS regulation and emerging CDR regulation, is for specific regulations to develop in a more reactionary mode, as commercial scale deployment begins. There is little evidence of anticipatory regulation intended to shape technological or development outcomes.

4.6 Social acceptability and public interest

Table 9 shows select policies related to social acceptability in Canada. Recent literature suggests that perceptions of risks and climate benefits associated with storage, rather than the capture process alone, are a key criterion for acceptance, as well as the use of renewables within DACCS systems (Arning et al., 2019; Cox et al., 2020; Satterfield et al., 2023). In particular, a recent study by Satterfield et al. (2023) surveyed Canadian and US residents in the vicinity of proposed pilot sites of DAC paired with sub-sea floor CO2 storage and found that participants were concerned with the impacts and risks of the whole DACCS system after being informed of the components of the process, including energy sources. These results suggest that public engagement efforts should be holistic, "fine-grained, and sensitive to public knowledge of NETs," as community values and perceived urgency of climate change will vary based on socio-political and environmental contexts (Satterfield et al., 2023, p. 13). Although public acceptability tends to be higher for nature-based CDR than for NETs, it also largely depends on how the risks and benefits of new infrastructure and technology projects are framed in public discourse; stakeholders may be more open to engineered solutions with gigaton-scale removal potential if they receive adequate information during the engagement process (Buck, 2016; Bellamy, 2022; Cooley et al., 2023; Satterfield et al., 2023). In turn, this depends on the dynamics and social relations in a particular social context, as well as effective government communications, which makes this policy dimension especially important in the early stages of the transition and DACCS scale-up. Canadian policy discourses on just transitions have encompassed the potential transitional role of CCS, providing a foundation for similar discussions in relation to DACCS.

Although recent government publications and plans have signaled that the Government of Canada intends to integrate CDR, CCS, and DACCS into the national climate strategy, there is generally insufficient public communication about the technology to accompany this signal for scale-up (Government of Canada, 2021; Environment and Climate Change Canada, 2022). Thus, the main policy concerns for this domain are tailoring and general improvements to public engagement processes. Existing processes for public consultation, such as environmental impact assessment, are project driven, which provide an opportunity for public understanding of localized, environmental impacts. There is, however, a significant gap in opportunities for higher order, strategic assessments, involving public awareness and consultations that would look at the long-term strategy associated with scaling up DACCS. The 2023 Carbon Management Strategy, which outlines long-term strategies for meeting Canada's net-zero commitments through CCUS and DACCS describes a public consultation process, but in doing so focuses exclusively on actions in support of the approach. Among the key policy tools identified in the strategy is the investment tax credit for CCS and DACCS, but when this instrument was released it was subject to trenchant opposition from some quarters. The close association in Canada between CCS and DACCS presents a risk that concerns over the ability of CCS to further entrench fossil fuel interests will spill over to DACCS (Anderson, 2022). Another potential mechanism for public awareness, the Canada Net-Zero Emission Accountability Act, which includes an advisory board that produces reports to guide the (federal) government's pathway to net-zero has not engaged in any significant analysis of the role of DACCS in transition plans.

The current, modest levels of CDR activity in Canada have not been without controversy. The ITC, which covers CCS and DACCS, was opposed by a number of environmental groups and academics in

TABLE 8 Summary of policy and objectives in removal & capture technology availability and regulation.

Key objectives	Policy examples	Objectives met	Policy gaps and tailoring needs
• Introduce CDR and CCS-specific regulations, development plans, and near-term incentives/R&D programs (and diversify investments in them) • Differentiate between types of CDR, NETs, and DAC to plan around their respective needs, limitations, potential, and impacts • Define the regime's model for DACCS policy (e.g., public utility/waste management model)	Federal: • NRCan: Carbon Management Strategy (in development) • NRCan-Energy Innovation Program: Carbon capture, utilization and storage RD&D Call • Department of Finance: Investment tax credit for carbon capture, utilization, and storage	• Government is beginning to develop CDR and CCS specific policies. • Diversifying NETs investments and plans.	• Long-term policy considerations: uncertainties in plans to help developers transition from pilot facilities to large-scale projects and NET-specific regulation • Non-market mechanisms: government (federal and provincial) strategy to avoid mitigation deterrence, plans for deployment mandates, CDR quotas, credit procurement, or framing CDR as a public good (if appropriate)

TABLE 9 Summary of policy and objectives in social acceptability and public interest.

Key objectives	Policy examples	Objectives met	Policy gaps and tailoring needs
• Increase public awareness and acceptability of DACCS via policies that establish public education campaigns, reduce uncertainty and address risk through local consultations and community engagement • Identify public concerns and community vulnerabilities to ensure technology projects minimize harm and confer community benefits • Design system changes in accordance with a 'just transition'	Federal: • Impact Assessment Act • Duty to consult, s. 35 of the Constitution Act • Cabinet directive on regulation s 4.1 • 2030 emissions reduction plan (increases awareness by discussing CDR and DAC) • ECCC Supporting Sustainable Jobs Program • Employment and Social Development Canada: Sectoral Workforce Solutions Program • Investing in Canada Community Employment Benefit for major infrastructure projects • NRCan: National Benefits-Sharing Framework Provincial: • Benefit agreements/resource benefit sharing agreements at provincial and municipal levels	• Some policies are in place to ensure job transition programs, public consultations, and impact assessments happen • In the process of increasing benefit sharing via national frameworks • Government communications and policy include 'just transition' framing of the decarbonization process	• Insufficient government support for public awareness, communication about NETs, and the need for scale-up • Requirements for iterative public consultations and community benefits (potential to amend existing requirements)

Canada on the basis that it was a further form of subsidization to the fossil fuel industry and would delay more meaningful decarbonization efforts (Anderson, 2022). DACCS-related infrastructure, particularly at large scales, may give rise to public and Indigenous opposition similar to what has been seen with pipeline and other large infrastructure projects in Canada (BBC World News, 2020). The dynamics of social opposition and acceptance will influence net-zero pathways at a systemic level. An important aspect of public consultation in Canada is the constitutional duty on the government to consult Indigenous groups where government decisions have the potential to impact Aboriginal and treaty rights under 35 of the Constitution Act (1982). Insufficient Indigenous consultation has had a major impact on numerous infrastructure projects in Canada, such as pipelines and dams, and has increasingly turned to discussions on benefit sharing arrangements between resource developers and Indigenous groups (Exner-Pirot and Ignasiak, 2023). There is little evidence of Indigenous engagement on the scale-up of CCS and DACCS in Canada, notwithstanding that storage activities occur in areas that are subject to Aboriginal and Treaty rights, and a rising recognition of the role of benefit sharing in carbon management activities (Government of Canada, 2022). Beyond the Canadian government's duty to consult Indigenous groups, these gaps and tailoring needs for policy extend to other countries planning to implement large-scale CDR-related infrastructure projects. Specifically, in preserving Indigenous peoples' right to free, prior and informed consent in countries that have ratified the United Nations Declaration on the Rights of Indigenous Peoples. In the context of a sociotechnical transition, infrastructure projects and land use changes must be designed to address rather than exacerbate the vulnerabilities of local communities by creating low-carbon job opportunities and providing benefits to aid sectors in transition. Improving the public's awareness of these technologies is important in the transition process. The socio-technical regime, according to Geels (2002), includes cultural and symbolic meaning. Context-appropriate communications about NETs at national, provincial, and local levels impact the symbolic meaning of the technologies in society, potentially reducing their perceived risks through techno-scientific knowledge sharing. This, in turn, influences user preferences and markets within the regime, helping project developers secure a social license to operate and avoid delays caused by societal backlash if a project is perceived as illegitimate or harmful. On the other hand, failures to address legitimacy concerns associated with technologies, or aspects of the transition can erode social acceptance.

5 Situating DACCS in a socio-technical transition

The MLP allows us to situate DACCS in relation to the key components of the existing system and the processes of change within the system. There are clear examples of niche development initiatives oriented toward the development and scaling of carbon capture technologies. These mostly include financial support for research and commercialization of the capture technologies and linked support for utilization markets, such as using carbon in cementitious material or in synthetic fuels. By introducing new 'rules' to the system through incentives and regulations, regulators can help niche technologies both enter the regime and fulfill a necessary role in the transition. Other technological niches will also help to leverage change and successfully implement DACCS while maximizing the efficiency of project sites (e.g., via utilization).

Our assessment has revealed that the current regime largely lacks sectoral policies specific to DACCS and CDR, which are necessary to establish a functional DACCS system. The absence of policy is obvious enough, given the newness of DACCS and other NETs. However, this analysis has also highlighted the importance of identifying the policies and infrastructure that are precursors to more specific policies and niche development. Coordinated regime changes will work to adapt infrastructure and attitudes around these technologies to weaken path-dependencies and diffuse the cost of restructuring the system and introducing new network technologies. Policies that support niche carbon utilization opportunities in the near term, for example, will influence the availability of mature utilization technologies by mid-to-late century, therefore affecting the commercial viability of DAC and opportunities to reduce removal costs further once the technologies have begun to scale. The development of a carbon utilization market will, depending on transport and energy infrastructure, also eventually influence where DACCS and CCS projects are sited, as well as more targeted regime policies on regional and national levels (Valiaho, 2020).

The scale-up of DACCS will occur in the context of regime change and a low-carbon system transition. DACCS will, in other words, become one of many technologies within Canada's climate mitigation toolkit and within the socio-technical system, rather than simply a technology introduced mid-century to mitigate overshoot. From an MLP perspective, the embeddedness of DACCS with other systems points to the importance of incremental shifts within the existing regime as an important determinant of future pathways. If energy infrastructure planning decisions remain separate from discussions of where to site DAC and coordinate carbon transport and storage networks, then the risk of technology lock-in in Canada will increase, since pipelines and energy infrastructure are capital-intensive, long-term infrastructures. This, in turn, factors into a firm's selection criteria when deciding where to site their facilities; in energy-intensive industries, for example, firms would be most willing to site facilities where they could access a cheap supply of energy.

Unlike many historical cases of technology transitions that have featured the substitution of one technology by another, DAC is not replacing a previous technology and taking on its role in the regime. Rather, DACCS is a technology that fulfills a service that was not previously necessary to maintain a stable regime but is increasingly viewed as fulfilling novel functions that are necessary due to landscape conditions. As Geels (2011) notes, sustainability transitions are purposive, in contrast to transitions driven by market structures. An important question in the Canadian context is who is shaping these purposes and the function of DACCS within the emerging net-zero transition. In this regard, DACCS has a complicated relationship to the existing regime. The dominant regime includes the infrastructure and technologies of a fossil fuel-intensive economy. Replacing this economy and repurposing existing infrastructure will be an important part of managing the transition. The process of developing a DACCS sub-system within the larger Canadian socio-technical system is largely congruent with that objective because, for the purposes of carbon storage and transport, DACCS and other NETs can make use of some existing pipelines and depleted oil wells. The storage dimensions of DACCS are similarly aligned with the dominant regime as they have potential to share transportation and storage infrastructure with CCS.

DACCS is portrayed as simply part of a larger carbon management plan that includes point source capture and carbon utilization (Natural Resources Canada, 2023), meaning the development of DACCS and CCS draw on common policy instruments and infrastructure. DACCS does not directly threaten the fossil fuel based political economy since it is not intended to replace existing energy sources. Nonetheless, DACCS may be a significant driver in future energy decisions, as its efficiency as a carbon removal process is strongly dependent on the scale of non-emitting energy.

Geels and Schot (2007) note that different configurations of landscape pressures and the extent to which niche innovations are competitive or symbiotic with the existing regime will lead to different transition pathways. At this early stage, the transition pathway for DACCS in Canada has some characteristics that are consistent with a "reconfiguration" pathway, where the niche innovations have symbiotic relations with the existing regime and are adopted as add-ons, which may be adapted over time and reconfigured in response to landscape pressures. What is unclear at this stage is whether DACCS is a means of catalyzing a shift within the broader system or if it will further entrench path-dependencies in the currently dominant regime. In exploring this tension that DACCS creates between transformation and stasis, Asayama (2021) sees some potential for policy design to limit the extent to which DACCS acts as a reinforcing technology. In our examination of the Canadian policy framework, we saw no indication of policies that would have as their goal the realignment of DACCS away from fossil fuel industry interests.

A key finding of this study is that many of the types of policy actions that the government should undertake do not belong to a single domain or sector. Rather, the objectives that DACCS system policies must fulfill extend to multiple parts of the system, which requires cooperation between different actors and coordination across government institutions. For example, clarifying carbon storage regulations not only enables developers to design transport and storage infrastructure, it also reduces uncertainty for investors, which helps DAC projects secure funding; with effective public communication, these clarifications can also promote social acceptability in Canada.

The interdependencies within the system are a defining characteristic of complex systems generally and suggest the presence of leverage points – points of intervention within the system that will most effectively transition the system (Meadows, 2008). Our study was not directed toward establishing leverage points, but we can observe a number of potential candidates that deserve further attention. For example, CCS development provides a commercially viable pathway to scale up storage sites and build related infrastructure and expertise. Carbon from CCS is often used for enhanced oil recovery (EOR) where it is injected to access an otherwise inaccessible output from depleted oil wells, which furthers its commercial value. While carbon from CDR may be used for EOR, many of the articles we selected cautioned against this business model due to its potential to detract from mitigation. However, other research has found EOR yields a net reduction in the carbon intensity of oil since injected carbon is stored permanently, which makes it a marginally more sustainable alternative to oil extracted through conventional methods (Sminchak et al., 2020; Clean Air Task Force, 2021). The CCS system is likely to influence the shape of a DACCS system that builds upon this foundation. The potentiality of CCS and EOR operating simultaneously suggests a need for policy to promote permanent carbon storage and utilization above other uses that entail reemission (or at least include a strategy for transitioning away from point-source CCS and EOR once fossil fuel production declines). In Canada, CCS is mostly being bought and paid for by the oil and gas industry, who are paying because they want to preserve the long-term viability of their industry, not just prolong its life by a decade. The Canadian ITC will not credit EOR uses of carbon (crediting only predefined "permanent" uses and storage) and has defined end-date, unlike the tax credit policy in the U.S which provides credits for CCS projects that use EOR; this difference may reduce lock-in risk by comparison (U. S. Department of Energy, 2021; Department of Finance, 2022), but may also place Canadian developers of DACCS at a competitive disadvantage.

Energy policy – specifically, the ability to provide large amounts of non-emitting power – drives the overall viability of a DACCS system and will drive siting decisions, which technology developers will need to leverage to support energy-intensive niches. A third potential leverage point is the presence of a robust carbon pricing system, which provides a commercialization pathway for DACCS. Carbon pricing alone will not be enough to incentivize uptake, but it does help to reorient the objectives of the system and support the viability of niche technologies during and after they 'incubate' with the support of subsidies, private investment, and regulatory support. The federal benchmark for carbon pricing in Canada will rise to 170 CAD by 2030; if policy support can help CDR and DACCS technologies scale and lower their prices by the end of the decade, removals could be cheaper than the carbon tax (Environment and Climate Change Canada, 2022). Both Climeworks and Carbon Engineering expect their technology's removal cost to fall below 100 USD per tonne in this approximate time frame, although other estimates are less optimistic (McQueen et al., 2021). Though the cost of nature-based removals and abatement are lower than both in the near term, their marginal costs will also rise as land becomes scarcer and firms exhaust lower-cost abatement options (Fuss et al., 2018; Gillingham and Stock, 2018). The policy framework in Canada is oriented toward a market structure for DACCS, as evidenced by the phase-out timeframe of the investment tax credit, which suggests an intention to limit subsidies over time, and an expectation that DACCS will transition to a self-supporting commercial model. We note that the alternative is a procurement or mandate model, but there are no indications within the policy framework that this is an anticipated orientation. A final potential leverage point is the degree of social acceptance of DACCS and its components. Social acceptance will influence the physical siting challenges, which will be shaped by risk perceptions. Acceptability may affect the ability of governments to subsidize DACCS development over an extended period and at what may be high levels. Social acceptance will also operate on a more diffuse level, affecting whether DACCS is viewed as a constructive element of the net zero transition or as a dangerous distraction. There is evidence of these opposing framings shaping the Canadian discourse around government support for DACCS.

6 Conclusion

Large-scale CDR and DACCS deployment will be highly context-specific, as will the long-term approaches for managing the technologies. This research was motivated by a recognition of the need to investigate the structure and policy content of national-level policy frameworks that will support and shape DACCS development and scale-up. The importance of national contexts for CDR and DACCS development pre-existed this study, but our study builds on the literature by providing a first in-depth analysis of a nascent national-level DACCS system and the findings provide empirical support for this position.

