GOVERNING CARBON DIOXIDE REMOVAL

EDITED BY: Rob Bellamy, Oliver Geden, Mathias Fridahl, Emily Cox and James Palmer

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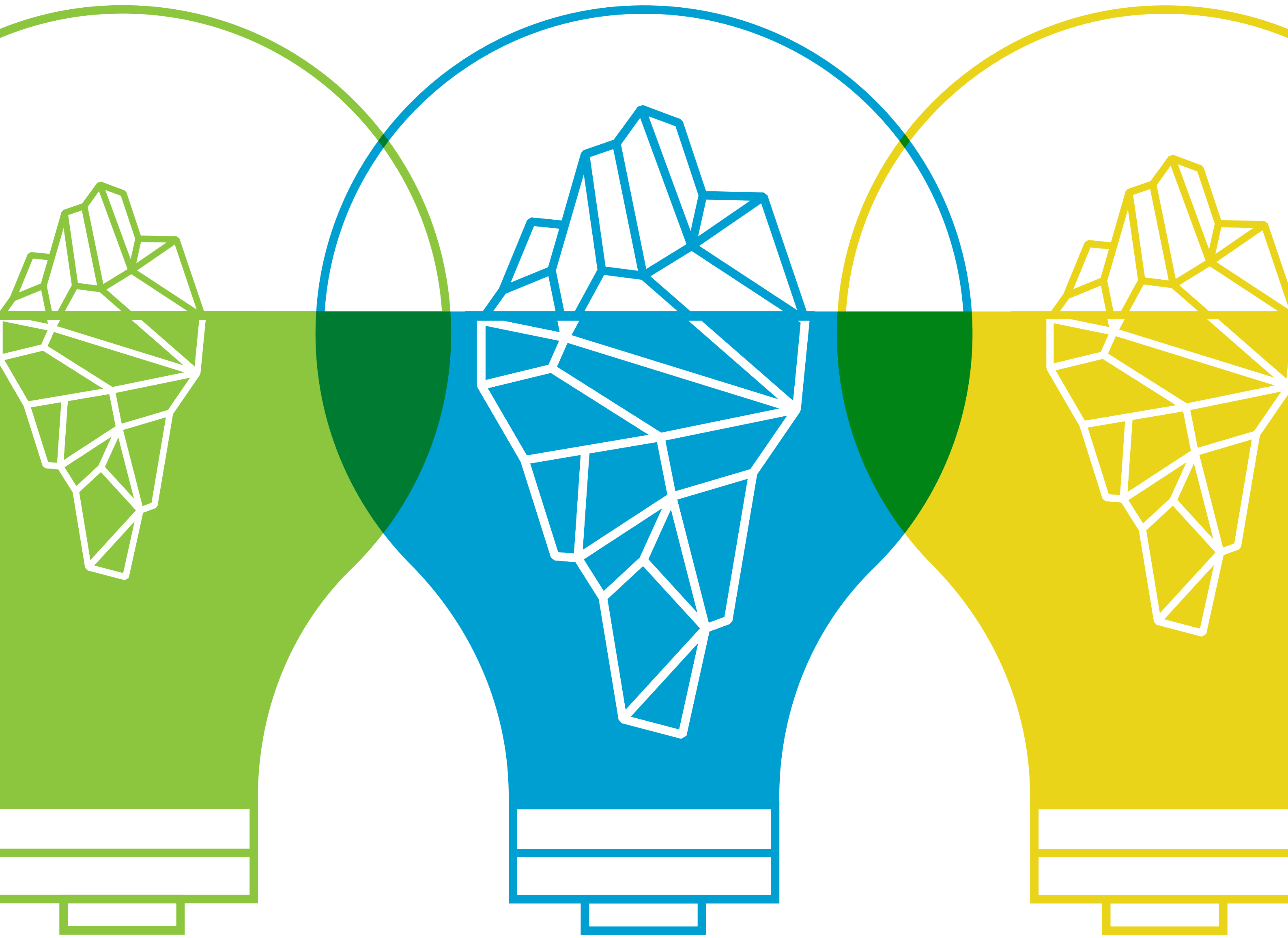

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GOVERNING CARBON DIOXIDE REMOVAL

Topic Editors:
Rob Bellamy, The University of Manchester, United Kingdom
Oliver Geden, German Institute for International and Security Affairs (SWP), Germany
Mathias Fridahl, Linköping University, Sweden
Emily Cox, Cardiff University, United Kingdom
James Palmer, University of Bristol, United Kingdom

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Editorial: Governing Carbon Dioxide Removal

Rob Bellamy[1,2]*, Oliver Geden[2,3], Mathias Fridahl[4,5], Emily Cox[6] and James Palmer[2,7]

[1] Department of Geography, University of Manchester, Manchester, United Kingdom, [2] Institute for Science, Innovation and Society, University of Oxford, Oxford, United Kingdom, [3] German Institute for International and Security Affairs, Berlin, Germany, [4] Department of Thematic Studies—Environmental Change, Linköping University, Linköping, Sweden, [5] Centre for Climate Science and Policy Research, Linköping University, Linköping, Sweden, [6] School of Psychology, Cardiff University, Cardiff, United Kingdom, [7] School of Geographical Sciences, University of Bristol, Bristol, United Kingdom

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Editorial on the Research Topic

Governing Carbon Dioxide Removal

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

****Correspondence:***
Rob Bellamy
rob.bellamy@manchester.ac.uk

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INTRODUCTION

Carbon dioxide removal (CDR), also known as negative emissions, greenhouse gas removal, or simply carbon removal, is in need of effective governance. If governments are to deliver on the growing number of pledges to meet "net zero" and "net-negative" emissions targets, and if the world is to successfully limit global warming to "well-below 2°C" compared to pre-industrial levels, then carbon dioxide (CO_2) will need to be removed from the atmosphere. This is because, at the very least, residual greenhouse gas emissions from hard-to-transition sectors like agriculture will need to be compensated for. Furthermore, if the world were to overshoot 1.5°, CO_2 concentrations will need to be brought back down. The central questions for CDR governance therefore no longer concern *whether* CDR should be pursued, but *how*; which CDR methods should be pursued, to what extent, when, where, and by whom (Bellamy and Geden, 2019). Despite this, the governance frameworks and democratic processes that will be needed to responsibly incentivize, develop, and sustain CDR remain largely neglected not just by policymakers, but also by much of the academic research community as well.

Spurring demand for CDR not just from multiple policy angles, but also multiple policy scales, will require an approach that minimizes negative trade-offs and identifies potential co-benefits (Cox and Edwards, 2019). Yet uncertainties around CDR effectiveness, technical efficiency, scale, risks, and interactions with other policy objectives—both within and beyond the realm of climate governance—all demand careful consideration (Fridahl et al., 2020). Moreover, effective CDR governance must also contend with conflicting interests and account for diverse and geographically varying societal values and knowledges in relation to technology appraisal and selection, policy instrument choice, and guiding principles (Bellamy, 2018; Bellamy et al., 2021). This Research Topic seeks to address such critical questions around CDR governance as it emerges: how is CDR framed and what are the governance implications? How can we account for societal values and knowledges in CDR governance? How do existing governance regimes relate to CDR and how might they be reformed? What new governance designs are needed? Are existing institutions and systems suitable for governing CDR?

FRAMING GOVERNANCE

Otto et al. undertake a secondary analysis of interviews with German environmental NGO representatives to identify CDR narratives. They find two stories that reflect dominant climate policy discourses around ecological modernization and civic environmentalism: that CDR is either a necessity or a risk to mitigation, respectively. Turning to the envisaged role of CDR in different countries' long-term low emission development strategies, Buylova et al. find that national plans echo such discourses. They identify three possible visions for CDR: as a panacea that risks deterring mitigation, as a necessary fallback in case mitigation is not enough, and as a chimera in which CDR is illusory due to a lack of specific targets and plans. Asayama argues that the apparent paradox of CDR being essential but also a potential distraction has less to do with CDR itself than with the difficulties of escaping carbon lock-in. To better situate CDR in the challenge of rapid decarbonization, he argues, we should be asking how it can be used in alignment with a managed decline in fossil fuel production.

Boettcher undertakes a sociology-of-knowledge discourse analysis of interviews with UK stakeholders working at the industry-policy interface, to explore the competing forms of knowledge shaping assumptions about appropriate governance instruments for CDR. She reveals three dominant knowledge types: political-realist, utilitarian-economic, and discourse-ethical; and highlights the need for further "opening up" of discursive diversity in the development of CDR governance. Castree draws attention to how metaphors in particular will help to govern future action on CDR by framing present-day understandings of a world to come, and in turn how we might responsibly steer the use of metaphors to avoid depoliticization, polarization, or oversimplification. He argues for a "post normal" discourse on CDR, where high-stakes decisions made in the context of epistemic uncertainty are informed by clear reasoning among divergent actors and their values.

Boettcher et al. explore the increasing attention paid to marine CDR, and in particular how developments within four intertwined knowledge systems and governance sectors—namely modeling pathways, climate policy, innovation, and international legal frameworks—could result in different futures. In one future, hype around marine CDR delays decarbonization, while in another, reforms to research and governance practices seek co-benefits between ocean protection, economy, and climate. Lezaun et al. review how the more specific climate policy of a 2050 net zero target in the UK is forcing the integration of two disparate policy domains—forestry and geoengineering—and a more explicit articulation of the role CDR is expected to play. Net zero, they argue, provides an opportunity to bring transparency and accountability to underlying tensions, such as around "natural" and "engineered" CDR, by making explicit the role of CDR and subjecting them to public debate.