An important contribution of this study is the methodological approach we developed to map the contours of the DACCS policy framework in national settings. A key advantage of our approach is that by starting with broader policy objectives and matching those objectives to a database of existing policies, we were able to identify the policy framework in a more comprehensive fashion, then analyzing policies that are framed as explicitly directed toward CDR or DACCS. We believe that the approach is replicable in other jurisdictions, and there would be benefit in further country-level studies that share a common approach to support inter-country comparability.

The policy objectives identified in the CDR and DACCS literature are represented within a complex array of pre-existing policy instruments and programs within Canada. These policies are in many cases not oriented toward DACCS, and as such will be subject to a variety of political and economic influences. The system may be characterized as having pockets of DACCS specific policies, which operate in a larger system that is not intentionally directed toward DACCS or CDR. This finding aligns with the MLP in that change within the system will be a function of both the pre-existing stricture as well as the exercise of agency within the system.

This points to a more overarching gap that is evident within the DACCS policy framework. Many of the existing policy processes drawn upon respond to local and often shorter-term priorities, at the expense of more strategic-level guidance. This, in our view, is most evident in the complex interplay between CCS and DACCS in Canada, where resource interests are able to shape the emerging CCS system and draw on the promise of DACCS to move the system toward net zero. However, there is little evidence of how the transition from a CCS-dominated system to DACCS would be managed. Existing policies will need to be tailored to enable a transition between the two and ensure CDR-specific strategies at all levels of government, including a robust MRV process, an overarching deployment plan, and cohesion across different policy domains.

Many of the policy domains for DACCS deployment, such as geological storage regulation and energy policy, are under the jurisdiction of provincial governments, which creates a potential disjuncture between the federal government's ambitions and long-term strategies for DACCS and the policy authority to influence those outcomes. Since DACCS deployment will depend on provincial involvement, federal/provincial cooperation appears to be a key structural variable within the system. Different provinces are likely to hold divergent interests in climate solutions that will shape the regime structures within their respective provinces. This is already manifested in the regionalized approach to CCS, which is focused in Alberta and directed toward the maintenance of oil and gas exploitation within that province. The federal government has its own levers, such as tax policy and innovation support, but climate and energy policy are deeply politicized in Canada, with implications for the exercise of power by both federal and provincial governments (Fertel et al., 2013; MacDonald, 2020).

The specificity involved in coordinating action and supporting CDR scale-up points to a further potential advantage of national-level policy studies for DACCS. Identifying the policy framework and mapping out the interconnections between policies provides a foundation to examine the political economy of DACCS. Political power and the ability to influence how DACCS is framed, is an important element that will impact the acceptability of DACCS (Buck, 2016; Bellamy, 2022). For example, the alignment of DACCS with existing resource structures provides a potential explanatory basis for the current government support of DACCS that requires further attention. The demand for CDR amidst the climate crisis will grow over the coming decades, along with the demand for NET-focused policy research. Thus, investigating the impact of DACCS politics on the transition process will be especially salient as the levels of technology deployment and CDR capacity rise.

Data availability statement

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

Author contributions

SC: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. NC: Conceptualization, Supervision, Writing – original draft, Writing – review & editing. JM-C: Supervision, Writing – review & editing. KM: Writing – original draft. VS: Funding acquisition, Supervision, Writing – review & editing.

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Conflict of interest

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

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2024.1338647/full#supplementary-material

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Expert insights into future trajectories: assessing cost reductions and scalability of carbon dioxide removal technologies

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Introduction: To achieve net-zero targets, it is essential to evaluate and model the costs and scalability of emerging carbon dioxide removal technologies like direct air capture with CO2 storage (DACCS) and bioenergy with carbon capture and storage (BECCS). Yet such efforts are often impeded by varying assessments of the climate impact and potential contributions of these technologies. This study explores the future costs and scalability of DACCS and BECCS to advance net-zero goals.

Methods: We analyze expert opinions on these technologies' potential costs and deployment scales for 2030, 2040, and 2050. Data was collected from 34 experts, comprising 21 DACCS and 13 BECCS specialists. They provided 90% confidence interval estimates and 'best estimates' for future costs and deployment under two International Energy Agency (IEA) policy scenarios—Stated Policies (STEPS) and Net Zero Emissions by 2050 (NZE).

Results: We find that BECCS costs start at a lower level but decrease more slowly, whereas DACCS costs decline more steeply from a higher initial cost. However, DACCS estimates varied significantly among experts, showing no convergence over time. Regarding potential scalability, both technologies are associated with substantially higher deployment under the NZE scenario. Yet the combined estimated capacity of DACCS and BECCS by 2050 is only about a quarter of the CO2 removals projected by the IEA for its NZE scenario (1.9 GtCO2).

Discussion: This study provides valuable insights into the future of DACCS and BECCS technologies in Europe, especially since our experts expect that DACCS and BECCS costs will be even higher (and deployment scales lower) than those predicted by recent IEA tracking, opening future research directions.

KEYWORDS
learning curves, direct air capture, BECCS, negative emissions, model uncertainties, expert elicitations

1 Introduction

The ultimate goal of the United Nations Framework Convention on Climate Change (UNFCCC) is to stabilize greenhouse gas concentrations in the atmosphere at safe levels to prevent hazardous anthropogenic interference with the climate system. This objective, as defined in the 2015 Paris Agreement, requires keeping the global temperature rise well below 2°C above pre-industrial levels, with efforts to limit the increase to 1.5°C. With global temperatures already 1.1°C higher than pre-industrial levels (IPCC, 2023), rapidly achieving carbon neutrality is imperative for a Paris-compliant trajectory. The Paris Agreement (Article 4.1) emphasizes balancing anthropogenic emissions with greenhouse gas removals in the latter half of this century. In pursuit of this balance, several countries including major economies such as the United Kingdom, France, the EU, Japan, South Korea, and the United States under President Biden, have set legally binding net-zero targets for 2050. Notably, major emerging economies such as China, Indonesia, and Saudi Arabia (targeting 2060), and India (targeting 2070) have also established carbon neutrality goals. Attaining these commitments solely through emission reductions is challenging. The energy sector, which faces rising marginal abatement costs and limited technical solutions in hard-to-abate sectors, exemplifies these difficulties (Davis et al., 2018). Consequently, achieving net-zero will require decarbonizing all viable sectors and utilizing Carbon Dioxide Removal (CDR) technologies to offset emissions from sectors that are difficult to decarbonize (Honegger and Reiner, 2018).

Reaching net zero requires political and economic decisions based on projections of technology deployment, which entails understanding the pace of cost reductions for different technologies, often referred to as 'learning curves', and assessing the potential scalability of these technologies under different policy scenarios. The modelling groups that contributed to the IPCC assessment report developed different socioeconomic development pathways for future CO_2 levels that are compatible with the Paris Agreement. These mitigation pathways include the generation of green electricity and e-fuels, replacing primary chemicals with new fossil-free alternatives, reducing total energy demand, improving energy efficiency, and removing residual emissions from hard-to-abate industries such as steel and cement.

CDR is a crucial element in most Paris Agreement-aligned scenarios. Conventional CDR, or 'nature-based' solutions, involve land-based carbon storage methods such as afforestation, reforestation, soil carbon sequestration, and biochar (Smith et al., 2023). In contrast, novel 'engineered removals' store carbon in oceans, geological formations, or products, including technologies like enhanced weathering and ocean alkalinization. Our study specifically examines Direct Air Capture with CO2 Storage (DACCS) and Bioenergy with Carbon Capture and Storage (BECCS), which chemically separate CO2 for potential long-term storage.

The IPCC (2018) Special Report on 1.5°C indicated that only one scenario (P1), which assumed a significantly downsized energy system, could meet the 1.5°C target without substantial reliance on CDR. However, the Sixth Assessment Report (AR6), which the IPCC published in 2022 (IPCC, 2022), suggests a more comprehensive use of afforestation, reforestation, BECCS, and, to a lesser extent, DACCS, to achieve the 2°C target. These scenarios reflect substantial uncertainties regarding the deployment scales of these technologies, which are influenced by social acceptability, institutional capacity, and deployment costs. AR6's Chapter Five further discusses how the scalability of emissions reduction and CDR are influenced by perceived and objective equity outcomes, trust in policymaking, socio-cultural preferences, and institutional governance capacity. Indeed, the (expanding) track-record of operational facilities shows that societal involvement in policymaking, building public trust and the existence of project outcomes that meet societal needs are often critical for successful deployment of these technologies (AR6; Clulow and Reiner, 2022; Erans et al., 2022).

While most models overlook these uncertainties, those that address them suggest significant implications for scalability. Accounting for cost uncertainty, for example, indicates a need for greater decarbonization in the 2020s to reduce long-term reliance on uncertain future CDR capabilities. According to one estimate, models that account for uncertainty predict a three-fold increase in renewable energy deployment by the 2030s compared to scenarios that do not consider uncertainty (Grant et al., 2021). From a policy standpoint, better modeling of these uncertainties could reduce reliance on CDR and pave the way for more ambitious emissions reduction commitments in the near-term. For policymakers to anticipate potential deployment trajectories and design effective support mechanisms, there is a need for reliable economic models that project cost and upscaling pathways for DACCS and BECCS. These models require two types of inputs; the uncertainty surrounding relevant parameters and expected best estimates for cost trajectories and the scale of deployment. Current cost data for these technologies is limited, mainly developed by private companies and not publicly available.

Our study investigates the future costs and deployment scale uncertainties of DACCS and BECCS technologies in Europe in 2030, 2040, and 2050. We also examine how future policies might influence these uncertainty levels. To gather experts' insights, we conducted 34 expert elicitations by interviewing 21 DACCS experts and 13 BECCS experts. Initially, experts were asked to provide their 90% confidence intervals for future costs, breaking down various cost items like Capex and Opex where possible, and then to give their 'best estimates'. These assessments contribute empirical data to the technology learning curves, which is crucial for projecting the future mitigation potentials of different options. Additionally, experts estimated the expected deployment scale of these technologies under two stylized policy scenarios: the International Energy Agency's Stated Policies (STEPS) and Net Zero Emissions by 2050 (NZE). This approach helps us understand how different policy frameworks could affect the deployment of DACCS and BECCS.

Following this introduction, our paper is structured as follows: Section 2 reviews extant studies about current and future DACCS and BECCS costs and scalability. Section 3 details our study's aims, research questions, scope and limitations. Section 4 describes our research methods and analytical tools, while Section 5 presents the results. Finally, Section 6 draws out conclusions, policy implications and recommendations for further research.

2 Literature review

2.1 Direct air carbon capture and storage

DACCS is a technology that addresses climate change by removing CO2 directly from the atmosphere. The process involves two main steps: (1) Direct Air Capture (DAC), which entails using chemical processes to capture CO2 from the ambient air; and (2) Carbon Storage, which entails injecting the CO2 into geological formations, such as depleted oil and gas fields or deep saline aquifers, where it is stored permanently and safely underground. Appendix A describes this technology in detail.

There are relatively few authoritative or peer-reviewed cost estimates of DACCS. Moreover, cost (and deployment) assessments vary widely because authors employ different analytical approaches and often start from divergent assumptions about cost drivers (summarized in Table 1). An early 2011 American Physical Society (APS) study estimated the cost of an aqueous technology similar to

TABLE 1 Summary of DACCS cost and scalability analyses.

Analysis	Approach	Cost estimate (if given)	Cost driver(s)	Estimated net zero contribution (if given)
Socolow et al. (2011)	Simplified costing approach used for early-stage industry projects: avoided cost for post-combustion CO2 capture from a coal power plant. OPEX/ CAPEX costs	780 X/t-CO2 avoided 550 $/t-CO2 captured	Improvements in components and systems; new sorbents, OPEX/ CAPEX costs	Estimates capture potential of hypothetical DAC facility/ system
Wilcox et al. (2017)	Thermodynamic analysis		Efficiency, carbon utilization outputs, energy needs, CO2 purity	
Deutz and Bardow (2021)	Lifecycle assessment		Energy source, absorbent choice, plant properties, efficiency	1% of global annual CO2 emissions by 2050
Brandl et al. (2021)	Archetypical CO2 capture process model	$14.4tCO2 (marginal cost when capture rate reaches above 90%)	Flue gas composition, policy initiatives, plant scale	
Ishimoto et al. (2017)	Review of literature and cost data from industrial sources	10 to >2500$/tCO2	Plant configuration, market size	
Keith et al. (2018)	Engineering and cost analysis for a 1 MT CO2/year DAC plant using Aspen process simulation	94–232$ per ton CO2 (levelized costs)	Energy source, costs, financial assumptions, choice of inputs and outputs; capital recovery factor	Same as Socolow et al. (2011)
Minx et al. (2018) and Fuss et al. (2018)	Literature review and review of IAMs	Near-term: $600-1000/tCO2 potential to decrease to 100–300	Capital cost, energy cost, regeneration and OPEX costs, sorbent costs, co-location cost savings, storage constraints	2050: 0.5–5 GtCO2 per year
Realmonte et al. (2019)	Long-term mitigation scenarios using TIAM-Grantham and WITCH IAMs	180 to 300 $/tCO2 (benchmarks taken from past studies)	Energy supply, sorbent production; carbon budgets imposed	3Gt/ year to 30Gt/ year (deployment scenarios not estimates)
Fasihi et al. (2019)	Literature review and techno-economic analysis of state of the art DAC technologies from an energy system perspective	2020: 222/133 2030: 105/60 2050: 54/32 Euro/tCO2 without/with utilization of free waste heat	Learning rates, choice of DAC technology and energy source, capital investment, energy demand and cost	
NASEM (2019)	Literature review, analysis of energetics, carbon footprints and economics based on liquid solvents and solid absorbents	$100 to $1000/tCO2	Private sector investment, technological development, solvent/ absorbent system, Capex, Opex	1 Mt./CO2 per year (baseline assumption of hypothetical plant not estimate)
McQueen et al. (2020a) (Frontiers)	Cost analysis of energy and capital needs of heat/ power generation, direct air capture and compression required by different configurations of gas and electricity	$250-150/tCO2 (estimates of costs associated with different technological configurations not temporal predictions)	Liquid-solvent design, leakage costs and energy source, compression, heat/power generation,	Unit plant capacity ~1 MtCO2/year
McQueen et al. (2020b)	Economic analysis of all aspects of DAC process including CO2 utilization, storage, energy source, transport, capture and injection costs	<$300/tCO2 per year (scenarios not estimates)	Economic incentivization, policy options, partnerships with geothermal and nuclear energy producers, sorbent DAC costs, energy access, TSM, co-location, market opportunities	19 MtCO2/year
Lackner and Azarabadi (2021)	Uses buy-down model to estimate the amount of capital investment needed to lower DAC cost to $100/ton CO2	100$/ton CO2 (a hypothetical benchmark not estimate) Levelized costs: 2030: 100 $/ton CO2 2040: ~65	Capital investment effects based on analogous technology costs, learning rate, economies of scale and modularity	

(Continued)

TABLE 1 (Continued)