INCLUSIVE GOVERNANCE

Borth and Nicholson focus in on this question of public debate by arguing for a deliberative orientation when it comes to the inclusion of CDR into country level climate policy goals. They offer a number of recommendations, including expressing the intent for deliberation directly in Nationally Determined Contributions; embedding considerations of people in institutions responsible for shaping the roles that CDR will play; and ensuring correspondence between project level questions and country level targets. Lezaun proposes a framework for increasing local participation in the assessment of marine CDR in particular, to counter framings such as planetary scale geoengineering that obscure the local and site-specific nature of many marine CDR proposals. He argues that this must begin with expanding the range of actors and factors included in discussions, for example in marine spatial planning. Thinking about global inclusion, Healey et al. warn how CDR policies may be inequitable if they are seen to avoid or delay gross emission reductions, use natural resources at a scale that threatens food security, leave knowledge of CDR as a Global North monopoly, or leave the implications of CDR for development unexamined. The use of CDR, they argue, requires global agreement on reducing emissions and enhancing removals, equity in burden sharing, and an interdisciplinary effort led by individual jurisdictions to create CDR portfolios that are matched to local needs.

REFORMING GOVERNANCE

Turning to the current state of existing CDR governance, Schenuit et al. synthesize commonalities and differences in recent developments in CDR policy in eight OECD countries and the EU, using an analytical framework that draws on the multi-level perspective of sociotechnical transitions. They propose a typology of three varieties of emerging CDR policymaking: incremental modification of existing national policy mixes; early integration of CDR policy that treats emission reductions and removals as fungible; and proactive CDR policy entrepreneurship with support for niche development. Fridahl et al. examine the extent to which existing international (UN), supranational (EU), and national (Swedish) climate policy instruments incentivize bioenergy with carbon capture and storage (BECCS). They find that no instruments create sufficient demand-pull to cover operational expenditure, economic instruments provide only partial technology-push support, and regulatory instruments provide only partial clarity on environmental safeguards and responsibilities. They conclude that the existing policy mix requires substantial reform if BECCS is to contribute to Sweden's or other EU Member States' climate policy targets.

The lack of demand-pull instruments in the EU is further explored by Rickels et al. They observe that despite the emissions cap in the EU Emissions Trading System (ETS) becoming net negative in one of the central EU-wide net zero scenarios, no mechanism allows for the inclusion of CDR credits. They conceptually discuss economic, legal, and political challenges surrounding the integration of CDR credits into the EU ETS. At the US State level, Sanchez et al. contemplate administrative changes to California's Low Carbon Fuel Standard to further stimulate commercialization of promising low carbon and carbon negative fuels. They propose embracing up-to-date science regarding lifecycle greenhouse gas emissions; creating additional, targeted incentives through a volumetric technology carve-out or credit multiplier; and ensuring that the standard stimulates the best-performing fuels across a range of sustainability criteria. In terms of international reforms, Honegger et al. develop six functions which they argue are jointly needed for policy mixes to mobilize CDR in a way that is compatible with the Paris Agreement. These include clarity on the role for CDR; accelerating innovation for affordable and reliable CDR options; ensuring public participation in decision making on CDR; transitioning from piloting to scaled operations; ensuring robust monitoring, reporting, verification, and accounting; and preventing adverse impacts and maximizing co-benefits for sustainable development goals.

More generally, Carton et al. highlight that the obfuscation of emissions reductions by treating emissions and removals as equivalent is not the only problem of equivalence in CDR accounting. To ensure a just response to the climate crisis, they argue for the "undoing" of three additional problematic equivalences in carbon accounting: the equivalence of fossil and biotic forms of carbon; the equivalence of emissions and removals across different geographies; and the equivalence of present and near-term mitigation actions and those projected in the distant future.

CREATING GOVERNANCE

However, reforms can only go so far, and Zetterberg et al. offer five possible models for creating new incentives and financing for BECCS, using Sweden as an example. These include: government guarantees for purchasing BECCS outcomes; quota obligations on selected sectors; allowing BECCS credits to compensate for hard-to-abate emissions within the EU ETS; using private entities for voluntary compensation; and other states acting as buyers of BECCS outcomes to meet their mitigation targets. They conclude that successful implementation of BECCS will require a combination of several of these, implemented sequentially. Also looking at BECCS, Klement et al. argue that pulp and paper mills have potential for commercial roll-out of BECCS, and they seek to find business-driven ways of incentivising BECCS within this industry. By projecting the costs and negative emissions related to BECCS from the pulp mill to typical consumer products, they show how BECCS can substantially reduce their carbon footprint, while only marginally increasing their cost.

GOVERNANCE SYSTEMS

Turning to the wider institutional contexts in which CDR governance is mediated, Hansson et al. analyse BECCS-related expert review comments and author responses on the Intergovernmental Panel on Climate Change (IPCC) Special Report on1.5°C. They show that boundary work at the science-policy interface acts to deflect fundamental critiques of BECCS, particularly regarding the way in which it is presented as a viable technology at a grand scale. This, they argue, threatens to undermine the IPCC's ambition of opening up its scientific work to include more diversity in the process of drafting reports, and potentially also influence the governance of CDR. Palmer and Carton then turn to examine how BECCS is evolving into "BECCUS"—bioenergy with carbon utilization and storage—seeing this as a "fix" for fossil fuel capitalism predicated on reconfiguring the relationship between climate change and energy use, and not simply as an attempt to make BECCS more economically viable. They call for CDR governance to adjudicate between conflicting ideas about the role of intensive energy use in future global sustainable development pathways. Finally, considering the wider systems in which CDR governance will emerge, Hall and Davis argue that critical social science should name and analyse the structural features of capitalism and their relation to CDR and its governance. They offer three principles to assist with this: that CDR is likely to emerge within capitalism, which is crisis prone, growth dependent, and market expanding; that there are different varieties of capitalism and this will affect the feasibility of different CDR policies; and that capitalism is ideologically and culturally maintained.

SUMMARY

The articles in this Research Topic contribute critical knowledge on the framing, inclusiveness, reformation, creation, and systems of emerging CDR governance. These contributions will be invaluable for government, industry and civil society stakeholders seeking to understand, reform and expand governance for CDR. They also represent an important resource for researchers seeking to build upon the nascent questions raised herein. What framings are still missing from the CDR governance debate? How can we implement and evaluate more geographically inclusive CDR governance? How do implemented reforms and new CDR governance creations perform in practice, and what other decision-making processes and policy frameworks might still be needed? How does CDR governance impact and interact with other systems and mechanisms for climate change mitigation and adaptation, and with non-climate goals? And finally, how can institutions and economic systems be reformed to account for alternative perspectives and to embed principles of just governance?

AUTHOR CONTRIBUTIONS

RB wrote the editorial with input from all authors to edit and improve the final text of the article.

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REFERENCES

Bellamy, R. (2018): Incentivize negative emissions responsibly. *Na. Energy* 3, 532–534. doi: 10.1038/s41560-018-0156-6

Bellamy, R., Fridahl, M., Lezaun, J., Palmer, J., Rodriguez, E., Lefvert, A., et al. (2021): Incentivising bioenergy with carbon capture and storage (BECCS) responsibly: Comparing stakeholder policy preferences in the United Kingdom and Sweden. *Environ. Sci. Policy* 116, 47–55. doi: 10.1016/j.envsci.2020.09.022

Bellamy, R., and Geden, O. (2019): Govern CO_2 removal from the ground up. *Nat. Geosci.* 12, 874–876. doi: 10.1038/s41561-019-0475-7

Cox, E., and Edwards, N. (2019): Beyond carbon pricing: policy levers for negative emissions technologies. *Clim. Policy* 19, 1144–1156. doi: 10.1080/14693062.2019.1634509

Fridahl, M., Hansson, A., and Haikola, S. (2020): Towards indicators for a negative emissions climate stabilisation index: problems and prospects. *Climate* 8, 75. doi: 10.3390/cli8060075

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Coming to GRIPs With NETs Discourse: Implications of Discursive Structures for Emerging Governance of Negative Emissions Technologies in the UK

Miranda Boettcher[1,2]*

[1] *Institute for Advanced Sustainability Studies (IASS), Potsdam, Germany,* [2] *Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, Netherlands*

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Edited by:
James Palmer, University of Bristol, United Kingdom

Reviewed by:
Rafael Mattos Dos Santos, University of Guelph, Canada
Mathias Fridahl, Linköping University, Sweden
Nils Markusson, Lancaster University, United Kingdom

***Correspondence:**
Miranda Boettcher
miranda.boettcher@iass-potsdam.de

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As the international community rallies around Net-Zero emissions targets, there is increasing interest in the development of governance for Negative Emissions Technologies (NETs), a range of proposed approaches which involve removing greenhouse gases from the atmosphere. It has been pointed out that the governance development process should include "opening up" the discussion of NETs governance, moving the debate beyond the bounds of technocratic, neoliberal discourse and thereby paving the way for more responsible, inclusive governance of technologies. The implication is that there is a constitutive and qualitative link between discourse and governance – that governance development is shaped by discourse. However, so far there has been limited work done to link empirical mapping of the discursive structures in different spheres of the NETs debate to theoretically-informed anticipation of how these structures may influence governance development. This paper presents a sociology-of-knowledge (SKAD) discourse analysis of a series of interviews with UK representatives from the industry/policy interface about what they consider to be appropriate governance instruments for NETs. Linking discursive structures to governance development using the concept of governmentality, the paper critically discusses how a set of political, economic and ethical discursive structures currently underpinning the industry and policy spheres of the UK NETs debate may be shaping governance development. The paper shows what types of discourse/knowledge and social actors are being privileged/excluded within the structure of the UK NETs debate, and highlights ways in which discursive mapping can play a key emancipatory role in "opening up" governance development processes.

Keywords: discourse analysis, anticipatory governance, governmentality, negative emissions, climate change, sociology of knowledge

INTRODUCTION

As the international community rallies around Net-Zero Emissions Targets, there is increasing interest in the development of governance for Negative Emissions Technologies (NETs) – a range of proposed approaches for removing greenhouse gases, such as carbon dioxide, from the atmosphere (Honegger and Reiner, 2018)[1]. Some argue NETs will be an essential part of future climate response strategies, and that enabling governance is needed to incentivize development. Others emphasize the need for regulatory governance to anticipate and mitigate the potential environmental and socio-political risks of NETs research, development, demonstration and deployment (RDD&D) (Bellamy, 2018; McLaren et al., 2019). However, as the need for near-term governance of NETs RDD&D becomes clearer, calls for the integration of wider societal perspectives into the development of responsible, reflexive governance have become louder on both ends of this spectrum. Prominent proposals for responsible NETs governance are based on the assumption that "opening up" governance debates will move discussions beyond the bounds of technocratic, neoliberal discourse, thereby paving the way for more inclusive, responsible governance of technologies (Stilgoe et al., 2013; Bellamy, 2018; Low and Buck, 2020). The implication is that there is a constitutive and qualitative link between discourse and governance – that governance development is shaped by discourse. However, so far there has been limited work done to link empirical mapping of the discursive structures in different spheres of the NETs debate to theoretically-informed anticipation of how these structures may influence governance development.

In this paper I contribute to filling this gap by presenting a sociology-of-knowledge discourse analysis (SKAD) of a series of interviews – conducted as part of the Greenhouse Gas Removal Instruments & Policies (GRIP) project – with UK representatives from the industry/policy interface about what they consider to be appropriate governance instruments for NETs. Linking discursive structures to governance using the concept of governmentality, I critically discuss how a set of political, economic and discourse ethical structures currently underpinning the industry/policy sphere of the UK NETs debate may shape governance development.

The following section outlines my analytical framework, and illustrates how it can complement existing understandings of the role of discursive diversity in governance development. The subsequent sections present my methodological approach and detail the results of my analysis, showing how discursive structures are bounding and shaping the why (rationales), what (objects), who (subjects and speakers) and how (modes and instruments) of NETs governance in the UK, and highlighting three potentially emergent systems of thinking about the nature of governance, or "governmentalities."

The final section concludes by reflecting upon how coming to "grips" with the structuring role of discourse can contribute to the development of responsible NETs governance by; (1) anticipating and critically reflecting upon how given discursive structures may be making certain types of governance more/less thinkable and practicable, (2) emancipating those engaging in the NETs debate to recognize and (potentially expand the bounds of) the discursive power/knowledge structures they are reproducing, (3) identifying what types of knowledge may be missing in the current debate, and (4) informing the design of deliberative processes to further "open up" discursive diversity in NETs governance development.

ANALYTICAL FRAMEWORK: MAPPING DISCURSIVE STRUCTURES TO ANTICIPATE GOVERNMENTALITIES

The role of discourse in governance development has been increasingly recognized. However, the concept of "discourse" has various theoretical origins, and understandings of the exact nature of its role in political and societal processes are correspondingly diverse (cf. Leipold et al., 2019). A school of thought driven by the work of Jürgen Habermas has often been (implicitly or explicitly) taken up by those who emphasize the need for new modes of responsible and reflexive governance development. The Habermasean theory of discursive ethics puts forward an agency-focused understanding of "discourse," as an debate carried out by strategic actors behaving according to the logic of "communicative rationality." Based on the idea that social actors will argue rationally and equally within an egalitarian "discursive space," this understanding of discourse posits that bringing a range of perspectives and arguments into play will lead to more collectively acceptable, procedurally and substantively "better" governance outcomes (Habermas, 1987, 1996; Kerchner and Schneider, 2006, 2010).

This understanding of the role of discourse has increasingly found resonance within the field of environmental governance, in what some have termed "the deliberative turn [...] an increased attention in environmental politics to procedural qualities such as participation, dialogue, transparency and accountability" (Bäckstrand et al., 2010, p. 3) As others have pointed out, calls for new modes of environmental governance which aim to "open up" politics and make environmental governance development more inclusive and reflexive rest upon this underlying assumption about the nature and role of discourse – that broad participation by public and private actors in (carefully designed) collective discursive processes can "bring about both more legitimate and effective policy outcomes" (Bäckstrand et al., 2010, p. 4). This school of thought has also been taken up within the literature on Responsible Research and Innovation (RRI) of NETs (and climate engineering more broadly), which discusses the potential for egalitarian-consensual deliberative processes to "open up" NETs governance development (for a comprehensive overview of this literature, see: Low and Buck, 2020). However, deliberative engagements on governance development are often far from Habermas' ideal egalitarian discursive space. On the contrary,

[1]Hereafter, NETs. Also known as Carbon Dioxide Removal (CDR) and Greenhouse Gas Removal (GGR). Often included under the umbrella term "climate engineering" (CE), which designates a set of heterogeneous proposals for intentionally intervening into the global climate system to reduce the risks of climate change (Shepherd, 2009).

such deliberative processes are more commonly "underpinned by large asymmetries of power and voice" which privilege certain types of knowledge, shaping what can be authoritatively said, and by whom (Young, 1996; Bäckstrand et al., 2010, p. 18).

I posit that a structural understanding of discourse can help to illuminate these underpinning power/knowledge asymmetries and how they may shape ongoing NETs governance development. In following with the Foucauldian-inspired Sociology of Knowledge Approach to Discourse (SKAD), I conceptualize a "discourse" as an often unrecognized power/knowledge structure – an interrelated system of ideas, concepts and categories – that shapes what it is possible to (legitimately, truthfully, authoritatively) know and say within a given debate. While not completely negating the agency of those engaged in debates, the SKAD approach posits that there is a difference between utterances made by individuals and the underpinning structures that shape such utterances. Rather than being completely free agents, this approach assumes that "in performing their articulations, social actors draw upon the rules and resources that are available via the present state of a given discursive structuration" (Keller, 2018, p. 20), and thus that specific utterances by individuals are (re)producing pre-existing discursive structures[2]. A SKAD analysis therefore aims to reverse-engineer such underlying structures from a pool of individual utterances, and to highlight the role they play in shaping social reality.

This understanding of the shaping function of discursive structures has twofold implications for how to conceptualize and analyze the role of discourse in environmental governance development. First, as discourses constrain how societal and political entities understand social and physical phenomena that are at stake in environmental governance, bringing more voices into deliberative processes may not change or "open up" the debate if all are operating within the bounds of same discursive structures. Rather, these privileged power/knowledge structures may continue to shape all new contributions to the debate, unless they are elucidated. Exposing such discursive structures may result in emancipating participants in a given debate to be more reflexive about the structures we/they are reproducing, and to potentially expand them. A structural understanding of discourse can therefore highlight the need for a different kind of "opening up" in governance development processes: There is a need to find the existing bounds of the discursive "blueprints" before the appropriate knowledge "walls" can be torn down. This is the main aim of mapping discursive structures underpinning governance debates: To assess what knowledge(s) and what truths about governance are influential and predominant, to explore the respective relationships of knowledge and power, and to subject them to criticism (Kerchner and Schneider, 2010; Bäckstrand and Lövbrand, 2016; Stielike, 2017).

[2]Although resilient, a given discursive structuration is not set in stone: by (re)producing selective elements of a given structure, social actors may in turn alter the structure over time. This is aided by the elucidation of the contingency of such structures.

Secondly, a structural understanding of discourse posits a constitutive link between discourse and governance development, emphasizing that "social objects, subjects and relations [...] are contingent and co-constituted through discursive practices that render some [...] knowable and governable and others not" (Leipold et al., 2019, p. 446). By limiting what knowledges and truths about a given issue can be imagined and debated, discursive structures shape the formation of socially meaningful governance rationales, objects, and subjects, and can manifest themselves in the development of corresponding governance modes and instruments (Boettcher, 2019).

The concept of governmentality has been shown to be a useful analytical lens for exploring this constitutive link between discourse and environmental governance development (Stripple and Bulkeley, 2014; Bäckstrand and Lövbrand, 2016). The concept of governmentality was originally introduced by Michel Foucault as "analytical framework" to identify a "concrete historical assemble of elements (objects of knowledge, technologies of governing, practices and fields of the exercise of power)" involved in governing society (Kerchner and Schneider, 2010, p. 15, author's translation). Foucault used this analytical tool to investigate how historically contingent power/knowledge structures shaped differing objects, subjects and practices of governing in western Europe from the 16th to the 20th centuries (Foucault, 2008, p.1978; Kerchner and Schneider, 2010). The concept has since been taken up by the field of Governmentality Studies and further defined as "a system of thinking about the nature of the practice of government (who can govern; what governing is; what and who is governed), capable of making some form of that activity thinkable and practicable to both its practitioners and to those upon whom it is practiced" (Gordon, 1991, p. 3).

The governmentality concept offers a lens which "problematizes the collective and often taken for granted systems of thought that make governing strategies appear natural and given at certain times in history" (Stripple and Bulkeley, 2014, p. 10). Governmentalities "define both the objects (what should be governed) and nature (how they should be governed) of governing, in effect rendering reality governable through the collecting and framing of knowledge" (Bulkeley et al., 2007, p. 2736). As discursive power/knowledge structures are conceptualized as (one of the) constitutive preconditions of governance practices and infrastructures, mapping these structures is aimed at "the making visible [...] of the different ways in which an activity or an art called government has been [is being] made thinkable and practicable" (Burchell et al., 1991, p. ix).