Analysis	Approach	Cost estimate (if given)	Cost driver(s)	Estimated net zero contribution (if given)
IEAGHG (2021)	Global assessment of DAC costs based on technological maturity, energy costs, capital costs and capital investment	2020s (FOAK plants): ~$400-700/net-tCO2 2050s (NOAK plants): ~$150-200/net-tCO2	Energy source and cost, technological maturity, capital costs, capital investment, uncertainty, learning rates, policy support	Assumes a baseline unit plant size of 1 MtCO2/year
Hanna et al. (2021)	Novel IAM that incorporates financial investment, learning by doing, energy supplies with carbon cycle models in emergency deployment scenario	Levelized costs by 2025: 2018$ per tCO2 140–1100 depending on choice of DAC method and energy source	Significant near-term global investment (1.2–1.9% GDP) in DAC; choice of energy source; learning rates	Large removal achieved only after 2050: 2.2–2.3GtCO2 per year, potential for significant upscaling by 2075
Lackner et al. (2012)		$600/ t CO2 baseline goal	Economics, technology innovation, geophysical conditions, responses to leakage,	
McQueen et al. (2021)	Review of applications	2030: 150tco2$-240 2040: 100–170	Cost estimates for liquid solvent and solid solvent DAC based on properties including mass transfer, heat transfer and chemical kinetics; learning-by-doing; capital and operating costs	2030: 10X double installed capacity in 2020 2040: 20X installed capacity in 2020 2050
Grant et al. (2021)	Expert elicitation and IAM		Uncertainty; carbon prices	~0.0012 GtCO2 per year 2030: 0.282 2040: 2050: ~3 GtCO2
Ozkan et al. (2022)	Literature review		Technology-based economic development in: Contractor; sorbent; regeneration; energy source and needs; industry growth; CAPEX, OPEX and sorbent costs	
IEA DAC Report 2022	IAM and review of operational facilities	$125–335 /tCO2	Carbon pricing scheme, energy prices, facility configuration, capture technology, OPEX, CAPEX	Could meet NZE targets
Erans et al. (2022)	Literature review	94–600 $/tCO2 for high TRL DAC 60–10(4) for low TRL DAC	TRL, raising R&D funding, investment, supportive business and policy models, public acceptance, regulation, compliance, liability concerns	Potential CO2 removal (GtCO2/year) 10(−7) to 10(−6) (high TRL DAC) 10(0) to upper boundaries
IEA (2023b)	IAM and review of planned and operational applications	Without a carbon price: 49-270USD/TCO2 20 With a carbon price: −140 to 195 USD/tCO2	Application cost, solid or liquid technology, energy source, storage and use needs, carbon intensity of energy source, carbon pricing scheme/ policy, heat, electricity and CO2 prices, comprehensive: learning by researching, doing, economies of scale, location,	2030: 85 Mt. CO2 2050: 980
Young et al. (2023)	Bottom-up engineering economic model with technological learning projections	$100–600 tCO2 per year	Capital cost reduction via aggressive deployment; policy support to create market opportunities; learning; location; energy source; capital and energy prices	

that presented here (Socolow et al., 2011). The APS "realistic" case had costs of 780 $/t-CO2-avoided and 550 $/t-CO2-captured, where the "avoided" value includes emission from electricity supply outside the plant boundary. Using a similar methodology, Keith et al. (2018) estimate levelized costs of $94 to $232 per ton CO2 from the atmosphere. The comprehensive review of NETs by the NASEM

(2019) concludes that DACCS costs could span a wide range of cost estimates from \$100 to \$1000/tCO2 as a function of commercialization, technological development, choice of technology and capex and opex costs. More optimistically, Lackner and Azarabadi (2021) find that capital investment of several hundred million dollars would be sufficient to bring down the cost of DAC to \$100/ton. Another relatively early analysis that combines a review of earlier literature with an analysis of data from industrial sources estimates a much wider cost range spanning \$10 to over \$2500/tCO2. The well-known comprehensive IAM reviews by Fuss et al. (2018), Minx et al. (2018) and NASEM (2019) find near-term costs of \$600-1000/tCO2 and estimate potential decreases to \$100-300/tCO2, which are associated with significant, though not necessarily (climatically) sufficient CO2 removals of 0.5 to 5GtCO2 annually by mid-century.

Using a different approach, Hanna et al. (2021) investigate an emergency DAC program that receives vast investment of 1.2–1.9% of global GDP annually and estimate a significant annual removal potential of 2.2–2.3 GtCO2 by 2050, which rises to 13–20 GtCO2 by 2075. In this analysis, significant near-term global investment, choices of energy and learning rates are the major cost drivers, which result in costs below \$100/t by 2075 for some low temperature configurations. Later analyses that explore the influence of near-term investment and learning rates also reach relatively optimistic conclusions; with near-term costs falling from ~\$400–700 tCO2/year in the 2020s to ~\$65–170 tCO2/year by mid-century (e.g., McQueen et al., 2020b; Lackner and Azarabadi, 2021). By contrast, more recent analyses (e.g., Young et al., 2023) find that DACCS capital costs do come down with large-scale deployment, but overall costs actually plateau by 2050 at a higher level of \$100-600/t, reflecting both greater pessimism and also greater uncertainty over potential cost reductions. The role of uncertainty is also considered critical.

A handful of engineering and cost analyses estimate costs (and sometimes deployment scales) based on an assumed unit plant capacity (usually ~1 MtCO2/year). Most of these analyses reach relatively convergent estimates about potential cost reductions between \$100–300/ tCO2 by mid-century (e.g., Fasihi et al., 2019; McQueen et al., 2020a; IEAGHG, 2021). By contrast, Realmonte et al.'s (2019) assessment of long-term mitigation scenarios using the TRAM-Grantham and WITCH IAMs reaches relatively pessimistic conclusions despite using relatively modest cost benchmarks (\$180–350 tCO2) from past analyses. The authors foresee that demands on sorbent production and high energy inputs severely obstruct dramatic upscaling and estimate that the risk of relying on (unrealizable) DACCS at scale could lead to a global temperature overshoot of up to 0.8°C. Most similar to our analysis, Grant et al. (2021) conduct an expert analysis on DACCS, BECCS and afforestation/reforestation and find that a high uncertainty scenario is associated with 10 Gt CO2 more emissions reductions than a scenario that does not consider uncertainty.

There has been a significant growth in support for DAC projects over the past few years. The UK government was the first to establish substantial funding when it created the £100 m Innovation Fund to support DAC and other greenhouse gas removal options in Aug 2020. That funding was soon dwarfed by funding from the US Inflation Reduction Act, which included a 45Q tax credit of up to \$180/t. The US Government also made a \$3.5bn commitment to four large DAC hubs, of which the first phase was launched in Aug 2023 and included \$1.2 billion in funding for new large projects in Texas (led by Occidental Petroleum/Carbon Engineering) and Louisiana (led by Battelle, Climeworks/Heirloom). The U.S. Department of Energy (2022) also established an overarching objective, termed the Carbon Negative Shot, of reducing costs to \$100/tCO2 over the next decade. Ozkan et al. (2022) describe how progress needs to be made in terms of the contactor, sorbent, and regeneration to achieve \$100/ton of CO2 or less. The policy environment, particularly the ambitiousness of carbon pricing and use of other incentivization mechanisms, also takes on a more prominent role in more recent assessments, which are increasingly broader and multidisciplinary in their analysis of cost drivers and feasibility. Indeed, alongside technological development, design problems, the DACCS process and investment, more recent cost and scalability estimates also consider the likely implications of learning by doing, co-location, governance, policy support, and synergies with other CDR and, increasingly, other mitigation approaches (e.g., IEA, 2021, 2023b; Erans et al., 2022; Young et al., 2023). Perhaps a reflection of the larger number of moving parts, later estimates are somewhat more cautious than earlier (purely engineering or economic/ investment) analyses, with annual costs estimated to reach \$49–600 tCO2 by mid-century.

2.2 Bioenergy with carbon capture and storage

BECCS technology combines producing energy from biomass with capturing and storing carbon dioxide (CO2), potentially resulting in a net reduction of atmospheric CO2 and contributing to climate change mitigation efforts. Appendix B describes this technology in detail.

In general, earlier literature reviews are more optimistic in terms of scalability, with BECCS estimated to contribute between 1 to 21 GT CO2 annually by mid-century (Kemper, 2015; Minx et al., 2018) (see Table 2). The BECCS chapter of the comprehensive NASEM (2019) review mentioned above estimates an annual carbon removal potential of 10–15 GtCO2 per year by mid-century depending on commercialization, carbon flux, electricity cost and technological development. Later literature reviews tend to posit more cautious scalability estimates. For example, Consoli (2019) estimate 16 GTpa by 2100. Interestingly, lower scalability predictions are not obviously linked to higher cost estimates as many more recent cost estimates such as Consoli's foresee notably low costs—as low as 20\$/tCO2 in some sectors.

The breadth of cost and scalability estimates reflects the large number of moving parts and potential sources of uncertainty of BECCS deployment. Compared to DACCS, the BECCS process encompasses a greater number of steps including processes required for biomass production, processing into fuel or electric power, CO2 storage, investment in the power plant or biofuel production facility, CCS infrastructure, OPEC costs and the possibility of offsetting costs from potential revenues from energy generation (Culow and Reiner, 2022). While economies of scale are expected to reduce costs until around mid-century, after a certain point, most analyses—whether from political economy (Honegger and Reiner, 2018), IAM (Fuss et al., 2018; Minx et al., 2018; NASEM, 2019; Butnar et al., 2020) or expert elicitation perspective (Grant et al., 2021)—concur that cost reduction and scalability will eventually be obstructed by limited resource inputs—mainly relating to land (and to a lesser extent water) for biomass generation and CO2 storage.

TABLE 2 **Summary of BECCS cost and scalability analyses.**

Analysis	Approach	Cost estimate (where given)	Cost driver	Estimated net zero contribution (where given)
Kemper (2015)	Literature review, particularly AR5		TRL, economic feasibility, sector, biomass crop, energy source and cost	2030: 2.5–21 Gt CO2 per year 2050: 1–21 Gt CO2 per year
Pour et al. (2018)	Case study of municipal solid waste power plant		Biomass source, economic incentives, environmental impact, resource needs	2.8 billion tCO2/year by 2100
Fuss and Johnsson (2021)	Mixed methods: review of IAMs and case study analysis (Sweden)		National conditions: point source availability, policy environment, social acceptance	
Fajardy et al. (2021)	Economic Projection and Policy Analysis (MIT Model)	$240 tCO2	Economics, global commodity prices, accounting system, environmental/ political constraints	
Fajardy et al. (2019)	Literature review and life-cycle analysis		Specific characteristics of the plant, side-effects, governance	
Donnison et al. (2020)	Systems service value and land-use optimization analysis		Energy needs, feedstock, trade-offs with other priorities, impacts on ecosystem services, co-benefits, welfare implications	
Minx et al. (2018)	Literature review 2011–2018	59–250$/tCO2 estimate for 2060	Land, biomass, CO2	2050: 2.4 GtCO2/year 2100: 69.7 GtCO2/year (flux estimates)
Fuss et al. (2018)	IAM review	US$100–200/ tCO2 by 2050	Land availability, biomass crop, source of CO2 capture	2050: 0.5 – 5GtCO2
Honegger and Reiner (2018)	Literature review and political economy analysis	~$200tCO2 by 2050	Political economic barriers, governance framework, policy incentives	
NASEM (2019)	Literature review, analysis of commercial status, energy-based carbon removal pathways, process economics and biomass supply potential	36–87 $/tCO2 depending on carbon capture approach	Commercial status, carbon flux, electricity cost, technological development	2050: 10–15 GtCO2 per year
Grant et al. (2021)	Expert elicitation and IAM		Consequences of uncertainty on investment and deployment	2030: 0.43 GtCO2 per year 2040: 1.7 2050: 2.58
Consoli (2019)	Literature review and operational facilities	20–288 US$/tCO2	Sector, modularity, biomass supply	2030: 0-8Gtpa Rising to 16 Gtpa by 2100
Butnar et al. (2020)	IAM review and bottom-up TIAM-UCL modelling	TIAM-UCL: $20–340/ tCO2 by 2050	Facility configuration; biomass availability, TSM	
IEA (2023a)	IAM and review of applications			2030: 50 Mt. CO2/year

Despite the high variability of estimated costs arising from the modularity of the technology, and widespread expectation that costs in at least some sectors will fall below the industry target ($100/tCO2), most analyses suggest that BECCS will contribute around 2.5GtCO2 by mid-century —only a fraction of the 1380 MtCO2 pa required to be NZE-compliant, with the most recent IEA (2023a) tracking predicting a relatively modest scalability of 50MtCO2 pa by 2030.

In summary, the existing literature reveals that while there are some emerging efforts to estimate future costs and scalability potential for DACCS and BECCS, the available estimates are sparse and divergent, which could potentially hinder policymakers' decision-making processes.

3 Aim, scope and limitations

Our study aims to provide model-builders and policymakers with a better understanding of the uncertainty surrounding the costs and scalability of DACCS and BECCS technologies. The following section presents the contributions as well as scope and limitations of the research. Specifically, we aim to understand the current state of DACCS and BECCS technologies and how they may evolve in the future as well as the potential scalability of these technologies under different policy scenarios. Due to the lack of data on these technologies, we undertook expert elicitations to answer the following research questions:

1) How do the costs of DACCS and BECCS technology change over time? Does the uncertainty increase or decrease?
2) What is the potential scale of BECCS and DACCS that experts project will be deployed under the IEA STEPS and NZE policy scenarios? How does uncertainty evolve under the different policy scenarios?

This research is developed along three axes, which have previously been addressed separately but not collectively: (1) comparing DACCS and BECCS technologies; (2) providing uncertainty knowledge on costs and scalability estimates; and (3) gathering novel qualitative insights to explore factors that can influence the cost and scalability of the technologies. Apart from its novelty, our research can assist in improving the models used to project and analyze future decarbonization scenarios. Our expert elicitation study provides valuable insights into the evolution and future prospects of DACCS and BECCS technologies in Europe for the short (2030), medium (2040), and long term (2050). It offers detailed assessments of the costs, scalability, and uncertainties associated with these technologies under varying policy scenarios. Additionally, the interviews shed light on the political and technological challenges Europe may face in implementing these technologies.

In this study, we interviewed a total of 34 experts from October 2022 to January 2023, focusing on DACCS (21 experts) and BECCS (13 experts), with the difference in numbers due to availability and time constraints. Most experts were from the academic or research sectors in Europe. The minority of experts that were not based in Europe were briefed to base their responses on the European context. We opted for live interviews over online questionnaires to capture qualitative insights alongside quantitative data, allowing for dynamic discussions and deeper understanding of expert opinions. This approach has helped to establish a foundational database of current expert judgments on DACCS and BECCS. Furthermore, the design of our elicitation protocol facilitates this research to be extended in the future, for example, by adding new expert interviews on DACCS and BECCS to the existing database or interviewing experts on other carbon dioxide removal solutions.

While a large number of studies employ expert elicitation to evaluate the potential scalability of CCS more broadly (e.g., Abdulla et al., 2021; Machado et al., 2022), only a handful investigate the deployment of individual CDR options. For example, Shayegh et al. (2021) conducted an expert elicitation to assess judgments on the future costs, capacity, energy requirements, and downstream use of CO2 from solid and liquid sorbent DAC technologies. Their analysis of 18 expert elicitations from industry and academia found that while DAC costs are likely to decrease significantly by mid-century, they could remain about twice as high as the industry target of $100/tCO2. Vaughan and Gough (2016) engaged 18 climate and BECCS experts and concluded that Integrated Assessment Models (IAMs) incorporated unrealistic assumptions about BECCS and its supporting infrastructure. Izikowitz et al. (2023) consulted 54 experts on various criteria to identify optimal locations for DACCS plants and found that the US, Canada, China, and Australia are most favorable. Another recent study by Perdana et al. (2023) analysed 260 expert opinions on the impact of different innovations for achieving Net Zero focusing on technological and non-technological decarbonization solutions (Perdana et al., 2023).

These previous elicitations have either concentrated on a single technology or used questionnaires for data collection. Our work, however, aims to highlight the differences between DACCS and BECCS technologies not only in terms of costs but also scalability under different policy scenarios and utilizes a methodology that facilitates a deeper understanding of expert opinions. Consequently, the methodologies, questions, and system assumptions used in these studies differ from ours, making direct comparisons challenging. The relatively novel status of DACCS and BECCS technologies and narrow pool of experts with expertise on both technologies necessitated us to select separate groups of experts for each technology. We sought to minimise potential biases arising from differences between the groups of experts by employing a common interview protocol and framing cost and scalability forecasting around the same (STEPS and NZE) policy scenarios to facilitate novel comparisons to be made about expert opinions on both technologies. The interviews were semi-structured, which ensured that respondents were asked to provide insights on key issues under investigation while providing flexibility and opportunity for individual respondents to provide more detailed insights which were recorded as qualitative insights or forego parts of the interview, for example, if knowledge was lacking on costs.

Our study faces certain limitations. DACCS and BECCS technologies encompass a great degree of heterogeneity in terms of the technologies, processes, and methods employed. For example, various solvents can be utilized in DACCS to capture carbon dioxide from the atmosphere, while BECCS can utilize a diverse range of biomass feedstocks, including different types of crops, for carbon capture and storage. Considering the relatively small scale of our study, we established strict boundaries around DACCS and BECCS technologies to ensure the comparability of expert responses. This entailed delineating a set of specific assumptions regarding the technologies and type of plants involved in both DACCS and BECCS, which are detailed in the methods section. The primary purpose of setting these boundaries was to facilitate comparability across the responses of different experts, ensuring that our analysis was coherent and focused on directly comparable insights. Consequently, our findings are not generalizable beyond these specific technological boundaries. Therefore, our study does not consider systems that involve other forms of carbon storage, such as in cement, chemical products, or e-fuels.

Secondly, the results are inherently linked to the background, expertise, and location of the participating experts. Most interviewees had academic backgrounds in engineering or natural sciences and were based in Europe. To contextualize the data and address limitations related to specific regional factors, we supplemented quantitative findings with qualitative insights from these experts.