For my analysis, I conceptualize a governmentality as a system of thinking about the nature and practice of governing which (a) is underpinned by a principle form of knowledge, (b) is linked to a particular governance rationale (why), (c) shapes particular governance objects and subjects (what and who), and (d) makes the development of specific governance modes and instruments (how) thinkable and practicable (Burchell et al., 1991; Gordon, 1991; Foucault, 2008, p. 1978; Kerchner, 2010; Kerchner and Schneider, 2010; compare Stripple and Bulkeley, 2014; Stielike, 2017 for discussions of both the Foucauldian original and the recent iterations of the concept)[3].

I use this concept as a heuristic lens to structure and discuss the results of my SKAD analysis. The discursive mapping of the emergence of governmentalities is often done retroactively – tracing the "history of the present" to see how past discursive structures have manifested into current institutions, practices, policies and technologies of governing (Kerchner, 2011; Stripple and Bulkeley, 2014). However, based on the SKAD understanding that the *ongoing* social construction of reality can be discursively traced (Hornridge et al., 2018), I use the concept in an anticipatory manner – by mapping how current discursive structures underpinning the UK NETs governance debate may be forming the "discursive blueprints" for three emerging governmentalities, and critically discussing how they may shape the development of future governance arrangements. Before I present and discuss the results of the analysis, the following section outlines my methodological approach.

METHODOLOGICAL APPROACH: BREAKING DOWN DISCOURSES TO OPEN THEM UP

Data Collection: Interviews

The data pool for my analysis was a series of 25 transcripts of interviews carried out with representatives from the intersection of the UK industrial and policy spheres[4], as discursive structures at the policy/industry interface have previously been shown to be particularly influential in shaping climate and technology governance (Litfin, 1994; Hajer, 1995, 2005; Stripple and Bulkeley, 2014). Sourcing the interviewees was based on two criteria: (1) an active role at the industry/policy interface in the UK, and (2) prior knowledge about NETs[5]. The initial interviewees were asked to suggest further relevant interview partners who fulfilled the above criteria. The resulting pool of interviewees included parliamentarians, ministerial employees, policy advisors, investment advisors, industrial advocacy group members, and industrial organization representatives. The UK was selected for this analysis as it was one of the first major economies to commit itself to achieving a Net-Zero emissions, and as such is one of the few countries with a relatively well-developed debate on the complex issues related to the development and governance of NETs (Daggash et al., 2019; Cox et al., 2020). However, although the interviewees were sourced to be representative of the industry/policy sphere in the UK, the discursive structures identified in this paper are certainly not the only ones being reproduced in the broader NETs governance debate. Rather, this analysis outlines one set of discursive structures at play within what is considered to be one key sphere of the NETs governance debate. Other analyses have shown the importance of assessing discourses and their potential effects on the development of NETs governance in a range of countries, and among diverse stakeholder groups (see e.g., Biermann and Möller, 2019; Cox et al., 2020; Möller, 2020). Mapping discursive structures in wider spheres (i.e., science and civil society) and countries (i.e., other leaders in NETs research such as Germany and the USA, as well as countries of the Global South) to allow for critical comparison with the results presented here is therefore the focus of ongoing research (see e.g., Boettcher, 2019).

The interviews were conducted as part of a larger NETs governance project, entitled the Greenhouse Gas Removal Instruments & Policies (GRIP) project[6]. The stated primary purpose of the interviews was to understand the policy instruments and policy pathways that could help encourage (or if necessary constrain) the research, development, demonstration and deployment (RDD&D) of NETs. Each interview was semi-structured around a series of fifteen questions eliciting the interviewees' opinions on (1) what sorts of NETs approaches should (not) be the focus of policy instruments, (2) why, and (3) how such instruments might be implemented in the UK context. The semi-structured nature of the interviews was designed to encourage further questions to arise as the interviews progressed, to allow responses to be fully probed and explored, and to allow the interviewers to follow up on relevant issues raised spontaneously by the interviewees (cf. Yeo et al., 2013).

Methods: Open Coding and Iterative Structural Mapping

The SKAD discourse analysis approach employed in this study is designed to systematically reverse-engineer discursive structures underpinning a pool of individual utterances: it is an empirical deconstruction and interpretative reconstruction of discursive power/knowledge structures, with the aim to map these structures and to make visible the contingencies in the work they do (Keller, 2018, p. 29). Following the SKAD approach, I first created a data pool of discursive products which contained a range of individual utterances related to a specific topic (in this case a series of interview transcripts about NETs governance), and a set of heuristic questions to guide the search for discursive elements and structuring rules. Reflecting the above elements of governmentality as a heuristic lens, these questions included: *What types of governance rationales are underpinning calls for NETs governance? What is being constructed as the object(s) of NETs governance? What speaker and subject positions are*

[3]I am using a limited governmentality concept which focuses on the discursive elements of emerging governmentality ensembles (which I call discursive 'blueprints'). Other elements of mature governmentality ensembles (i.e. infrastructures, practices, policies, technologies) are not yet able to be assessed because they are in the process of being formed.

[4]This sample size in line with the standard practice in qualitative interview-based research of including between 15 and 30 interviews in case-studies such as this. This ensures that data saturation can be achieved, but does not result in a data pool too large to permit detailed in-depth qualitative analysis. (cf. Guest et al., 2006; Baker and Edwards, 2012).

[5]The initial interviewees had all previously attended workshops, conferences and engagement events on NETs and Climate Engineering more broadly and thus were known to be well-informed on the topic.

[6]The interviews were carried out by a two-person team (a social scientists and a natural scientist) with extensive background knowledge on proposed NETs technologies and policies.

available within the structure of the UK NETs governance debate? What knowledge types are linking these discursive elements into emerging systems of thinking about the practices of governing (governmentalities) in which certain governance modes and instruments are thinkable and practicable?

I undertook a preliminary analysis of the material to identify how the discursive elements "rationales" (why) "governance objects" (what), "speaker/subject positions" (who), and "governance modes/instruments" (how) appeared in the transcripts. I then systematized the transcribed interview data for analysis through a process known as "open coding," which involved inductively organizing the elements identified in the transcripts into categories with the help of the qualitative text analysis program MAXQDA (Hardy et al., 2004). The next step involved identifying recurring rules with which discursive elements were related. These included patterns of classification and differentiation, relationships of equivalence and contrariety between elements of the discourse. This was a recursive process in which preliminary findings were checked against further empirical material from the data pool. My iterative analytical approach is outlined in **Figure 1** and has been described in more detail elsewhere (Boettcher, 2019). The result of this analysis was a map of discursive structures shaping governance rationales, objects, subjects, speakers, modes and instruments in this sphere of the NETs governance debate, and the identification of the types of knowledge linking them into systems for thinking about the nature and practice of governing. The results and their potential implications for NETs governance development are detailed and discussed in the following section.

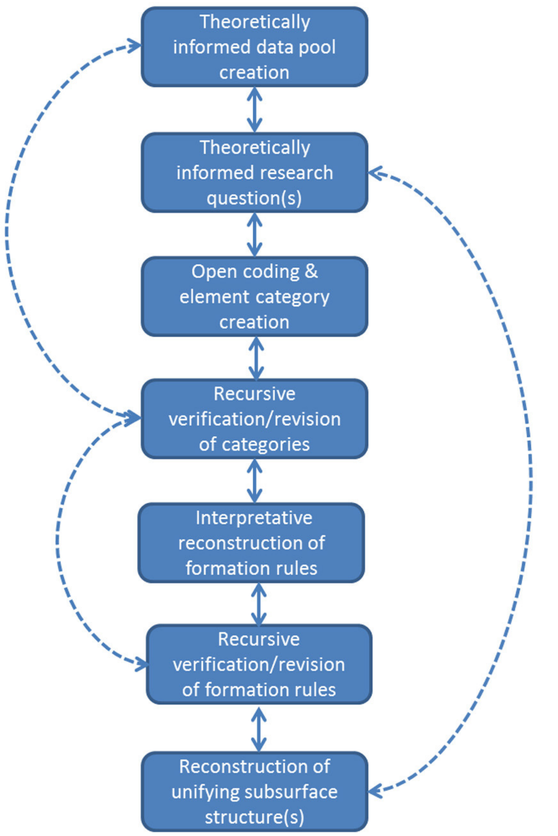

FIGURE 1 | Iterative analytical approach (Boettcher, 2019).

RESULTS AND DISCUSSION: THREE EMERGENT GOVERNMENTALITIES LINKING THE WHY, WHAT, WHO AND HOW OF NETs GOVERNANCE

Results

My analysis showed that the individual discursive elements structuring this sphere of the NETs governance debate are bound by distinct types of political, economic and discourse ethical knowledge, in what may be three "discursive blueprints" for emergent NETs governmentalities (**Table 1**). The following section describes individual elements of these three emergent governmentalities, showing how each (a) is underpinned by a principle form of knowledge, (b) linked to a particular governance rationale (why), (c) shapes particular governance objects (what), provides certain speaker and subject positions (who), and (d) makes the development of specific governance modes and instruments (how) thinkable and practicable.

Governmentality 1: "Keeping It Real"

Key discursive elements of emergent governmentalities are rationales for why governance is needed. Such rationales provide a narrative basis for the formation of the what, who and how of governance. Among the range of rationales (re)produced by interviewees for why they considered the governance of NETs necessary, three categorization patterns based on differing knowledge types emerged (**Table 2**).

The discursive governmentality template G1 is underpinned by a form of realist political knowledge which focuses on power balancing. This is reflected in the strategic governance rationales which provide the "why" within this emerging system of thinking about the nature of governing, positing that the purpose of NETs governance is relative power and responsibility balancing, and strategically positioning the UK within a wider system (i.e., of international climate politics) (cf. Jinnah, 2018; Boettcher, 2019). According to these strategic rationales, governance is deemed necessary for planning of NETs to ensure that the UK is able to meet its agreed political climate targets and establish/solidify its leading position relative to other nations as this new branch of climate policy accelerates, as the following example illustrates: "So our current Conservative government could press ahead with this, with relatively little opposition and a lot of political agreement from Lib Dem and Labor opposition. So if we have that consensus in Britain, why not carry on with this political pretense that the UK is a world leader in tackling climate change, showing how to decarbonise our economy?"(I21)

The interviewees discussed a wide range of proposed NETs approaches, including, peat bog enhancement, biochar, enhanced weathering, ocean alkalinity enhancement, ocean

TABLE 1 | Discusive "blueprints" for emergent NETs governmentalties in the UK industry/policy sphere.

	Knowledge type	Rationales (Why)	Objects (What)	Speakers & *subjects* (Who)	Mode (How)	Instruments (How)
G1 "Keeping it real"	Political realism	Strategic: governance as relative power & responsibility balancing, strategic positioning	External differentiation Approaches suited to achieving strategic aims/political targets	Ambitious leader Conflicted strategist *Uninformed optimist*	Coercion: Punishment and control within a hierarchical structure	Regulation, enforcement of technology standards, MRV, icensing/certification procedures
G2 "Winners come out on top"	Utilitarian economics	Functional: governance as problem solving, risk management, cost-benefit implementation	Internal specification I.e., approaches with best cost/benefit rating	Innovation catalyser: Responsible information provider Profit-maximizer *Unconstructive agitator*	Incentive: Competition within an egalitarian marketplace	Financial incentives, tax rebates, subsidies, prizes, government expenditure
G3 "Let's talk about it"	Discourse ethics	Normative: governance to strengthen existing norms or create new ones, to ensure/increase justice and equality	Internal specification I.e., approaches which are the most societally acceptable, just, equitable	Principled gatekeeper Wise policy demander *Passive policy recipient*	Persuasion: Arguing & bargaining, strategies of communication within a "flat" deliberative space	Education, public deliberation, moral persuasion, political signaling

TABLE 2 | Rationales and knowledge types structing calls for governance.

Governance rationales	Examples	Rationales & knowledge types
NETs governance is need for long-term strategic planning to meet political targets	We need a strategy for developing options to remove greenhouse gases from the atmosphere because they will be vital for the kinds of deep de-carbonization targets. We already have 80 per cent by 2050, but also on the path to Net-Zero emissions and possibly beyond (I2)	G1: Strategic/political: Governance as relative power & responsibility balancing, strategic positionig
NETs governance is needed for the UK to keep up, get ahead: China, America, Germany and other nations are moving ahead on NETs RDD&D.	There are questions around whether the UK wants to – the UK government wants to be a world leader, as it were, in CCS, or whether it would prefer to allow a sort of technology transfer from abroad (I6)	
Mitigation is not enough to mitigate climate risks. Governance should also incentivize development of deployable NETs approaches.	We're not going to make it by mitigation alone, we're failing on mitigation anyway, and that there are these potentially cost-effective win/win solutions that are not being explored (I19)	G2: Functional/economic: Governance involves efforts toward rational problem solving, driven by utilitarian cost-benefit calculations and risk management concepts
Governance policy should not pick winners, but support development of everything that might be useful	My interest I guess is in maintaining a broad sweep of solutions in as far as they are solutions and providing policy to support them (I11)	
The role of governance is to provide market security to ensure investment into NETs development	I think there's enough unused innovation that you could use price signals to unleash some of that (I12)	
Governance is needed to build trust in and understanding of NETs.	That's why I talked about trying to build trust, because at the moment there is very little. And if we could generate that and get people to understand, get governments to commit themselves; […] I think could generate some more trust, and maybe a sense of contracting and converging at the same time (I22)	G3: Discourse ethical/normative Governance to strengthen norms such as justice and equality through the promotion of participation, transparency, legitimacy and responsibility
Governance should ensure broad perspectives are taken into consideration to make decision-making on NETs RDD&D legitimate and robust	If you can actually get to those true constructive multi-stakeholder dialogues you can design really cool policies that are genuinely win-win, internalizing all of that external complexity, have a lot of momentum and support behind them because everyone was involved in their creation, be less likely to fall foul to nature in the real world because you've got more perspectives feeding into it before it needs to go out there and get tested in the real world (I23)	

TABLE 3 | Governnace objects shaped by discusive stuctures.

Categorization structures	Classification criteria	Examples	Rationales & knowledge types
External differentiation: Lumping NETs for governance purposes based on intent	All techniques that help achieve political climate targets by removing CO_2 from the atmosphere	Potentially all negative emissions, one day, will be playing a pivotal role as well, in order to achieve the temperature cap (I5) Well, in the context of the Paris Agreement I suppose it's the concept of Net-Zero that's the key thing, so yes we probably will need GGRs to offset the hard-to-treat sectors to reach net-zero (I8)	G1:Strategic/political: governance as relative power & responsibility balancing, strategic positioning
Internal specification: Splitting NETs for governance purposes based on specific criteria according to underpinning knowledge type	Cost-effectiveness	Cost per ton of carbon removed is an obvious metric. It's a kind of bread and butter metric that's used and there is guidance for policy appraisal on what the value of carbon should be in thinking about whether a strategy is sensible to pursue or not (I2)	G2:Functional/economic: governance as problem solving, risk management, cost-benefit implementation
	Verifiability	From a policy perspective if our reporting and the inventory shows no change but we're deploying all these technologies then it might be good for the atmosphere and the greenhouse gases but it means we can't actually demonstrate that we deliver it. So there is a need to develop the methodologies of how we actually acknowledge the reductions, well the capture (I4)	
	Permanence	But in terms of the interventions required in the carbon cycle, probably 100 years is the target time line. If it isn't going to stay locked up and somehow repurposed for 100 years then it's not going to deliver the climate stability that we need (I21)	
	Scalability	It's the scalability and the impact that we're going to get at the end, isn't it? So how much of this could actually be done really matters, because we're short of capacity to get the job done (I12)	
	Co-benefits	At the other end, it has to be that this is big business. You run the co-benefits properly, you get big numbers (I12)	
	Social acceptability	In terms of public engagement and how the very necessary conversation with the public or involved actors more generally would be, be they individuals or some companies or farmers, whatever, my sense is a more useful engagement for all involved may hang on discussing specific technologies and their range of characteristics going beyond climate change than it would by having a discussion about greenhouse gas removal technologies and how that specific technology fits into the greenhouse gas removal picture (I5)	G3: Discourse ethical/normative: governance to strengthen existing norms or create new ones, ensure/increase justice and equality

fertilization, bioenergy and carbon capture at source (BECCS), ocean afforestation, direct air capture and storage of carbon dioxide (DACS), and methods for enhancing carbon drawdown through agricultural and forestry management practices. As is to be expected when governance for an as-yet nascent set of technologies is being discussed, there was little agreement among interviewees on what specific set of criteria should make a certain NETs technique an object (what) of (enabling or restrictive) governance. However, the cross-cutting analysis revealed two shared structures underpinning the multitude of ways in which interviewees referred to the "what" of NETs governance: The categorization and classification of NETs approaches drew upon patterns of external differentiation - what counts as an a NETs governance object and what does not - and internal specification of specific types of NETs as the objects of enabling or restrictive governance, based on differing types of knowledge (**Table 3**).

The object - the "what" of governmentality G1 - is in keeping with the underpinning political knowledge type: NETs is conceptualized according to the structuring rule of external differentiation as a unified governance object. External differentiation refers to the ways in which objects are defined in contrast to what they are not. As the examples in **Table 3** exemplify, external differentiation of NETs for governance purposes focused on the technologies' intent: According to this broad categorization structure, all proposals with the intent to remove CO_2 from the atmosphere to achieve climate targets (temperature or emissions targets) can be lumped together for governance purposes. Those proposals that do not intend to remove CO_2 from the atmosphere for the purpose of achieving climate targets would not be categorized as NETs for governance purposes (for example CO_2 capture and utilization for enhanced oil recovery). Likewise, measures that aim to achieve climate targets through other means (i.e., emissions reductions or altering the earth's solar radiation balance) are externally differentiated as not falling within the bounds of a broad NETs governance object. External differentiation based on intent is therefore linked to strategic rationales and the associated political logic of G1 which posits NETs governance should enable strategic planning to achieve political ends.

The discursive structures underpinning a given debate offer a range of active speaker positions and passive subject positions to social actors who engage with the topic. Whereas, active speaker

TABLE 4 | Speaker positions (active) offered by discsive structures.