Finally, expert elicitations are susceptible to biases, which can stem from the methodology, experts preparation, or the interviewers' own skill (Apostolakis, 1990; Morgan, 2014). We minimized common biases by employing a well-tested protocol and ensuring that experts were thoroughly briefed. However, cognitive biases such as anchoring or overconfidence, which are common in social sciences, are more challenging to eliminate. Anchoring bias can lead experts to overly rely on specific information like the 2020 cost breakdown, while overconfidence might result in inflated self-assessment of one's own knowledge (Block and Harper, 1991). To mitigate these biases, experts were encouraged to use simple models to predict future costs and scalability and to consult relevant literature during the interviews as needed.

4 Method: Expert elicitation

DACCS and BECCS are technologies that have been tested at pilot scale and are in the process of being deployed at larger scale. Despite this, the amount of public information on active projects is limited. There exists an array of qualitative forecasting methods which facilitate the creation of knowledge on subjects where real-life data is limited. For this research we decided to undertake expert elicitation, a method that supports the systematic gathering of quantitative and qualitative expert opinions. Our sample size was similar to those of previous studies. The in-person aspect ensures that experts provided quality answers, while giving them the freedom to provide context to the quantitative figures.

Historically, expert elicitations stem from probabilistic risk assessments of technological systems such as nuclear power plants or chemical process facilities. Interviewing a variety of experts using a formal protocol is one of the few ways to generate knowledge and quantitative data to characterize the risk or frequency of certain hazardous events. In past decades, expert elicitations gained attention in the field of climate science, particularly for IAMs or climate change modelling (Apostolakis, 1990). Expert elicitations have also been conducted for individual negative emission technologies (Vaughan and Gough, 2016; Shayegh et al., 2021; Perdana et al., 2023), but none employ a holistic elicitation method and use the same set of questions to compare DACCS and BECCS costs and scalability. In a field where there is so much uncertainty and where future trajectories are highly dependent on current political decisions, it is imperative to use a structured method. Expert elicitations typically constrain expert answers to a particular system or framework. Although this impedes the generalization of findings to a wider range of technologies, it allows for a coherent and systematic modelling of uncertainty for a set of given technologies (Zickfeld et al., 2010; Rai, 2013).

The experts for this elicitation were selected based on evidence of previous research or activities undertaken in this area. We compiled a database of more than 500 technical experts who have worked on carbon dioxide removal, who were then reviewed in terms of their level of expertise to answer the questions under consideration. 112 DACCS experts and 88 BECCS experts were contacted by email. Mailchimp was used to reach out to most of the experts. In total, 21 experts for DACCS and 13 for BECCS agreed to participate in the elicitation (equivalent to response rates of 19 and 15% for DACCS and BECCS respectively).

The selection of experts for both technologies included a diverse range of participants, encompassing academics and researchers from universities, research institutes, or think tanks and government, as well as practitioners working in firms developing these technologies. Moreover, they also are drawn from a number of different disciplines and background, so some will have more expertise in technical, or economic or policy dimensions. We recognize the variation in perspectives, motives, and assumptions across these distinct groups. Despite these differences, each expert could contribute a high level of familiarity and expertise with the technologies. Since perspectives on cost and scalability can vary, leading to differing degrees of optimism, it is crucial to encompass the entire spectrum of expert opinions. By including a wide range of viewpoints, we mitigate the risk of bias—whether overly optimistic or pessimistic—that could arise from focusing solely on one subgroup of experts. This comprehensive approach ensures a more balanced and representative understanding of the field.

The study was developed in the context of the European Commission Horizon 2020 Project, NEGEM. We therefore carried out two pilot elicitations for both DACCS and BECCS using experts from within the NEGEM consortium. The goal of these interviews was to ensure proper understanding of the system assumptions and questions. Despite some minor changes that were made to the reference assumptions following the pilots, the responses of these four experts are included in the larger study as none of the changes significantly affected the overall consistency of the questions. Table 3 lists the experts (including their primary affiliation) who participated in the expert elicitation in alphabetical order.[1]

Due to the multidisciplinary scope of the research, a mix of experts from academia, industry, policy, and technology fields was sought. Academics represent the largest share, comprising 62% of DACCS experts and 81% of BECCS experts, respectively.

4.1 Elicitation protocol and assumptions

Prior to the elicitation, experts were sent a two-pager along with the meeting invitation. The goal of this document was to inform experts on the NEGEM project and technological and policy assumptions used in the study. While these are presented in detail for each technology in Appendix C, it is worth noting that starting cost and scale assumptions were based on recent operational facilities; DACCS was based on the Climeworks process with total costs of 581 Euros/CO2t operating at ~1 Mt. CO2 capture capacity; and BECCS assumptions were derived from a Drax power plant with total costs of 172 Euro/CO2t operating at 909.5 Kt CO2 capture capacity.

A multi-page Excel-based protocol was developed to facilitate the visualization and organization of interview responses. The protocol included expert information, a review of system assumptions, questions on costs and energy usage (for DACCS) or costs, feedstock type and land usage (for BECCS), scalability under the two policy scenarios, and limiting factors and enabling policies.[2]

Experts provided their details, and then responded to quantitative questions about costs, energy, and other variables for 2030, 2040, and

1 Subsequent to the expert interviews conducted for our study, we extended an invitation to one of our interviewed experts, Zeynep Clulow, to join the authorial team. Her inclusion was specifically due to her demonstrated expertise in DACCS, which proved invaluable during the manuscript revision process and in the interpretation of our results.

2 The protocol can be obtained from the authors on request.

TABLE 3 Interviewed experts on DACCS and BECCS technologies and their principal affiliation.

DACCS experts	BECCS experts
Alauddin Ahmed – University of Michigan	Astley Hastings – University of Aberdeen
Eadbhard Pernot – Clean Air Taskforce	Caspar Donnison – University of California, Davis
Gaurav Sant – University of California, Los Angeles	Catriona Reynolds – Drax
Greg Mutch – Newcastle University	Clair Gough – University of Manchester
Howard Herzog – Massachusetts Institute of Technology	Constanze Werner – Potsdam Institute for Climate Impact Research
Jennifer Wilcox – US Department of Energy	Eric Larson – Princeton University
Mai Bui – Imperial College London	Fabian Levihn – Stockholm Exergi
Maria Erans – King Juan Carlos University	Ilkka Hannula – International Energy Agency
Matteo Gazzani – Utrecht University	James Palmer – University of Bristol
MennatAllah Labib – University of Edinburgh	Mathias Fridahl – Linköping University
Nixon Sunny – Imperial College London	Mathilde Fajardy – International Energy Agency
Noah McQueen – Heirloom	Stefan Grönkvist – KTH Royal Institute of Technology
Peter Kelemen – Columbia University	Stephen Smith – University of Oxford
Petri Laakso – Soletair Power	
Selene Cobo-Guttierrez – Swiss Federal Institute of Technology (ETH) Zurich	
Shareq Mohd Nazir – KTH Royal Institute of Technology	
Stefano Brandani – University of Edinburgh	
Stuart Haszeldine – University of Edinburgh	
Volker Sick – University of Michigan	
Webin Zhang – Nottingham Trent University	
Zeynep Clulow – University of Cambridge	

2050, including minimum, maximum, and best estimates to represent a 90% confidence interval. The protocol also allowed experts to assess scalability under different scenarios, discuss technological variations, and rank limiting factors and enabling policies, and add new elements where necessary. Supporting information in the form of tables and graphs was available for visualization, review and amendment of answers.

In total, four different sets of data were examined for DACCS and BECCS technologies: future total costs, future breakdown costs, and scalability under the STEPS and the NZE policy scenarios, which are expected to substantially affect scalability.

Costs were described along three dimensions: (1) cost type: total cost, capex, opex, heat and fuel, feedstock, revenue, and CO2 transport, storage and monitoring; (2) year: 2030, 2040, or 2050; and (3) estimate type: minimum, maximum, or best estimate (BE). First, the trajectories of all obtained min-max ranges were analyzed using a scatterplot. For this, only the total costs and breakdown total costs are discussed. To portray the spread of the answers, five experts were selected, and their results are presented in detail. These experts were selected according to their 2030 cost best estimate. The smallest, second smallest, median, penultimate, and largest best estimates were chosen. The second smallest and penultimate expert responses were included to prevent affording too much importance to possible outliers. The trajectories of these experts represent the span of responses and are discussed in detail using insights from the respective experts.

We next asked experts their views on the potential scalability of both technologies. The scalability answers were also characterized along three dimensions: (1) the policy framework; STEPs or NZE scenario (2) variable type: minimum, maximum, or best estimate and (3) year: 2030, 2040 or 2050. The International Energy Agency's Stated Policies (STEPS) and Net Zero Emissions by 2050 (NZE) scenarios were used as the basis for two key stylized scenarios to explore how different policies could influence the deployment of these DACCS and BECCS. The STEPS is a scenario where only existing or proposed policies are in place, while the NZE describes a scenario whereby the global energy sector reaches net-zero emissions by 2050. For this part of the elicitation, we describe stylized versions of these two scenarios and experts were asked what role DACCS and BECCS could play in those scenarios. They were also free to assume the deployment of technologies other than those specified in the previous stage of the elicitation. Appendix D provides a description of these scenarios.

As for the costs, the uncertainty of the scalability results was analyzed through the evolution of the min-max ranges throughout the years and within the experts. For this, we discussed the trajectories of all potential scale results under the two policy scenarios in 2030, 2040 and 2050. Five representative expert answers were selected to gain a better understanding of the span of these results. Since scalability depends on the policy scenarios, two sets of experts were chosen for each technology. The first batch of experts was selected based on the potential scale best estimate under STEPS in 2030. The second batch of experts was chosen based on the potential scale best estimate under NZE in 2030. For both sets of experts, the smallest, second smallest, median, penultimate, and largest potential scales were selected, and the best estimate and min-max trajectories analyzed. Both under STEPS and NZE, up to three experts had the same scalability as the median result of BECCS scalability in 2030. Due to the already low number of respondents, showing all these experts in the trajectories analysis would have been counterproductive. For this reason, the median result of the last expert interviewed was selected. Uncertainty is additionally analyzed using the average widths of the min-max ranges. As explained above, a narrow width indicates that experts agree on the min-max range and are more confident in their predictions in a certain year. The percentage changes are also indicated to capture the increase or decrease in uncertainty over a 10-year period. Finally, we compared the potential scale best estimates of the technologies under both policy scenarios to understand the effect of policies on future scalability.

Qualitative insights gathered during the interviews are used to discuss the results. During our interviews with the experts, qualitative insights, including expert views and comments, were recorded and transcribed. Important or recurring insights were then collated into a separate document and categorized according to various themes reflecting either specific questions of the protocol (like comments on assumptions, future costs and scalability) or transversal themes like barriers and factors limiting each technology. This data provided a rich context for explaining our results, and while they have been anonymized to maintain confidentiality, we have included selected quotes to substantiate and illustrate the points made within our manuscript. This further analysis serves illustrative purposes and adds nuance to our quantitative analysis of expert opinions and expectations. However, it is important to note that these insights are not intended to be exhaustive or generalizable, but rather to enrich the understanding of the specific contexts within which the results were obtained.

5 Results and discussion

This section discusses the results from the expert elicitations by focusing on both the uncertainty range and the best estimates, scalability under the different policy scenarios, and, finally, limiting factors and enabling policies. This order of presentation is motivated by the elicitation methodology where uncertainty ranges were probed before the best estimates. Importantly, the numbers used in this section do not correspond to the order of the expert list and all expert answers were anonymized.

5.1 Cost uncertainties

The following sections investigate the trajectory and evolution of uncertainty of DACCS and BECCS technology costs in 2030, 2040 and 2050 using the elicitations for both the total costs and the cost breakdowns.

5.1.1 DACCS costs uncertainty

Figure 1 shows the ranges provided by all experts in €/tCO_2 for DACCS total costs trajectories over the years. Of the 21 DACCS experts, 18 provided an estimate of total costs, with 13 also giving a cost breakdown.

There is a clear disparity across experts with some providing very narrow ranges and others spanning over two orders of magnitude. Starting in 2030, there is a tendency for experts that gravitate towards higher costs to also provide wider min-max ranges while those gravitating towards lower costs provided narrower ranges. This can indicate that the higher the cost, the larger the uncertainty of the experts or that experts which are confident in their belief of attaining low costs provided narrower intervals.

Experts 10, 12, 13, 14 and 15 did not provide a detailed breakdown of the costs. In most cases, reluctance to give cost breakdowns stemmed from experts' (self-perceived) lack of expertise and/or knowledge about the technology's different cost items. One expert did not offer cost breakdowns, for example, because of their 'lack of technical expertise around the component cost items [of DACCS]' (DACCS Expert 15). Similarly, another expert opted not to give cost breakdowns because of the high uncertainty surrounding 'too many moving parts' (DACCS Expert 13).

On comparing the total costs and total costs obtained from the cost item breakdown (from here on called 'breakdown cost'), it is apparent that experts that gave a breakdown of the costs tended to provide cost ranges that span higher than the five experts which only provided total costs. One possible explanation for this is that by separating the costs in different items, a buffer for uncertainty is added to each item which leads to higher overall costs.

No expert employs the 2020 reference costs (provided to respondents in the two-pager) for their 2030 costs, although some said that they used it as a starting point and then assumed some learning and gains from upscaling over the intervening seven years (specifically, Experts 6, 10, 11, 15, 16, 10 and 18). A minority of experts said that the 2020 reference costs were too low and instead based their assessments on different (higher) starting costs that they regarded as more accurate reflections of world average costs (Experts 8 and 13). Strikingly, some experts do not even include that starting point within their min-max ranges for 2030. Nevertheless, when asked if they agreed with the 2020 starting costs, most DACCS experts answered affirmatively. Half of the experts' ranges lie outside of the reference provided, which further indicates that our experts answered the questions according to their own knowledge without being strongly anchored by the reference costs. All expert ranges decrease throughout the decades, except for expert 11. This expert provided a very wide range that does not change throughout the years, skewing the average min-max range over the years. This expert expected that different cost components would follow contradictory trajectories which would result in consistently wide ranges: for example, 'changing sorbent chemistry might reduce OPEX, it would also increase CAPEX' (DACCS Expert 11). In the interviews, experts consistently commented that extrapolating future energy costs was difficult. Reasons given include the volatility of the energy market driven in part by the Russian invasion of Ukraine (DACCS Expert 11), increasing energy prices throughout Europe (DACCS Expert 11, 13 and 18), and the uncertainty surrounding the rate of adoption of renewable energy and the timing of fossil phase-out in the European grid (DACCS Experts 10, 11, 18, 20 and 21), uncertainty over the investment in DACCS (DACCS Experts 12 and 21) and 'how quickly the voluntary market will saturate in Europe' (DACCS Expert 21). A number of experts mentioned the uncertainty regarding the ambition and stringency of European energy policy as a justification for the wide ranges (DACCS Experts 1, 10, 11, 12, 15 and 16). Although not stated explicitly by our experts, hopes for energy prices to settle back to pre-war levels could explain the decrease of the energy cost min-max ranges over time.

Due to the limited pool of experts interviewed and dispersed nature of the estimates, the data cannot undergo traditional inferential statistical analysis. As shown in Table 4, the smallest, second smallest, median, penultimate, and largest, best estimates were selected from the pool of 2030 cost best estimates to represent the obtained data and span the space without giving too much weight to single outliers. Figure 2 and Table 5 show the trajectories of the min-max ranges of these selected experts over the years. Experts 11* and 18* are indicated with an asterisk as they provided a cost breakdown.

Of the five selected experts, experts 11*, 15 and 18* believe in a general reduction of costs. Expert 18* uses the 2020 starting costs as a maximum point for 2030 and 2040 costs. Expert 15 starts with the highest costs and ends in a similar range as the median cost in 2050. This could point again to the behavior that experts that start with large costs tend to decrease these more over time than experts that start with smaller costs. Finally, despite a decrease in costs over time, Expert 11* provides high costs and has a 2050 best estimate that is higher than the 2020 starting costs.