Speaker position	Roles in governance	Examples	Social actors	Knowledge types
Conflicted strategist	Strategically balancing planning long-term policy to prevent dangerous climate change, and acting reactively short-term to maintain political power	Politicians have become less interested in development of ideological thinking that they sell to their constituents, and actually just want power now (I24) If there is a sort of deeper strategic reasoning behind that for how to still actually get to the end goal of 1.5 degrees and saving the future of humankind and back to stable climate and healthy oceans, I've not yet see that manifest within that strategic reasoning. I think it is often thinking one move ahead (I23)	Policymakers, government leaders	G1: Political
Ambitious leader	Taking the lead on NETs, setting an example, developing governance standards for the world	[…] people are saying the UK is one of the more forward thinking countries on GGR against a very sparse background of competitors (I2)	Policymakers, government leaders	
Responsible information provider	Providing unbiased information on risk/benefits of NETs to inform the development of governance	[…] understanding of climate science and the requirement of what needs to be done and then set the challenges around what needs to be done and demonstrate the practicality of achieving some of those challenges (I13)	Scientists, civil society	G2: Economic
Innovation catalyst	Bridging the policy gap to catalyze innovation through investment, thinking long-term, acting rationally to incentivize NETs	I do think the sort of private sector groupings be it within their own industries or with charitable organizations is very important in giving government sometimes a catalyst for action I would say (I1)	Philanthropists, investors	
Self-benefit maximizer	Calling for/supporting NETs polices which maximize their own (financial) benefit/profit	We think regulatory certainty around carbon price is a very good thing, but needs careful thought. In terms of what the money is used for I think there will be lots of people saying it should be used for me, me, me please and Net-Zero technology should be one of a number of things (I15)	Industry	
Wise policy demander	Calling for action in the form of long-term NETs/climate policy for the common good	We think the wider climate change discussion at the moment is about sacrifice and it's about altruism, but it's really taking direct sacrifice and taking a direct hit to your stakeholder group to benefit another stakeholder group (I23)	Publics, civil society	G3: Discourse ethical

positions provide access points for social actors to actively contribute by reproducing certain power/knowledge structures, passive subject positions are discursive "templates" for roles which are commonly associated with silent "others" (Keller, 2018: 36). My analysis revealed a relatively wide range of discursive templates for governance roles available within the structure of the UK NETs debate, as outlined in **Tables 4**, **5**. Six of these are active speaker positions ("conflicted strategist," "ambitious leader," "wise policy demander," "responsible information provider," "innovation catalyst" and "self-benefit maximizer"). Three are passive subject positions ("passive policy recipient, "unconstructive agitator" and "uninformed optimist")[7].

The configuration of speaker and subject positions ("who") available within governmentality G1 privileges political knowledge: If the "what" of governance consists of all NETs approaches that help the UK achieve strategic political goals, and the "why" is relative power balancing by the UK in international (climate) politics, a limited spectrum of active speaker positions are available to social actors who (re)produce this type of political knowledge, while relegating other societal actors to passive subject positions. For example, the "conflicted strategist" speaker position provides a discursive template for social actors strategically balancing long-term NETs policy planning and acting in the short-term to maintain political power. On the one hand, this speaker position is associated with enabling strategic NETs planning to achieve long-term climate targets; on the other, there is also a focus on short term gains, associated with office-seeking policy-makers. An example of an interviewee assigning this speaker position is: "Governments with their short-term views and so forth will wriggle as much as they can and seize on anything instead of tackling the really difficult issues of reducing our energy consumption and emissions" (I22).

Likewise, the "ambitious leader" speaker position offered within G1 involves taking the lead on NETs by setting an example and establishing governance standards for the world, and is associated with policymakers and government leaders, as reflected in the following example: "So both in terms of [. . .] scale up within the UK but also potential where UK has a natural leadership or expertise which it can become a market leader in really. I think that's something it is always quite keen on" (I1).

Also in accordance with the privileging of political knowledge, the "uniformed optimist" subject position available within

[7]Speaker and subject positions are not mutually exclusive. They can be adopted by different types of social actors, and social actors can adopt or be assigned a range of speaker and subject positions, as indicated in **Tables 4**, **5**.

TABLE 5 | Subject positions (passive) offered by discusive structures.

Subject position	Roles in governance	Examples	Social actors	Knowledge types
Uninformed optimist	Optimistic about climate governance, without understanding what needs to be done to achieve political climate targets	There's this huge gap between what people believe is possible and what is actually needed to address the two degree target" (I25) So I would say most people would say you need GGRs in the 2050's without understanding that […] the Committee on Climate Change has set it out as they see I think 48 million tons of […] CO_2 being removed by BECCS by 2050 and that's just there in the model without any understanding of that's a lot and also how […] do we get to that position? (I1)	Civil society, publics	G1: Political
Unconstructive agitator	Raising (unjustified) concerns which risk putting undue restrictions on development of (cost) effective (NETs) solutions to address climate risk	The NGOs [are] all screaming about how this is watering down efforts to invest [in] the things that they want to see delivered (I11) […] but were very clear cut that green groups were being unhelpful and being essentially a blocker to CCS (I14).	Civil society, publics	G2:Economic
Passive policy recipient	Passively waiting to be persuaded, placated, convinced that a given NETs policy is in their best interests	Again, in fields where you could have strong benefits that people get behind, but I feel like you'd need to convince people, you'd need to get the information strategies right (I9) Just giving meaning to the greenhouse gas removal so that people understand it better, and then are able to align the values with what these effectively technical solutions might bring. It just needs to soften them up a bit (I24)	Civil society, publics	G3: Discourse ethical

this governmentality provides a template for a governance subject who does not fully understand the seriousness of the (climate) situation and what needs to be done, but trusts that political actors will be able to solve the problem. This subject position implies elements of technological optimism and a lack of understanding of the socio-political complexity of dealing with climate change. This subject position locates non-political actors (i.e., publics, industries) at the end of the governance development pipeline, where they can only wait to be informed why a policy is in their best interests (see **Table 5** for examples).

My analysis of the shared structures underpinning the multitude of ways in which the interviewees categorized the "how" of NETs governance, and revealed three categorization patterns of coercive, incentivizing and persuasive governance modes and corresponding instruments (**Table 6**).

The "how" of NETs governance within G1 is linked by the realist political logic to the coercive mode of governance which focuses on punishment and control within a top-down, hierarchical structure. This could translate into governance instruments such as bans and moratoria for those types of NETs deemed unsuitable to help achieve strategic political aims, and the enforcement of regulatory control over the development of those that are deemed suitable (**Table 6**). Concretely, this mode of governance can be linked to instruments, including regulations to restrict certain types of NETs activities, the establishment of NETs technology standards and licensing/certification procedures, the enforcement of monitoring, reporting and verification (MRV) procedures, and the development of policy frameworks forcing polluters to finance and/or implement the development of NETs.

Governmentality 2: "Winners Come Out on Top"

This potential governmentality is structured around utilitarian economic knowledge that focuses on the pragmatic weighing of overall costs against overall benefits. As **Table 2** shows, this system for thinking about the nature of governance incorporates functional governance rationales ("why"), positing that NETs governance is primarily about problem solving, risk management, and cost-benefit implementation (cf. Jinnah, 2018; Boettcher, 2019). Economic rationales emphasize that governance policy should not pick NETs winners, but rather allow free competition between alternative options, and that the primary the role of governance is to provide market security to ensure investment into NETs development, as the examples in **Table 2** illustrate.

As shown in **Table 3**, in contrast to the "lumping" categorization of NETs based on external differentiation evident in G1, the economic logic of G2 underpins patterns of internal specification which split NETs into specific objects of governance ("what") based on a range of cost-benefit criteria, for example by specifying governance for more vs. less cost-effective NETs techniques, as the following passage illustrates, "I think anything in the UK context, in the current context, at least, everything is within the current sort of financial – the tone of finances at the minute. Everything must be cost-effective, there's very much a policy focus on making sure that we get the most cost-effective solutions for everything. And I think that would apply to GGR as a whole" (I6).

Within this emergent governmentality, active speaker positions ("who") are offered to those social actors who (re)produce economic knowledge, while passive subject positions are associated with those who do not conform to the utilitarian logic, as illustrated in **Tables 4**, **5**. For example, the "self-benefit maximizer" speaker position provides a template for social actors to push for governance which maximizes their own (financial) benefit and is associated with industrial actors, as the following quote illustrates; "Well, strategy and governance,

TABLE 6 | Governance modes and instruments shaped by discusive structures.

Governance mode	Governance instruments	Examples	Knowledge types
Coercion: Prohibition and punishment within a hierarchical structure	Regulations to restrict certain types of NETs activities, and/or require polluters to implement NETs to comply with emissions limits Enforcement of NETs technology standards, licensing, monitoring, reporting and verification (MRV)	I think that ought to be regulation […] I think with financial incentives, you could create, very quickly, false incentives which you haven't really foreseen (I5) Something else which I think is important is enforcement. […] If you are operating any of these systems and offering any incentives to them, you've got to have a system for monitoring whether or not they are doing what they said they would do, because mostly they don't do it. (I12) I suppose technology standards - we could think about emissions limits. Which would essentially mean that some embitters would require [NETs] in order to comply with those (I14)	G1:Political
Incentive: Competition within an egalitarian marketplace	Financial incentives to conduct certain types of NETs RDD&D, carbon pricing, tax rebates, subsidies, prizes, government expenditure	So you want to get it down to something that's cost effective in a market, which has a sensible carbon price. […] To get there you probably need some kind of tax break or prize and then a little bit more support. And ideally you would bring down that support at the right rate, that you don't spend too much of tax payer's money, but you'd get it into a position where, where there is a carbon tax or a carbon price of some sort, it can compete on its own two feet (I2) [..] effectively a subsidy or a prize for people who are building units of kit, whether it's BECCS or direct air capture or something along those lines. Because then you show that there is financing in here and that the government is serious about trying to make a route to a market of some sort. And also you can flush out what price people think they need to get their stuff to run (I2) It's about incentivising a change in land management which is perceived to have a negative impact on the income of land owners and land managers, so they are looking for some sort of compensatory payment so payment for ecosystem services we think is the most likely way of doing that (I4) I would see the way forward in the financial incentives, and that is the push via the research support and that, potentially, the pull via carbon price (I5)	G2:Economic
Persuasion: Arguing & bargaining within a "flat" deliberative space	Education, moral persuasion, political signaling, public deliberation & dialogue on the potential advantages/disadvantages of NETs	It's really important that if we're going to do big things, like making some interventions in the balance of land use around the planet, in order to help stabilize our planetary system for future generations, there needs to be a dialogue to explain to the people who can be bothered to read about it why this is necessary and why on balance it's the right thing to do (I4) And then the other kind of model that's coming out of this discussion is one where communities feature in some kind of sense […] because they have a certain interest in preserving a certain kind of environment or a certain kind of livelihood, and that therefore they have to be the arbiters of what works (I22)	G3:Discourse ethical

I mean I would have thought you'd be looking at the fit with our existing economic pressures, so the potential for this to be of benefit to us given market opportunities etc. would be influential" (I16).