Expert 14 has a constant min-max range and best estimate over the three decades. This expert's reasoning is that by 2030, DACCS will rely 'only [on] processes which are already in industrial use. There may be some economies of scale, [but DACCS] will not be cheaper'. Finally, DACCS Expert 10 shows a min-max range and best estimates which shift right. As previously highlighted, increasing costs in the first years of deployment of a technology is not uncommon. Here, the increase in minimum costs is due to the belief that, while it is 'very likely that innovation… [in capture methods reduces] capex and opex, …

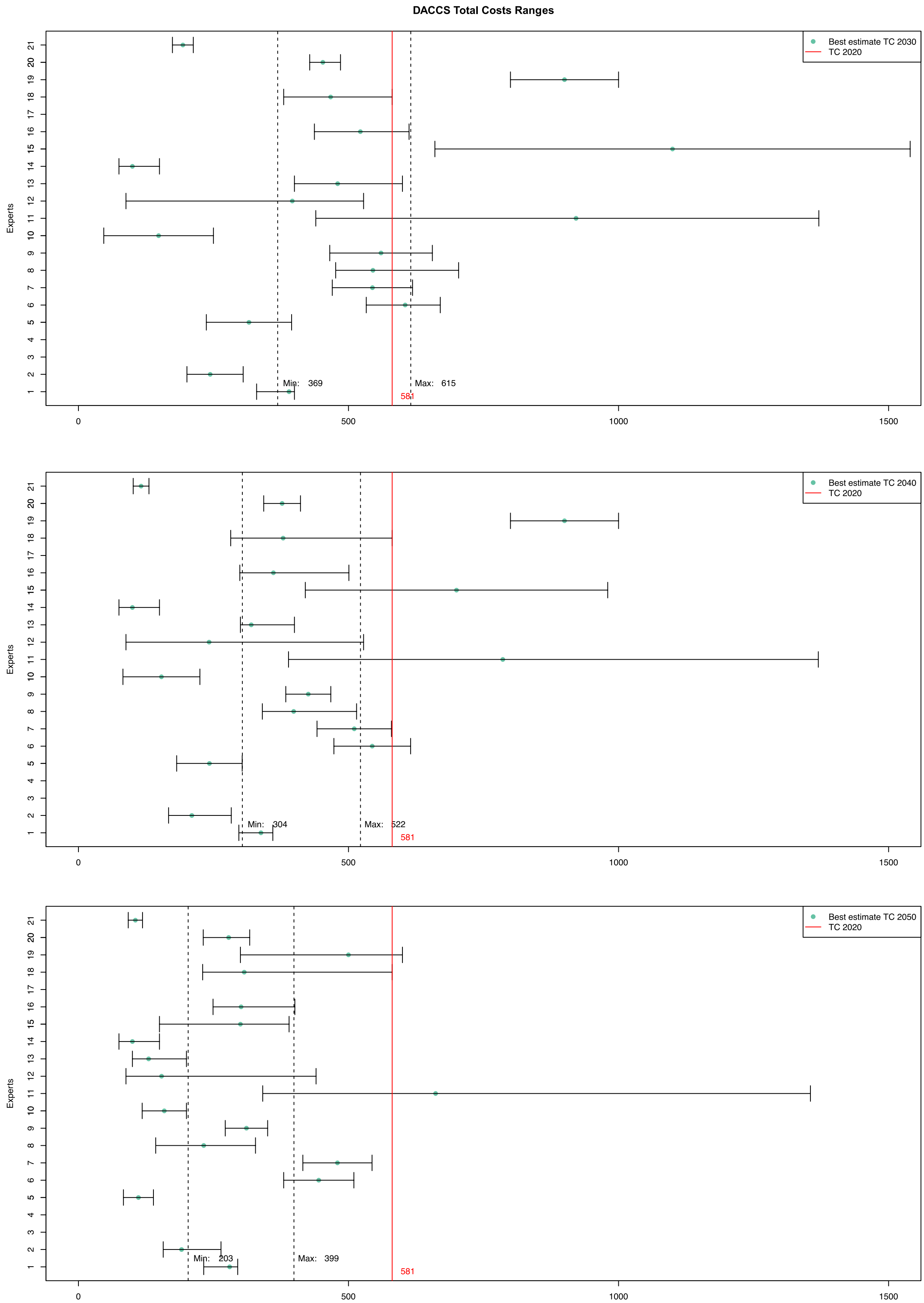

FIGURE 1
DACCS total costs ranges. DACCS total costs estimates with minimum, maximum, and best estimate of each expert in €/tCO_2. Figures are given for 2030, 2040 and 2050. Best estimates are the blue dots, and the 2020 total cost is shown by the red line. Dashed lines show the average min and max ranges.

TABLE 4 DACCS total cost best estimates of selected experts for 2030, 2040 and 2050.

DACCS total costs BE (€/tCO_2)	Min (Expert 14)	Min + 1 (Expert 10)	Median (Expert 18*)	Max – 1 (Expert 11*)	Max (Expert 15)
2030	100	149	467	921	1100
2040	100	154	379	786	700
2050	100	159	307	661	300

A star indicates experts that provided a breakdown of the costs.

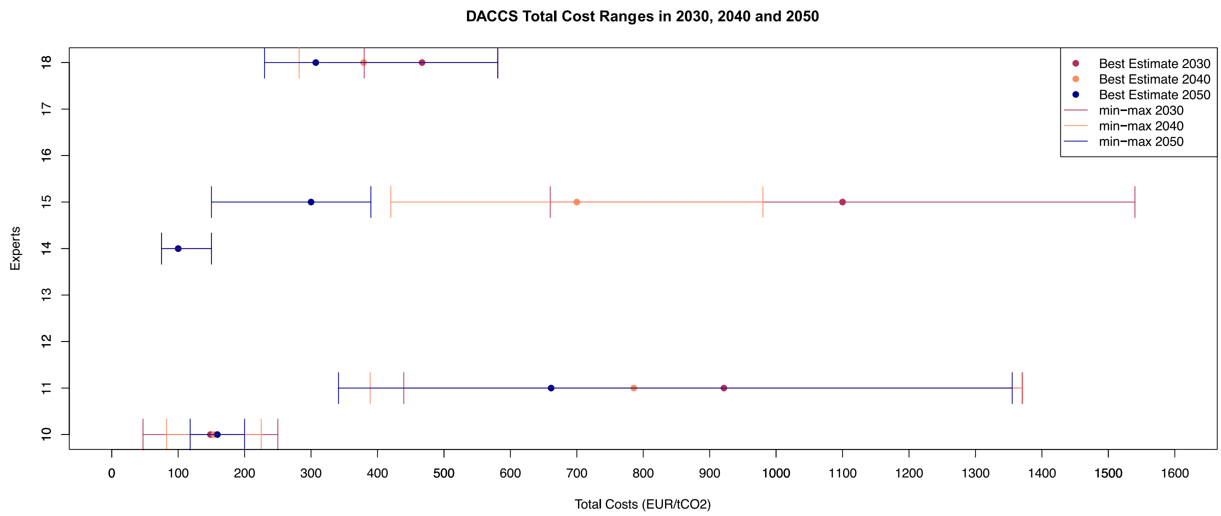

FIGURE 2
DACCS total cost ranges in 2030, 2040 and 2050. DACCS total cost range and best estimate evolution of five selected experts in 2030, 2040 and 2050.

TABLE 5 DACCS costs min-max range of selected experts for 2030, 2040 and 2050.

DACCS total costs min-max range (€/tCO_2)	Min (Expert 14)	Min + 1 (Expert 10)	Median (Expert 18*)	Max – 1 (Expert 11*)	Max (Expert 15)
2030	75–150	47–250	380–581	440–1,370	660–1,540
2040	75–150	83–225	282–581	389–1,370	420–980
2050	75–150	118–200	230–580	341–1,355	150–390

A star indicates experts that provided a breakdown of the costs.

you might need to pay a lot more for transport and storage' (DACCS Expert 10). However, the min-max range, or the uncertainty range of this expert narrows over the years. This again could indicate that experts which believe that low costs can be attained in 2030 are confident in this prediction and provide narrower intervals.

To conclude, many experts assumed that the introduction of more renewables into the energy grid would reduce energy costs, and that novel and more efficient sorbents will reduce capex and opex costs by 2050. Additionally, experts also mentioned that minimum costs can be capped by technological or thermodynamical feasibility. For example, when making minimum cost predictions, DACCS Expert 19 reasoned that 'we have, historically, not been able to get much improvements in… solvents and sorbents developed for DACCS and industrial applications.' Similarly, another expert felt that DACCS cost reductions will eventually be limited as 'old industry [used for DACCS compression] is already optimised' (DACCS Expert 18). Another expert perceived a fundamental design problem: 'DACCS [will be] locked in a certain technological design space due to sorbent' (DACCS Expert 4). These factors are expected to constrain the minimum to certain ranges below which the costs cannot feasibly go.

Looking at the uncertainty within experts, Table 6 shows the average width of the min-max ranges of the costs throughout the decades and its relative percentage changes. It is important to note that these figures are not actual costs but the average difference between the minimum and maximum. A greater width indicates less expert agreement on the costs and a positive percentage change indicates increasing uncertainty for that cost item. These figures show that, on average, the five experts who only answered the total cost question provide wider ranges than those that also answered the cost breakdown questions.

Looking at the evolution in uncertainty over the years, the percentage changes of the total costs decrease compared to the

TABLE 6 DACCS min-max range width average across experts in €/tCO_2 (the percentage change for each decade is provided in parentheses).

DACCS min-max average width (€/ton CO_2)	Total costs (18 experts)	Breakdown costs (13 experts)	Capex	Opex	H&F	TSM
2030	246.46	202.92	45.68	43.60	106.11	7.53
2040	218.58 (−11%)	201.28 (−0.8%)	45.45 (−0.5%)	45.45 (+4.2%)	102.48 (−3.4%)	7.90 (+4.9%)
2050	195.81 (−10%)	205.79 (+2.2%)	45.67 (+0.5%)	48.10 (+5.8%)	103.40 (+0.9%)	8.62 (+9.1%)

breakdown costs. The increase in uncertainty when experts provide a cost breakdown of the technology can be due to two factors. First, it could stem from a difference of opinion: the five experts that did not provide a cost breakdown could be cost optimists and be certain of a strong reduction in costs. Second, providing a breakdown of the costs could lead to an overhead or a "safety-range" that is added to all cost items, leading to an average increase of the range width over the years. To conclude, these results could suggest that experts that provide a cost breakdown agree more on their answers and know that they cannot predict the far future as well as the near future.

To summarize, the trajectories and uncertainty in DACCS costs point to the following results. First, higher costs in 2030 seem to lead to an increase in expert uncertainty while experts with lower starting costs seem to be more confident. Second, experts which provide a cost breakdown seem to agree more on the min-max interval (smaller ranges) and are less certain of future costs (increasing percentage change).

5.1.2 BECCS costs uncertainty

For BECCS, 13 experts were interviewed in total, 9 experts provided total costs and 6 of those were able to also break the costs down into different items. Figure 3 shows the trajectory of expert total costs, min-max ranges and best estimates in 2030, 2040 and 2050. Expert 1 did not answer the cost questions and is not included in the graphs. Expert 4 expected efficiency levels and (high) TSM costs to remain fairly constant over time and has a min-max range that is the same as the best estimate in 2030 and 2040.

Particularly when compared with DACCS, there is widespread agreement over the min-max ranges of the total costs as seen by the overlapping intervals (Figure 3). Unlike DACCS, we cannot state that the higher the costs, the larger the min-max interval due to the small sample size.

Expert 2 shows an interesting behavior. For this response, the min-max range is relatively narrow in 2030 before widening in 2040 and 2050. This expectation appears to be based on the belief that deployment costs 'depend on where you put the BECCS… [project developers] would go to the optimal [sites] ones first… [then] smaller unit [deployments will be] situated in more remote places which are more expensive' as they are located further from CO_2 transport and storage infrastructure and feedstock supply chains.

For BECCS, some experts appear to disagree with the starting costs. Experts 4, 10, 11 and 13 have 2030 costs that sit above the reference value which was considered too low. Expert 13, for instance, commented that 'the more recent MONET results… [in] lots of model changes [and] less conservative numbers' and asserted that the existence of 'so many different BECCS systems… [gives rise to] lots of different cost profiles'. Importantly, while for DACCS all of the experts responded based on the assumptions provided, in the case of BECCS, extensive conversations were had with experts on the system assumptions and costs. The complexity of BECCS lies not in the technology itself but in the case-by-case deployment thereof. Each expert has a specific feedstock, supply chain, plant location, furnace type and energy production that they are accustomed with. Imposing a reference plant configuration on experts was in many cases prohibitive. For this reason, not only were the feedstock assumptions dropped, but as most experts were based in Europe, they were also told to answer the questions with either the Drax or Stockholm Exergi plant in mind. That way, experts could choose the plant configuration that they were the most familiar with to answer the questions. Due to this disparity, the obtained cost ranges could contain varying underlying system assumptions that lead to some unavoidable differences that can undermine comparability.

As with DACCS, five BECCS experts were selected based on their best estimate and their trajectories were analyzed in detail. For BECCS, experts 6, 7*, 8, 11* and 10 were selected as the smallest, second smallest, median, second largest, and largest best estimates, respectively. An asterisk indicates that experts 7* and 11* also provided a breakdown of the costs. Table 7 shows the best estimates and Figure 4 and Table 8 show the evolution of the ranges over time. Interestingly, all best estimates decrease over time, except for expert 11*. The reasoning behind this is that capex and opex do not decrease and feedstock costs increase over the years due to higher competition for waste material.

For four of the five experts, the cost ranges shift towards lower costs over the years. Expert 6 believes that the minimum achievable costs stay constant over time. According to this expert, 'You start by integrating CCS into existing CHP plants… use the feedstock from today: woodchips from the pulp industry', which are only integrated by the energy sector later. Furthermore, 'the way to get started would be to make it in smaller scale at the beginning, then you will have high costs… [then see] costs go down with larger plants.' (BECCS Expert 6) Expert 7* first sees an increase in the minimum costs and later a decrease. The initial increase in minimum costs is due to an increase of capex between 2030 and 2040. As mentioned previously, an increase in costs is not unlikely for a new technology. The increase in maximum costs between 2040 and 2050 is caused by a reduction in energy revenues that is higher than the combined decrease of capex and TSM costs for the same period. Despite the forecasted increase in feedstock costs, which are linked to both forestry and adapted crop requirements, Expert 8 predicts a constant decrease in BECCS costs over the decades and expects that increasing deployments will give 'time to iron out [problems], reduce costs and benefit from learnings'. By contrast, Expert 10 does not believe there will be much deployment between now and 2030 because of the time and scale needed to setup new deployments: 'it takes seven years to build a 500 MW plant'. According to this expert, 'co-generation with heat and power… [yields] different

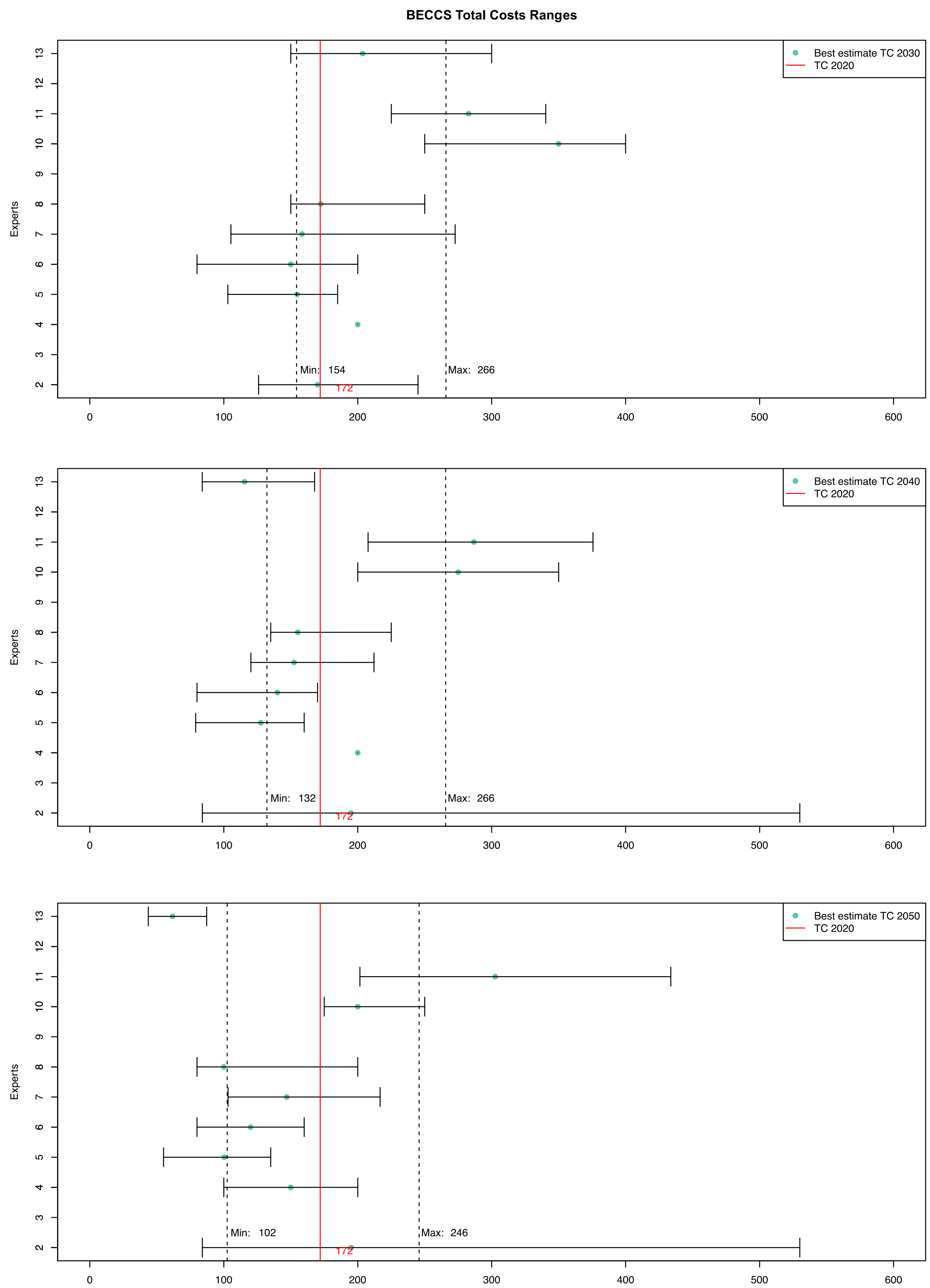

FIGURE 3
BECCS total costs ranges. BECCS total costs estimates with minimum, maximum, and best estimate of each expert in €/tCO_2. Figures are given for 2030, 2040 and 2050. Best estimates are the blue dots, and the 2020 total cost is shown by the red line. Dashed lines show the average min and max ranges. Note that our Expert 1 was only able to provide scalability estimates and not costs so we do not include Expert 1 in these figures.