The utilitarian logic likewise underpins the "responsible information provider" speaker position available within G2. Social actors adopting this speaker position are offered a privileged role in providing unbiased information to help weigh up the risks and benefits of NETs and thus inform the development of governance. This speaker position is associated primarily with scientific experts, as can be seen in this example, "You need simplification and clarity around the regulation. So you need a scientific consensus over what is the lifecycle of the various kinds of materials that might be used in this way" (I12).

The "innovation catalyst" speaker position available within G2 likewise reproduces an economic logic, providing a template for governance roles: acting (economically) rationally to incentivize NETs RDD&D, and bridging the policy gap by driving innovation through investment. This speaker position is associated with both private and public financial investors. An example of an interviewee reproducing this speaker position is: "Another way to this has got to be the institutional investors. If you can convince the institutional investors that they need to take this more seriously, that is as powerful as BlackRock – [as the] top 10 largest countries in terms of the size of their funds. If you can get them to start paying, I think that's just as powerful as the government coming out with strategies. It's never going to be great, but the institutional investors are highly rational, they think long-term" (I25).

Conversely, the "unconstructive agitator" subject position within this governmentality assigns a discursive template for social actors raising (unconstructive and unjustified) non-utilitarian concerns about NETs governance which risk putting undue restrictions on the development of potential (cost-effective) solutions to address climate risks. Rational economic actors are thus posited as being confronted with "the wrath of the highly polarized argumentation that the NGO and advocacy movement has around greenhouse gas removal" (I25).

The constellation of economically informed rationales, objects and subjects within this governmentality has consequences for the "how" of NETs governance: The economic logic translates into the governance mode of incentivisation to promote competition among different types of NETs activities within an open market place, and could materialize into governance instruments such as direct government expenditure or subsidies for NETs development, as outlined in **Table 6**. Concretely, this can be related to the establishment of instruments which provide financial incentives to conduct certain types of NETs RDD&D, including carbon pricing, tax rebates, subsidies, prizes, and direct government expenditure.

Governmentality 3: "Let's Talk About It"

The elements that make up the discursive blueprint for this potentially emergent governmentality are organized around a form of discourse ethical knowledge that focuses on consensus-building around the "common good" and the persuasive powers of communication in deliberative democratic processes. This governmentality incorporates normative governance rationales ("why"), which advance that governance should strengthen norms such as justice, equality, transparency, legitimacy and responsibility through, inter alia, the promotion of stakeholder participation in deliberative democratic practices (**Table 2**).

The governance objects ("what") within the nascent governmentality G3 are shaped by patterns of internal specification based around ethical criteria in line with its underpinning knowledge type, primarily resulting in a split between more (potentially) socially acceptable vs. less socially acceptable NETs approaches as potential governance objects, as the following example shows: "So some of these techniques are actually quite radical and will require some strange things to happen, so understanding how the public perception would be on this, especially as you're looking at something which needs to be approved by ministers and MPs and they reflect the public opinion of their constituents. So if it's something that's going to engender a lot of negative public reaction you've got to be aware of that quite early on" (I4).

The configuration of speaker and subject positions ("who") within G3 offers the "wise policy demander" as an active speaker position to publics to participate in calling for long-term NETs policy for the common good. This stands in contrast to the passive subject positions assigned to publics in the other governmentalities (**Table 4**), and is associated with publics and civil society actors. An example of an interviewee reproducing this speaker position is: "And so I think the public [...] can be very wise on these subjects and worth consulting; and I think that is a policy option is for governments at many levels [...], to consider proper public consultation [...] Then they will very likely come out with a wise suggestion" (I22).

The discourse ethical knowledge that links governance rationales, objects and subjects in this "system of thinking about the nature and practice of governing" also has implications for the types of governance modes and instruments ("how") which may emerge if this governmentality manifested: In accordance with the discourse ethical assumption that persuasive communication with an egalitarian deliberative space will lead to a consensus around the most collectively acceptable governance options, the governance mode "persuasion" is key: facilitating societal decision-making on NETs RDD&D through communication, education, moral persuasion, political signaling, public deliberation and dialogue on the potential advantages and disadvantages of individual NETs approaches (**Table 6**). This could, in turn, materialize in NETs governance instruments that focus on education, moral persuasion and political signaling, with increased emphasis on deliberative and participatory governance processes.

Discussion

These three discursive blueprints for emerging governmentalities are not to be taken as firmly established, mutually exclusive, or exhaustive. As pointed out in the methods section, the selection of interviewees from the UK policy/industry sphere means that the results outlined here only represent discursive structures underpinning one *sphere* of a larger NETs debate within the UK, which is in turn part of a much larger transnational discussion. This means that the discursive blueprints detailed above and outlined in **Table 1** are ideal types, elements of which are being reproduced by those engaged in this specific sphere of the UK NETs debate. Using these ideal types as a reference, we can inquire if similar systems of thinking about the nature and practice of governance may also be underpinning broader discussions of NETs and climate policy, and help to identify what types of knowledge present in the wider debate may be marginalized in the UK industry/policy sphere.

In their review of multilevel policies with potential relevance for NETs in Sweden, Fridahl and Bellamy identified a similar set of incentivisation, coercion, and persuasion governance modes as those outlined above, which – building on a categorization of policy instruments introduced by Bemelmans-Videc et al., – they call "carrots, sticks, and sermons" (Bemelmans-Videc et al., 2010; Fridahl and Bellamy, 2018). Their mapping exercise showed that the majority of current policy instruments with relevance for NETs in Sweden fell into the "carrots" or economic incentivisation category, underpinned by an economic logic analogous to the one I identified as being key to G2. Similarly, in their exploration of potential policy levers for negative emissions technologies, Cox and Edwards highlight the predominance of economic incentivisation logics in policy proposals based on carbon taxation in the NETs literature (Cox and Edwards, 2019). Further recent examples of NETs policy proposals which similarly reflect an economic logic include: Direct governmental payments to land managers and farmers for the provision of ecosystem services through carbon sequestration in soil and the biosphere (Lal, 2020), including bioenergy with carbon capture and storage (BECCS) in the Swedish carbon tax incentive mechanism (Karlsson et al., 2017), an international market mechanism to link financing of NETs to sustainable development (Honegger and Reiner, 2018) and the proposed introduction of negative emissions credit mechanism in the UK (Platt et al., 2018).

The literature also contains NETs policy proposals reflecting coercive, political logic similar to the one I identified underpinning G1. Fridahl and Bellamy call policies which reflect a coercive governance mode "sticks," and the examples they highlight in the Swedish case include regulatory instruments to provide "clarity on rules and responsibilities related to prospecting, building, and operating transport and storage facilities" for captured CO_2 (Fridahl and Bellamy, 2018, p. 66). Other authors have similarly highlighted proposals for the enforcement of top-down regulatory control over NETs RDD&D processes, for example via Environmental Impact Assessment procedures (EIAs) and the establishment of legal authorization processes for (surface and subsurface) land use (Hubert and Reichwein, 2015; Hester, 2018). Others have called for the establishment of centralized monitoring, reporting and verification (MRV) procedures to hold companies, industries and states accountable for their NETs achievements, identify "leaders and laggards" and ensure that those who lag behind politically prescribed Net-Zero targets can held (financially) responsible (Geden and Schenuit, 2020). Some have also suggested direct coercive measures which place an obligation on emitters to implement NETs – for example by "requiring new and/or existing fossil fuel power plants to be converted to biomass and fitted with a CCS [carbon capture & storage] facility" (Bellamy, 2018, p. 533).

In contrast to the economic and political logics, the discourse ethical knowledge type I identified underpinning G3 seems less well represented in the wider NETs policy literature. In their abovementioned review, Fridahl and Bellamy noted there was a "dearth" of NETs policy instruments in line with the persuasive governance mode in the Swedish case (Fridahl and Bellamy, 2018, p. 67). Similarly, in an international comparison of emerging policy perspectives on climate engineering more broadly, Huttunen et al. noted a dominance of techno-economic logics in policy documents which may preclude the participatory integration of wider societal and political perspectives in policy development (Huttunen et al., 2015). In one of the first reviews of the international peer-reviewed literature on the social and political dimensions of large-scale NETs, Waller et al. also show that techno-economic framings of NETs feasibility remain predominant, but that a "responsible development" framing is emerging which focuses on "opening up" NETs governance to include perspectives, reflecting a similar discursive logic to that outlined in G3 (Waller et al., 2020). Some concrete suggestions have been brought forward from within the Responsible Research and Innovation (RRI) community on how to develop policy for NETs in ways which adhere to the discourse ethical logic (Stilgoe et al., 2013). Proposals in this vein include deliberative workshops with both experts and members of the public designed to elicit diverse understandings of NETs experiments and their governance (Bellamy et al., 2017) and deliberative mapping processes with citizen panels to "open up" socio-technical appraisals of NETs for governance purposes (Bellamy, 2016; Bellamy et al., 2016, 2017).