TABLE 7 BECCS total cost best estimates of selected experts for 2030, 2040 and 2050.

BECCS total costs BE (€/tCO_2)	Min (Expert 6)	Min + 1 (Expert 7*)	Median (Expert 8)	Max – 1 (Expert 11*)	Max (Expert 10)
2030	150	158	172	283	350
2040	140	152	155	287	275
2050	120	147	100	303	200

A star indicates experts that provided a breakdown of the costs.

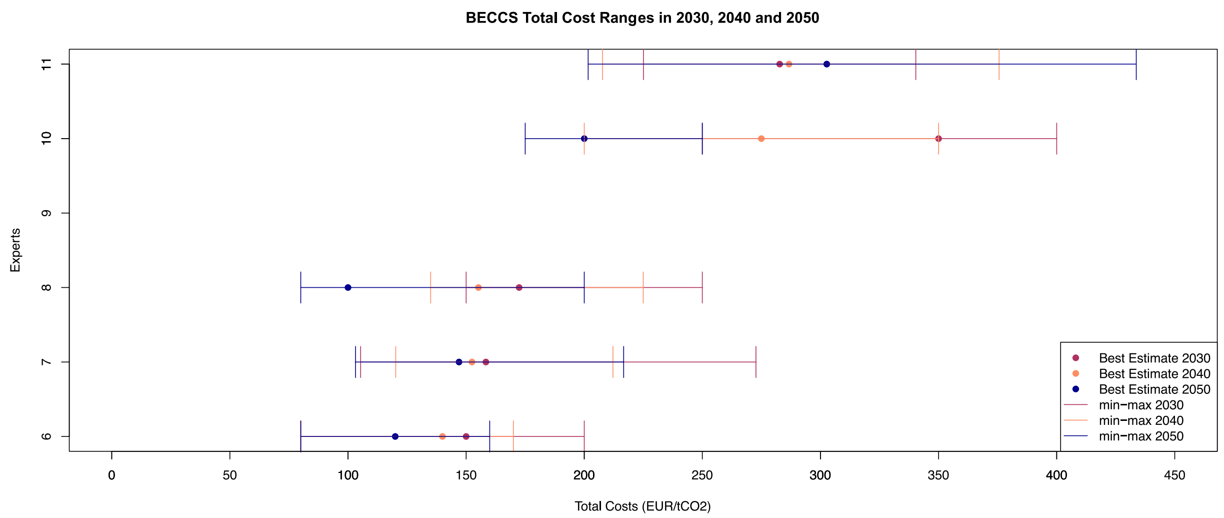

FIGURE 4
BECCS total cost ranges in 2030, 2040 and 2050. BECCS total cost range and best estimate evolution of five selected experts in 2030, 2040 and 2050.

qualities of energy… [but] the average fleet of BECCS plants will not change much'. Therefore, this expert expects most of the cost reductions will to in the capex and to a lesser extent in the feedstock costs. Additionally, it is interesting that both experts 6 and 10, which have the smallest and largest ranges, show increasing confidence over time. This behavior is at odds with the common assumption that future values are more uncertain.

Finally, Expert 11* shows a min-max range that shifts towards higher costs, and which becomes wider over the years. As mentioned before, this increase in costs is largely due to increasing feedstock costs which, despite increasing energy revenues and decreasing TSM costs, leads to an overall increase of costs. Because these dynamics happen simultaneously, this expert asserted that the widening 'minimum and maximum ranges show the variety of costs you can have'.

Table 9 portrays the uncertainty evolution of BECCS costs by showing the average min-max ranges for the total costs and the cost breakdown items. Again, a wider span indicates less expert agreement on the costs and a positive percentage change indicates increasing uncertainty for that cost item.

For BECCS, the total cost intervals are on average larger than the ones from those who offered the breakdown costs. This again shows a higher agreement for experts providing a costs breakdown. The increasing ranges for the total cost of breakdown show that on average experts become less confident of their answers over the decades. This increasing uncertainty reflects what one expects in general from technology estimates but in the case of BECCS could also reflect the case-by-case deployment of the technology, and hence the high intrinsic uncertainty.

There is not only a clear increase in uncertainty for TSM costs but also a significant difference between these costs for DACCS and BECCS respondents. These differences may reflect the fact that DACCS plants are newbuilds which can be located right next to a storage site, reducing the transport distance and total infrastructure investment needed whereas BECCS plants are less modular and must be fully integrated within the existing energy system. For instance, while 'optimizing of location will be much more important [for driving down DACCS costs] (DACCS Expert 9) and 'DACCS can be utilizing flexibility [of location]' (DACCS Expert 5), experts expected that 'smaller [BECCS] units which are situated in more remote places will be more expensive' (BECCS Expert 2). This could lead to longer transport routes to the storage sites and higher costs. Most experts stated that this supporting infrastructure is crucial, and its development will greatly depend on the government and consortium's willingness to invest. Experts also believe that a large part of this investment will happen between 2030 and 2040. Any differences between BECCS and DACCS TSM costs may also reflect the composition of the experts recruited for each technology and the small sample size for BECCS.

To summarize, BECCS experts tend to be less confident in costs than for DACCS. They believe that future costs depend on many different parameters and that overall, the uncertainty of BECCS costs should grow in the future. Finally, the cost breakdown leads to more

TABLE 8 BECCS costs min-max ranges of selected experts for 2030, 2040 and 2050.

BECCS total costs min-max range (€/tCO_2)	Min (Expert 6)	Min + 1 (Expert 7*)	Median (Expert 8)	Max – 1 (Expert 11*)	Max (Expert 10)
2030	80–200	105–273	150–250	225–340	250–400
2040	80–170	120–212	135–225	208–375	200–350
2050	80–160	103–217	80–200	202–434	175–250

A star indicates experts that provided a breakdown of the costs.

TABLE 9 BECCS min-max range width average across experts in €/tCO2 (the percentage change for each decade is provided in parenthesis).

BECCS min-max average width (€/ton CO_2)	Total costs (9 experts)	Breakdown costs (6 experts)	Capex	Opex	Feedstock	Revenues	TSM
2030	111.52	96.27	65.16	13.59	41.04	−56.03	32.51
2040	133.42 (+20%)	134.10 (+39%)	73.42 (+12%)	17.54 (+29%)	57.04 (+39%)	−66.16 (+18%)	52.26 (+60%)
2050	143.35 (+7.4%)	154.31 (+15%)	85.42 (+16%)	19.43 (+11%)	82.22 (+44%)	−89.28 (+35%)	56.52 (+8.2%)

optimistic cost ranges than the total costs. In some extreme minimum cases, experts place the cost of BECCS below €100/tCO_2.

5.1.3 Costs uncertainty discussion

The previous section discussed the uncertainty surrounding DACCS and BECCS costs. Notable findings are that for DACCS, high costs are associated with higher uncertainty and rate of change over time. For BECCS, experts that offered a cost breakdown provided more optimistic ranges than those who only offered total cost estimates. Collectively, our results pertaining to both technologies suggest that experts that provide a cost breakdown tend to suggest narrower ranges.

Finally, the total costs for DACCS might indicate a degree of overconfidence bias as ranges become narrower over time whereas this effect disappears in the cost breakdown. In contrast, there appears to be no clear overconfidence bias for BECCS. This can be explained by the difference in complexity of the two technologies as DACCS technology is still undergoing significant development and various novel processes are under consideration or could emerge over time. It might be difficult to reflect the full complexity of the technology in a single total cost metric because the technology could take on a very different form in the next decade.

5.2 Cost best estimates

The following section presents the best estimates for DACCS and BECCS total costs in 2030, 2040 and 2050. Figure 5 shows the best estimates of all experts for DACCS and BECCS in 2030, 2040 and 2050. It is apparent that DACCS cost estimates, which span over two orders of magnitude, vary much more widely between experts compared to BECCS estimates, which fall within the same order of magnitude.

DACCS expert 10 is the only expert for either technology that expects costs to (slightly) increase. As mentioned before, this expert's reasoning is that the technology cannot achieve any lower minimum costs because although 'it is very likely that innovation in DACCs… [reduces] capex and opex costs… optimal sites [become scarce with upscaling]. For BECCS, the results for experts 2 and 11 show interesting behaviors. They both believe that the costs will increase between 2030 and 2040 and stay constant or, respectively, increase by 2050. The reason for this is the existing gap between early cost-effective projects and later more expensive projects as BECCS projects developers 'would go to the optimal ones first' (BECCS Expert 2) and 'we [need to] factor in increasing feedstock costs' (BECCS Expert 11).

This sort of dip has been found previously in other technologies such as flue gas desulphurization (FGD) as described by Rubin et al. (2015).

Table 10 shows the average of the best estimates. The BECCS results suggest that, on average, experts expect a higher starting cost in 2030 than the 2020 reference cost and a gradual cost reduction thereafter over the following decades. DACCS results suggest that, on average, DACCS costs will decrease more steeply in the coming decades than BECCS. Despite the narrowing between the two costs, however, DACCS costs are expected to be 83% higher than BECCS costs by 2050.

In summary, experts posited various reasons for expecting that DACCS costs will decrease; fabrication costs will fall due to economies of scale and process optimization (DACCS Experts 6, 9, 13, 14, 15 and 19), including the development of more efficient and less costly sorbents (DACCS Experts 5, 7, 9 12, 19, 20 and 21). In addition, the ability to 'integrated DAC with all renewables' (DACCS Expert 16), where costs are also falling, 'should [make DACCS] energy prices go down' (DACCS Expert 17). While BECCS costs are also expected to decrease, the cost reductions are not of the extent envisioned for DACCS. One expert said 'you can have renewable (free) energy next to the system to avoid the grid (DACCS Expert 5). Some experts firmly believe that BECCS costs will increase in the coming decades due to increasing running costs of up- and down-stream operations (BECCS Expert 5, 7, 11 and 13). BECCS is currently the far cheaper technology of the two, but for deployment at scale, 'we need a lot of

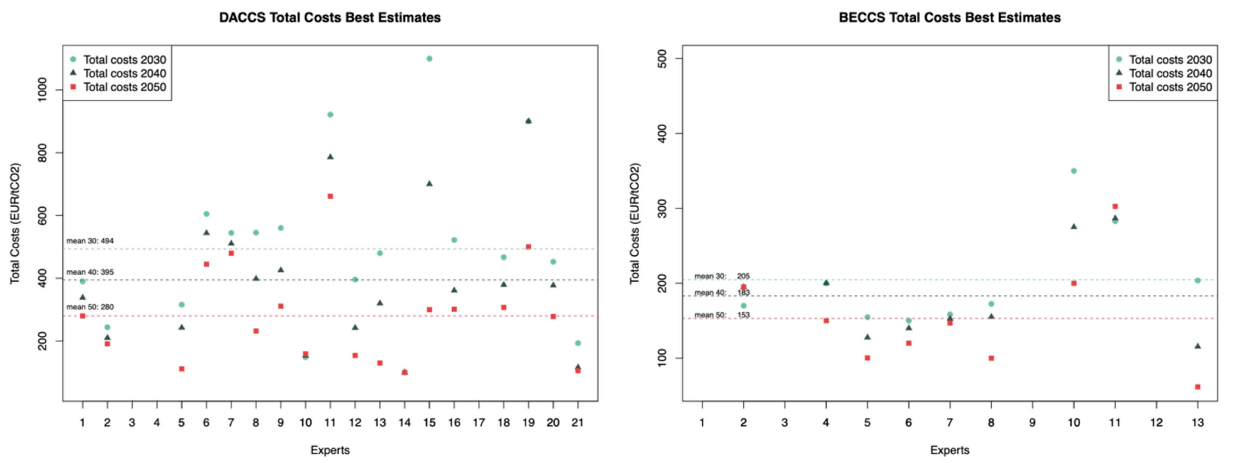

FIGURE 5
DACCS and BECCS total costs estimates. DACCS and BECCS total cost estimates by experts in 2030, 2040 and 2050.

TABLE 10 Average DACCS and BECCS total costs and the decadal learning rate.

Total costs (€/ tCO_2)	DACCS	Learning rate	BECCS	Learning rate
2020 (ref)	581		172	
2030	494	−15%	205	+19%
2040	395	−22%	183	−11%
2050	280	−27% (−52% since 2020)	153	−16% (−11% since 2020)

investments, transport networks and preparation of sequestration sites' (BECCS Expert 5). Additional investments will also be needed to distribute any biomass energy that is generated (BECCS Expert 9). While the former costs would also be incurred for DACCS at scale, the potential for location-independent sourcing of CO_2 means that capture facilities can be located near renewable energy sources, thereby avoiding costly infrastructural and regulatory challenges that are associated with transporting biomass for powering BECCS.

5.2.1 Costs best estimates discussion

To summarize, the nominal difference between DACCS and BECCS costs can be explained by differences in both technology and perceptions. DACCS is a more novel technology which can still undergo significant improvements, which is especially visible in expectations about decreasing operational costs arising from sorbent improvements and novel materials. BECCS, on the other hand, uses common industrial processes with lower current costs, but also has limited room for improvement. The results confirm that the learning rate between 2020 and 2050 is significantly higher for DACCS than for BECCS.

Interestingly, both technologies are highly dependent on the evolution of power markets. For DACCS, energy represents about a third of its total costs and experts hope that an expanding role for renewables in the energy grid will lower costs. For BECCS, as a power producer, the market price of feedstocks and energy influences plant revenues. BECCS power production, however, could be a strategic advantage for the technology in the future. Some of the experts we interviewed suggest that, by providing baseload power, BECCS could help stabilize a more volatile green grid. One expert, for example, described this potential as 'energy gain' (BECCS Expert 5); another expert noted that different 'possibilities' are raised by the 'co-generation with heat and power' (BECCS Expert 10).

By way of a benchmark, over the course of 2022 and 2023, prices in the EU Emissions Trading Scheme (ETS) approached or even exceeded €100/t on several occasions. For BECCS, three of twelve experts believe that BECCS costs will reach at least €100/t or lower by 2050. For DACCS, seven out of eighteen experts believe that total DACCS costs will be below €200/t in 2050 and only one of them places the costs at €100/t. This again shows that, despite the relative improvements, DACCS is expected to remain a relatively costly technology. Improving the current processes or subsidizing the technology will require heavy investments, large subsidies or technological breakthroughs.

5.3 Scalability under different policy scenarios

Unsurprisingly, a more ambitious global decarbonization scenario is expected to lead to higher levels of deployment of both DACCS and BECCS. However, the specific results are less intuitive. Figure 6 shows the DACCS potential scale trajectories for 2030, 2040 and 2050 from all experts. The graphs on the left show the responses under the STEPS policy scenario and the ones on the right show those under the NZE policy scenario.

The ranges provided by the experts shows that the two scenarios are associated with different behaviors. In STEPS 2030, four experts believe that the minimum scale (measured in $MtCO_2$/year) is zero,

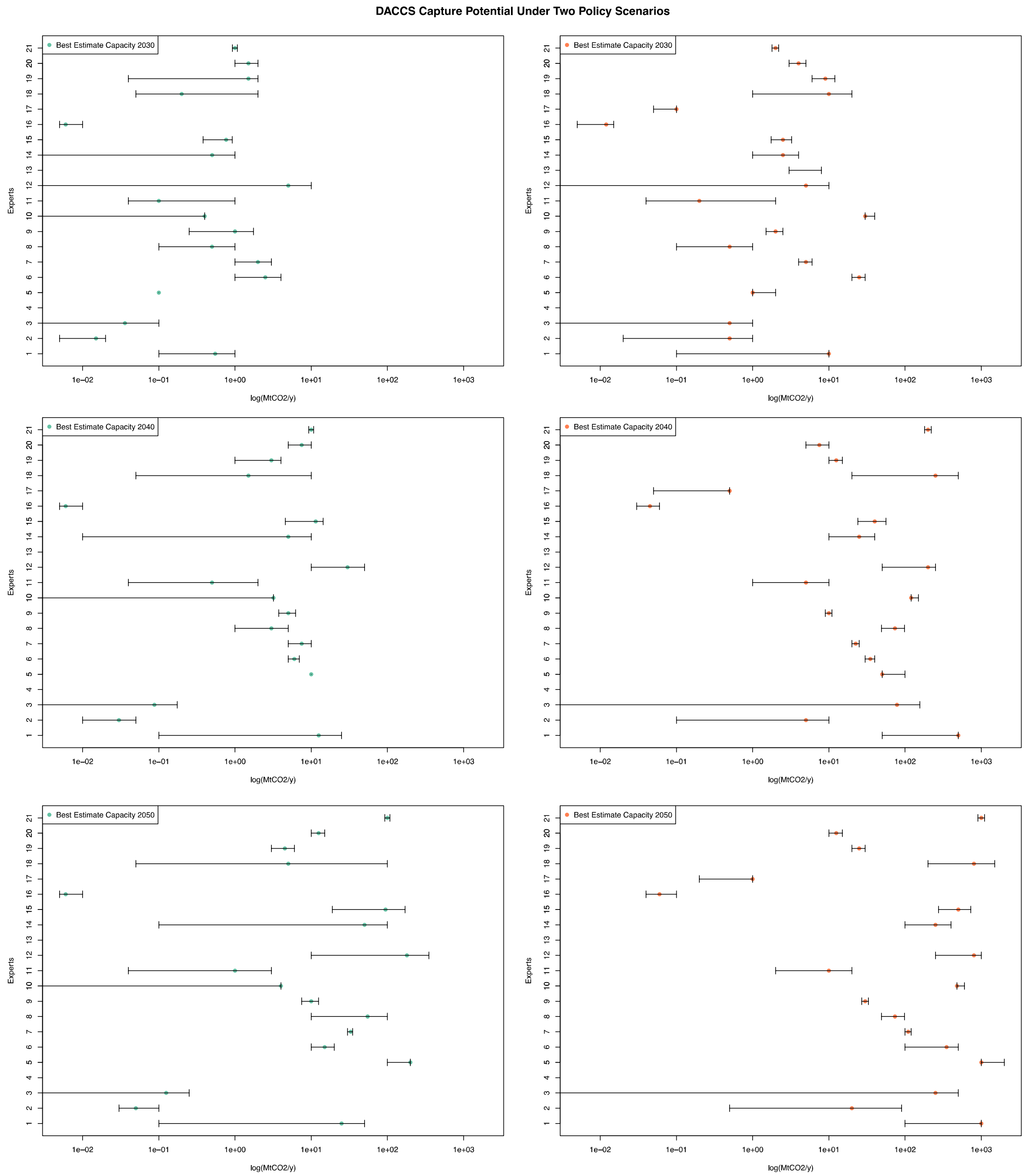

FIGURE 6
DACCS capture potential under two policy scenarios. DACCS potential scale under two policy scenarios in 2030, 2040 and 2050. Estimates with minimum, maximum, and best estimate of each expert in log(MtCO2) captured per year. Left graphs are the STEPS scenario, right graphs are the NZE scenario.

with two of these experts expecting that this will still be the case in 2040 and 2050. Under NZE 2030, two of the same experts believe the minimum scale is 0 while only one of them believes this for 2040 and 2050. Overall, there is a clear increase in the potential scale under NZE, as the ranges shift to the right. Looking at STEPS and NZE range evolution over time shows that a clear majority of experts increase their ranges. In STEPS, expert 2 decreased their range and experts 14 and 15 kept them unchanged. In NZE all experts increased their ranges over time. On average the ranges are narrower for STEPS than for NZE. This could indicate that experts tend to agree more on potential scale under STEPS than NZE. This could be because most experts agree that the possible scale attained under STEPS is limited because only voluntary market forces are at play. Additionally, the NZE scenario is less familiar and requires more stringent measures than the STEPS scenario.

As for the costs, the trajectories of selected experts are followed over time. As two different policy scenarios were used during the elicitations, five experts were selected once based on of their STEPS

2030 best estimates (1) and a second time based on their NZE 2030 best estimates (2). Table 11 shows the obtained best estimates that span across the STEPS 2030 results and Figure 7 shows the trajectories of the best estimates and min-max ranges.

Figure 8 shows expert uncertainty ranges for BECCS deployment in Europe in 2030, 2040 and 2050. The graphs on the left show the ranges under the STEPS policy scenario and the ones on the right show the ranges under the NZE policy scenario. Of the 13 interviewed BECCS experts, experts 12 and 13 did not answer the potential scale questions and expert 3 only provided the best estimates. The NZE scenario leads to higher deployment scales in all three decades than the STEPS scenario. Compared to DACCS, BECCS ranges are narrower and overlapping, and there is no clear outlier in the results. All min-max ranges increase or stay constant for STEPS and NZE.

For STEPS, some experts stated that only the UK and Scandinavian countries would operate BECCS plants (BECCS Experts, 4, 5, 8 and 9). One expert believes that only the currently developed DRAX and Stockholm Exergi projects would be operational as 'there is no other funding [in the EU], only the Stockholm Exergi Project (BECCS Expert 3). A number of experts concur that Scandinavia is an ideal choice to develop the plants due to the large amount of waste that can be used from forest residues and the pulp and paper industry. One expert comments, for example, said that 'pulp plants is the first portion [determinant of deployment capacity], not the energy sector' (BECCS Expert 6). Sweden is predicted to assume about one third of European BECCS as the country has existing policies encouraging the deployment of the technology (but this can also be influenced by the overrepresentation of Scandinavian experts in our sample). Such considerations lead one expert to expect that by mid-century, all additional BECCS plants will be located only in Sweden (BECCS Expert 2). Finally, strong opinions were expressed on the uniqueness of each BECCS project: experts made the following comments to describe this heterogeneity 'all options/ plants are different' (BECCS Expert 6) and 'one of a kind… modular [projects]' (BECCS Expert 13). Experts therefore expressed strong beliefs that BECCS be treated on a case-by-case basis there is no one-size-fits all deployment strategy, which creates an expectation that NZE targets will not be met. While several experts emphasized the potential role for more effective policy to drive future deployment (e.g., BECCS Experts 3, 5, 8, 11 and 12), the overall cautious or even pessimistic expectations about BECCS scalability suggest the need for exploring other negative emission technologies that can undergo large-scale deployment.

The trajectories of two different expert batches are shown below. These trajectories help understand the specific evolution of expert ranges that span throughout the obtained result range. Table 12 shows the best estimates of the experts selected based on their span of the STEPS 2030 best estimates. Figure 9 shows the trajectories of these selected experts. Expert 3 provided only the best estimate and no min-max ranges.

Table 13 shows the average of the best estimates for the potential scale of DACCS and BECCS in Europe under STEPS and NZE for each year. In the first decade, DACCS is deployed more slowly than BECCS, before the trend reverses. For DACCS, the

TABLE 11 DACCS potential scale best estimates of selected experts (1) under STEPS and NZE policy scenarios.

DACCS best estimate	Expert 4 (Min)		Expert 17 (Min + 1)		Expert 14 (Median)		Expert 6 (Max – 1)		Expert 12 (Max)	
$MtCO_2$ / year	STEPS	NZE	STEPS	NZE	STEPS	NZE	STEPS	NZE	STEPS	NZE
2030	0	NA	0	0.1	0.5	2.5	2.5	25	5	5
2040	0	NA	0	0.5	5	25	6	35	30	200
2050	0	NA	0	1	50	250	15	350	180	800

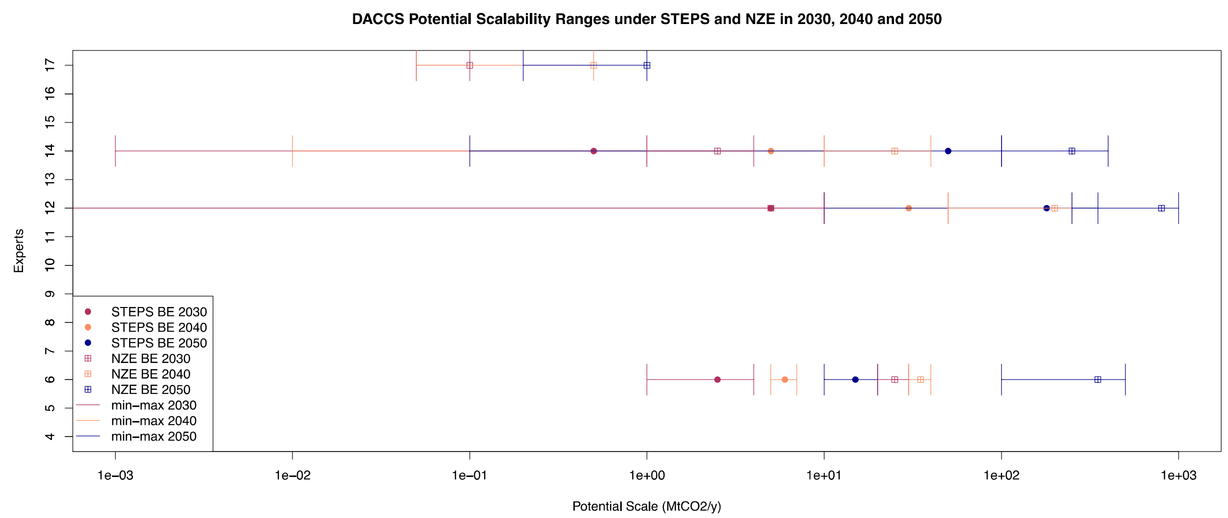

FIGURE 7
DACCS potential scalability ranges under STEPS and NZE in 2030, 2040 and 2050.

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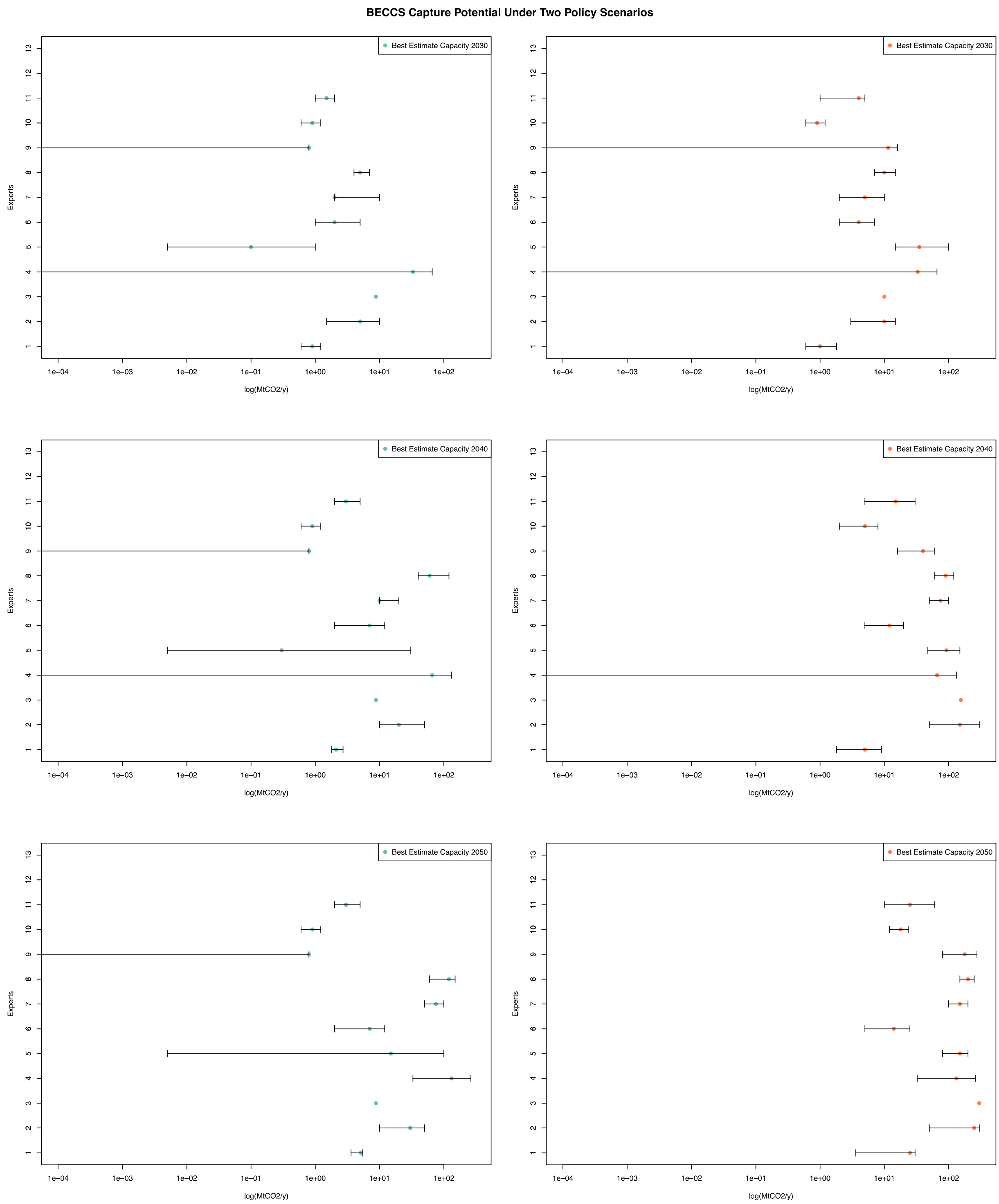

FIGURE 8
BECCS capture potential under two policy scenarios. BECCS potential scale under two policy scenarios in 2030, 2040 and 2050. Estimates with minimum, maximum, and best estimate of each expert in log(MtCO2) captured per year. Left graphs are the STEPS scenario, right graphs are the NZE scenario.

assumptions under the STEPS scenario lead to a linear increase up to 39.5 $MtCO_2$ captured per year. The expected development under the NZE scenario, however, involves a sharp increase in the 2040s, leading to up to 353Mt CO_2 captured per year. For BECCS, the NZE scenario leads to additional capture capacity, but the change is not as drastic as for DACCS. Under NZE the deployed scale would average 131 Mt. CO_2 capture per year, not even half that of DACCS.

To summarize, the best estimates show that stringent climate policies are expected to result in larger capacity deployment for both DACCS and BECCS. Enabling policies have a particularly strong effect on the deployment of DACCS, with a sharp increase in the years leading to 2040. With the ongoing research and investment in that field, experts expect that a dominant design will be adopted by 2040. This would reduce DACCS costs and, combined with the modularity of the technology, would enable a quick scale-up of capacity. However,

TABLE 12 BECCS potential scale best estimates of selected experts under STEPS and NZE policy scenarios.

BECCS best estimate	Expert 5 (Min)		Expert 9 (Min + 1)		Expert 7 (Median)		Expert 3 (Max − 1)		Expert 4 (Max)	
$MtCO_2$ / year	STEPS	NZE	STEPS	NZE	STEPS	NZE	STEPS	NZE	STEPS	NZE
2030	0.1	35	0.8	11	2	5	8.8	10	33	33
2040	0.3	93	0.8	40	10	75	8.8	155	66	66
2050	15	150	0.8	178	75	150	8.8	300	132	132

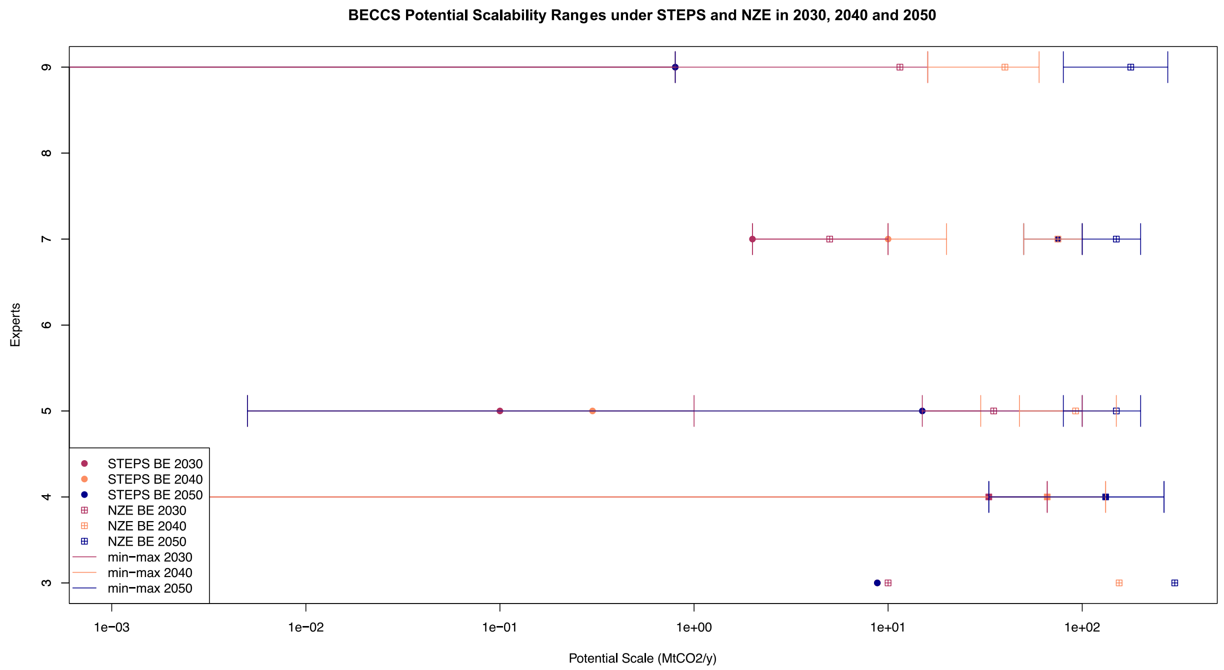

FIGURE 9
BECCS potential scalability ranges under STEPS and NZE in 2030, 2040 and 2050.

the figures show that for this to happen, it is crucial to develop and implement the right policies.

5.3.1 Scalability discussion

In sum, our experts expect that under the NZE scenario, the average best estimate for the potential scale of DACCS is 353Mt CO2/year, which is a ninefold increase from the STEPs estimate (39Mt CO2/year). By contrast, despite nominally lower costs, BECCS struggles to achieve similar scales in 2050, reaching an average capture capacity of 131Mt CO2/year under NZE and 36Mt CO2/year under STEPS, which amounts to less than a fourfold increase. Of course, any comparison of the DACCS and BECCS expert elicitations must be treated with caution since they involve two distinct and independent groups of experts.

The NZE scenario is associated with substantially higher deployment of both technologies, but the average estimated combined capacity of DACCS and BECCS in the expert elicitations for 2050 amounts to only about a quarter of the CO2 removals that the IEA envisions would be needed in its NZE scenario (1.9 GtCO2). This reinforces the view expressed by several experts that 'a suite of technologies will' (DACCS Expert 12) be needed to meet net-zero ambitions. Alongside the higher expected deployment for both technologies under the NZE scenario, the uncertainty associated with these estimates is also higher. As one expert puts it, 'Huge uncertainty [exists] because what will be done has a range of technologies available… depends on policymakers' (BECCS Expert 8). Although the most conservative DACCS estimates the risk that DACCS will not be deployed at all, expert projections suggest that this technology shows promising deployment scale under NZE with the confidence interval maxima reaching up to 1Gt CO2/year captured in 2050. Most experts concurred that the deployment levels of both technologies depend on the successful implementation of early plants and that this requires negative emission technologies to be clearly defined in European policy frameworks. Hence, the prospects of future deployment were described as 'contingent on EU policy decisions' (DACCS Expert 1), particularly regarding the development of regulations around 'who is paying for what' (DACCS Expert 10), especially 'in the EU, when it is not the ideal place to develop it [CCS-based NETs due to] energy costs and proximity to storage…' (DACCS Expert 13). As one expert put it, 'the EU Commission should not think in terms of stated policies, but in terms of policy reform' (BECCS Expert 11). For the STEPS scenario, the most conservative estimates (i.e., the minimum of the confidence interval) for BECCS deployment shows a higher potential scalability compared to DACCS. However, BECCS shows a maximum deployment scale that remains limited to around 0.3Gt CO2/year captured in both scenarios. We found higher uncertainty for the scalability of BECCS, which can

TABLE 13 Average of capacity best estimates for DACCS and BECCS technologies under STEPS and NZE.

Average capacity ($MtCO_2$/y)	DACCS		BECCS	
	STEPS	NZE	STEPS	NZE
2030	0.88	5.78	5.46	11.31
2040	5.82 (+561%)	86.04 (+1389%)	16.27 (+198%)	64.14 (+467%)
2050	39.49 (+579%)	353.27 (+311%)	36.16 (+122%)	131.10 (+104%)

be due to the need for one-of-a-kind plants and local supporting infrastructure.

6 Conclusion

The results of our study imply the following conclusions about our key research questions over the change in cost uncertainty over time and learning rates. We find that for both DACCS and BECCS technologies, cost uncertainty increases over time. We also find the learning rate for DACCS tends to be higher than for BECCS. In particular, experts expect operational costs for DACCS to decline more sharply than BECCS costs. It is likely that higher learning rates associated with DACCS stem from the novel status of the technology and potential for larger improvements.

This study provides valuable insights into the future of DACCS and BECCS technologies in Europe. The experts' quantitative inputs, supported by their judgement of the factors that influence the field, shed light on the cost uncertainties of these technologies. In the interest of achieving a nuanced understanding of expert perceptions, our analysis is based on in-depth insights provided by a select group of 34 experts, prioritizing depth of insight over statistical representativeness. Consequently, the generalizability of our results is inherently limited, and we cannot presuppose that a larger or different cohort of experts would necessarily concur with the findings presented. The discussion that follows is purely our interpretation of the insights garnered from the 34 experts interviewed through this research effort and does not purport to extend beyond the specific set of experts consulted in this study.

6.1 Costs

Although DACCS total costs exhibit decreasing uncertainty over time, the cost breakdown displays increasing uncertainty. This could be a reflection of the difficulty of grasping the full complexity of the technology in one total cost metric arising from the potential of the technology to take on a vastly different form in a relatively short time period. Additionally, DACCS involves an energy intensive process and therefore depends on energy prices. The current geopolitical climate does not favor energy cost certainty and the experts which provided the cost breakdown found it hard to speculate on this cost item. DACCS experts were confident that in the future new and better materials as well as economies of scale would lower the costs of the technology, but overall, the uncertainty of European energy prices remains a hurdle to the deployment of the technology.

BECCS costs show growing uncertainty over time due to the unique aspect of each plant development. BECCS plants are developed as a one-of-a-kind plant, with specific up- and down-stream supply chains, leading to high uncertainty. As for DACCS, the energy revenue of BECCS is linked to European energy prices and hence, uncertain. However, the revenues obtained through energy sales help make the technology financially attractive and BECCS is consistently cheaper than DACCS, with some extreme minimum cases attaining costs below €100/tCO_2.

Overall, our experts expect BECCS costs to decrease in the coming decades but not as dramatically as DACCS costs. On average, by 2050, DACCS reaches costs of €280/tCO_2 and BECCS costs of €153/tCO_2. Despite being the cheaper technology, large-scale BECCS deployment would require both significant investment and international coordination for regulating relatively diverse plants, sourcing and transporting biomass upstream and distributing biomass energy downstream. By contrast, by facilitating location-independent sourcing of CO_2, DACCS avoids some of the transport and regulatory challenges that are encountered for powering BECCS at scale and regulating potential biomass energy generation. However, some experts believe that by providing baseload power, BECCS could be strategically positioned to help stabilize a volatile green energy grid and, unlike DACCS, could accrue revenues from power generation rather than consuming vast amounts of electricity.

To conclude on the cost best estimates, our experts expect that the major cost reductions will be driven by economies of scale, process optimization and energy cost reductions. As the costs of both technologies are linked to European energy prices, policymakers must prioritize securing a stable green energy grid to reduce the uncertainty arising from the energy prices of these technologies.

6.2 Scalability and policy implications

This study highlights the need to understand the nature and sources of uncertainty surrounding key emerging climate technologies for reaching realistic assessments about the potential of CDR to achieve climate neutrality. Our results show that expectations about costs vary widely and tend to expand with increasing time horizons. As discussed above, past research (e.g., Grant et al., 2021) shows that experts that hold different expectations about costs of CDR options tend to hold different expectations about deployment scales. While the IEA (2021) identifies NZE-compliant DACCS and BECCS deployment scales for each decade, no such cost targets have been stipulated beyond the $100/tCO2/year removal industry target for advanced economies. Nonetheless, it is possible to explore the scalability implications of our cost uncertainty analysis by comparing the average cost and deployment estimates provided by our experts with the decadal cost and deployment estimates from recent IEA tracking data as summarised in Table 14 (Sources for tracking data are specified in the Table caption).[3] The average 2030

3 Unless specified otherwise, the present discussion considers the scalability estimates that experts predicted in relation to the STEPs scenario.

TABLE 14 Comparison of our cost and scalability estimates with IEA tracking and NZE scenario goals.

Year	Our analysis		IEA tracking estimates		NZE scenario[e]	
	Cost[a]	Scale[b]	Cost[c]	Scale[d]	Cost	Scale
DACCS						
2030	494	0.88 (5.78)	45.50 to 199.78 (without carbon price) −81.73 to 131.67 (with carbon price)	0.01<	90.74 (industry target for advanced economies)	85
2040	395	5.82 (86.04)				620
2050	280	39.49 (353.27)	45.50 to 154.35 (without carbon price) −81.95 to 22.70 (with carbon price)	75		980
BECCS						
2030	205	5.46 (11.31)	9.08 to 77.16	50	90.74 (industry target for advanced economies)	190
2040	183	16.27 (64.14)				900
2050	153	36.16 (131.10)				1380

Cost estimates are given in Euros/ tCO2 (USD estimates were converted to Euros using 2023 exchange rates), scale estimates are MtCO2/year.
[a]Average total costs per decade from Table 8.
[b]Average best capacity estimates under the STEPs and NZE (in parentheses) scenarios from NEGEM deliverable 5.4.
[c]DACCS = Estimated large-scale applications in Europe from IEA (2021) 'DAC: A key technology for net zero special report', BECCS = IEA (2020) special report on CCUS in clean energy transitions.
[d]IEA Clean Energy Progress Tracker (2023). Available at: https://www.iea.org/reports/tracking-clean-energy-progress-2023.
[e]IEA (2021) Special Report on Net Zero by 2050.

DACCS cost estimated by our experts is significantly (approximately two to ten-fold) higher than current IEA tracking data (that does not assume the existence of a carbon price). While our average 2030 DACCS scalability estimate is more optimistic than the equivalent IEA projection (0.88 versus <0.01 Mt./CO2/year respectively), this is still significantly lower than the NZE target for that decade (85 Mt./CO2/year). Although the gap between expected DACCS costs and deployment predicted by our experts and the NZE scenario narrows by mid-century, our experts expect that DACCS costs will be four-times higher than current IEA tracking projections suggest and deployed at less than half of the scale predicted by IEA tracking – around a quarter of the scale needed to be NZE-compliant.

Compared to DACCS, our experts' expectations about BECCS are relatively more pessimistic. By 2030, our BECCS costs are expected to be significantly higher (around two- to twenty-fold) than those predicted by IEA tracking, which is more than twice as high as the NZE industry target. While a lack of decadal data obstructs our comparison with tracking and NZE estimates beyond 2030, it is striking that despite expected declining costs and increasing deployment, our experts predict that throughout the 2030s to 2050s, BECCS deployment relative to NZE targets will be significantly insufficient—around one 36th of the scale needed to reach negative emissions by mid-century.

Moreover, it is striking that even when experts were asked to estimate scalability under the NZE scenario (see separate NZE estimates presented in parentheses in Table 14), the scalability of both technologies were still only a fraction (around a third for DACCS and tenth for BECCS) of the levels required to reach net zero by mid-century.

In conclusion, our experts expect that DACCS and BECCS costs will be even higher (and deployment scales lower) than those predicted by recent IEA tracking. While, relative to NZE requirements, DACCS scalability is assessed more favorably than BECCS, our experts' wide uncertainty ranges suggest that current IAM projections about the scalability of these technologies are likely to be more optimistic (closer to NZE targets) than is actually feasible. Better understandings about the uncertainty surrounding costs, particularly in relation to the distant future, would significantly improve projections about the relative role and scalability of different CDR options and other technologies and processes within the wider portfolio of climate policy options and ultimately assist policymakers design effective legislation for meeting decarbonization and net zero targets.

6.3 Future research

The results and insights gathered in this work present a preliminary assessment of the uncertainty of future costs of DACCS and BECCS technologies. Our study focuses on both shorter and longer-term technology evolution from 2030 to 2050. In so doing, we provide a first understanding of selected expert views on parameters which influence future emission scenarios and European wide policies.

As a first effort, the scope of this study was inevitably limited. In the process of conducting the study we identified a number of extensions or additional angles that could be explored by future research.

1) It would be helpful to find experts who would be able to appraise multiple options at the same time, which would allow for direct comparison of options. Additionally, ensuring that more industry experts are represented is crucial in building an accurate view of the challenges developers face.
2) Finally, this research could be extended along other geographical and sectoral dimensions. We focused primarily on Europe, but other regions such as North America, where important carbon capture clusters and supporting policies are being developed would also benefit from expert elicitation analysis. We could also extend the study to explore uncertainty surrounding the

supporting infrastructure such as infrastructure companies that develop the transport routes from carbon capture to carbon storage sites and the carbon storage companies including oil and gas companies or companies that specialize in carbon storage. Improving understandings of the challenges and uncertainties that these companies face is crucial for developing a robust carbon capture supply chain.

3) Relatedly, similar analyses could be conducted with experts from industrializing economies, which are increasingly emerging as critical for hosting or funding CDR (e.g., Peters and Geden, 2017; Pozo et al., 2020). At scale deployments in these countries are likely to encounter both similar (e.g., infrastructural, resource needs) and different (e.g., social/ethical acceptability, fragile energy system, poor energy access) challenges to those identified by our European experts. Therefore, expert perspectives from developing economies would yield valuable insights into the wider global infrastructural and social acceptability challenges that are likely to arise under climatically-relevant deployment.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Judge Business School research ethics review group. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MA: Data curation, Formal analysis, Investigation, Visualization, Writing – original draft. ZC: Writing – review & editing. LN: Conceptualization, Methodology, Supervision, Visualization, Writing – review & editing. DR: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

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Conflict of interest

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

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2024.1331901/full#supplementary-material

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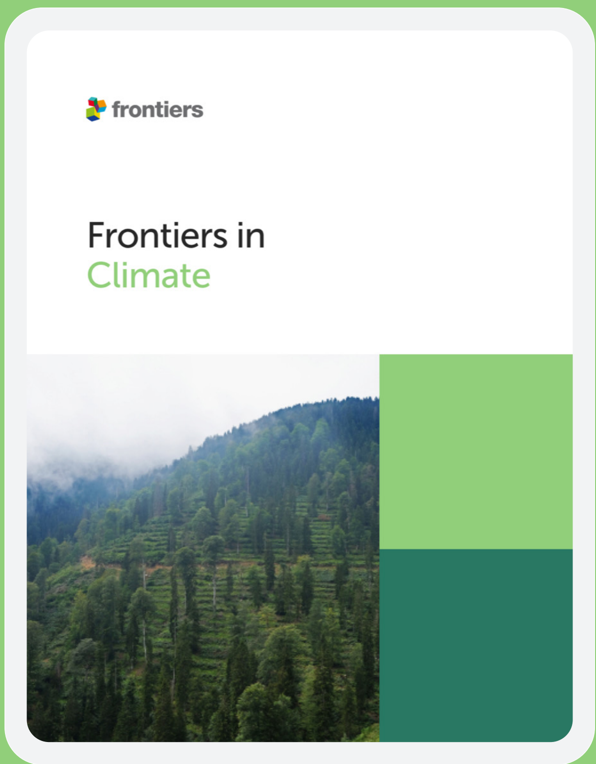

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