Zooming out even further, the above results – outlining what may be discursive precursors to future "systems for thinking about the nature of NETs governance" – also allow comparison with established governmentalities which have been shown to structure climate change and environmental governance more broadly. Historical analyses of climate governance by Bäckstrand and Lövbrand have identified three competing "meta discourses" underpinning climate governance in the last 20 years: "green governmentality" which is based on a hierarchical, administrative logic, "ecological modernization," which reflects a neoliberal market logic, and "civic environmentalism," which is built upon a logic of democratic participation (Bäckstrand and Lövbrand, 2006, 2016). The political knowledge system of G1 outlined above shares the top-down logic of green governmentality. G2 and ecological modernization are both based on economic knowledge. The discursive structures which make up G3 share much with what Bäckstrand and Lövbrand term the "reformist" strand of civil environmentalism, which calls for "opening up" decision-making processes to deliberation by a wider range of stakeholders (ibid). These governance meta-discourses, in turn, can be tied to a longer arc of liberal and neoliberal governmentalities outlined by historical Foucauldian analyses of western democracies (Foucault, 2008; Kerchner, 2010; Kerchner and Schneider, 2010). Governing logics which have historically underpinned climate and carbon governance (and western democratic governance *per se*) are therefore seemingly being reproduced within NETs governance discourse, highlighting the persistent shaping function of existing power/knowledge structures on the emergence of new objects, subjects and instruments of governance (Carton et al., 2020; Low and Boettcher, 2020; McLaren and Markusson, 2020).

Comparing the discursive structures I identified in my analysis with those present in wider NETs and climate governance literatures can also help point out what types of knowledge may be being marginalized in UK industry/policy sphere of the debate. Multiple authors have shown that principles of distributive and intergenerational justice and equity will be key to developing responsible governance of NETs and other global climate response strategies, and have correspondingly called for the integration of relevant knowledge types into policy development processes (Clingerman and O'Brien, 2014; Jenkins, 2016; Clingerman and Gardner, 2018; Cox et al., 2018; Lenzi, 2018; Lenzi et al., 2018; McLaren, 2018; Schneider, 2019). Although governmentality G3 is based on the rationale that deliberative democratic practices are needed to strengthen norms such as equality, transparency, legitimacy and responsibility in governance development processes, the discourse ethical logic that underpins it focuses on issues of procedural justice. Rationales, objects and speaker positions focusing on issues of distributive and intergenerational justice and equity were not integral to this emergent governmentality. The discursive structures I identified only offered one active speaker position to social actors who may reproduce a limited kind of (discourse) ethical knowledge ("wise policy demander"), as compared to much wider range of active speaker positions available to political and economic social actors in this sphere of the UK NETs governance debate (see **Table 4**).

Similarly, the "system critical discourse of climate justice" identified as having emerged in wider discussions of climate change governance in recent years, which calls for fundamental power/knowledge shifts to give marginalized groups democratic control over climate governance, was not directly reflected in my findings (Bäckstrand and Lövbrand, 2016). Indeed, the presence of the negative "unconstructive agitator" subject position being assigned to non-utilitarian "others," and the way in which it is juxtaposed with economic and political speaker positions, indicates that this type of system critical discourse *is* present, but is being constituted as external to the discursive structure that shapes what it is possible to (legitimately, authoritatively) know and say within the industry/policy sphere of the NETs debate (Torfing, 1999; Hajer, 2005).

The triad of political, economic and discourse ethical power/knowledge types I identified at the UK industry/policy interface may therefore be marginalizing ethics and justice-based knowledge types that have been posited as having relevance for the governance of NETs specifically and climate governance more broadly.

CONCLUSION: COMING TO GRIPs WITH THE SHAPING EFFECTS OF DISCOURSE ON EMERGING GOVERNANCE

As the above results highlight, a structural discourse analytical approach can illuminate discursive power/knowledge relations at work within governance debates. I have shown that three types of knowledge are currently present at the industry/policy interface of the UK NETs governance debate; one political, one economic, and one discourse ethical. Each of these knowledge types links a particular governance rationale (why), certain governance objects (what), particular speakers and subjects (who), and specific governance modes and instruments (how) into a system of thinking about the nature and practice of governing.

Correspondingly, I have shown that three "discursive blueprints" for political, economic and discourse ethical governmentalities may be emerging in this sphere of the NETs governance debate: The political governmentality "Keeping it real" is based on a strategic governance rationale, lumps NETs approaches together for governance purposes based on their suitability in achieving political climate targets, privileges political actors in the development of top-down NETs governance, and is linked to coercive, hierarchical governance instruments. The economic governmentality "Winners come out on top" is based on a functional governance rationale, splits NETS approaches for governances purposes based on their relative costs and benefits, privileges utilitarian actors in a competitive governance development space, and is linked to instruments of incentivisation. The discourse ethical governmentality "Let's talk about it" is based on a normative governance rationale, splits NETs approaches for governance purposes based on their relative social acceptability, privileges rationally arguing actors in a deliberative governance development process, and is linked to persuasive governance instruments (**Table 1**). My analysis has shown that these three discursive blueprints for systems of thinking about the nature of NETs governance may also be present in wider discussions of NETs policy instruments, and be further reproducing elements of green governmentality, ecological modernization and civic environmentalism which have historically shaped wider climate governance. This raises the question as to whether NETs governance may end up being shaped by the same power/knowledge structures that have been criticized for producing climate governance arrangements which delay the decarbonization of the global economy, and how this could be circumvented (Low and Boettcher, 2020; McLaren and Markusson, 2020).

In this vein, my findings have implications for recognizing, reflecting and acting to overcome the power dynamics both between and within different knowledge systems in the NETs governance debate. First of all, contrary to expectations sometimes put forward by those who call for the NETs governance debate to be "opened up," my analysis has shown that the technocratic, utilitarian, neoliberal knowledge system is not the only one currently underpinning NETs discussions at the policy/industry interface in the UK (cf. Bellamy et al., 2012; Low and Buck, 2020). While the "Winners come out on top" governmentality (G2) adheres to this type of knowledge system, the other two are based on different types of knowledge (political and discourse ethical). Interestingly, the deliberative democratic approach to governance often advocated by those calling for more perspectives to be integrated into NETs governance development is already present in the debate in the form of the discourse ethics governmentality (G3).

Second, although it highlighted that there is more than one type of discourse/knowledge system at play within this sphere of the NETs governance debate, my analysis has shown that the range of knowledge(s) being systematically reproduced is still limited. Comparing my findings with the wider literature has shown that the discursive structures I have identified in this sphere of the NETs debate reflect western, liberal-democratic and anthropocentric dynamics that have been shown to be dominant in broader climate governance (Bäckstrand and Lövbrand, 2016; Hamilton, 2018; McLaren and Markusson, 2020). Climate ethics and justice knowledge is seemingly being constituted as largely external to the discursive structure that shapes what it is possible to (legitimately, authoritatively) know and say within the industry/policy sphere of the NETs debate.

Third, my analysis has shown that "publics" in this sphere of the NETs debate are often constructed within systems of knowledge that perpetuate external control and decision-making structures in which they are constituted as passive governance *subjects* rather than active governance *speakers*. As **Table 3** shows, the range of active speaker positions offers multiple access points for political and economic social actors to actively contribute to the UK NETs governance debate, but only one speaker position ("wise policy demander") is associated with publics. Conversely, as **Table 4** illustrates, passive subject positions provided by the structure of this sphere of the NETs governance debate were all associated with publics and civil society actors. These are the "passive policy recipient": A governance subject who is passively waiting to be persuaded, placated, convinced that a given NETs policy is in their best interests; the "unconstructive agitator": A governance subject who is counter-productive, raising (unjustified) concerns which risk putting undue restrictions on the development of potential (cost-effective) solutions to address climate risks; and the "uninformed optimist": A governance subject who does not fully understand the seriousness of the (climate) situation and what needs to be done. This imbalance in the distribution of active speaker positions and passive subject positions may give social actors who reproduce political and economic knowledge more privileged positions in this sphere of the NETs governance debate.

These findings emphasize the continued need for increased recognition of the shaping effects of discursive power/knowledge structures on governance development, and improved strategies for those engaged in these processes to reflect upon and expand them. In this vein, those attempting to "open up" the NETs governance debate should ensure that they (and those they are encouraging to enter the debate) are able to recognize and critically reflect upon of the discursive power/knowledge structures within which they are operating (and may end up reproducing), and how these may solidify into governance instruments and infrastructures. Herein lies the emancipatory function: By mapping how certain types of governance are discursively being rendered thinkable and practicable, my analytical framework exposes the contingent nature of emerging NETs governance, and enables critical reflection of seemingly self-evident or necessary governance developments (Lövbrand and Stripple, 2011, p. 188). Such critical reflection may help anticipate how NETs governance can avoid the pitfalls of previous climate governance (Low and Boettcher, 2020).

In addition to this emancipatory function, my structural analytical approach can have some practical value when designing and facilitating future deliberative processes which aim to increase discursive diversity in NETs governance development: As my findings suggest, simply bringing together a diverse range of types of stakeholders to discuss NETs governance does not guarantee that a broad range of discourses will be represented equally, as existing power/knowledge dynamics may mean diverse stakeholders reproduce the same discursive structures. Rather, before designing a deliberative process, it is important to first have a structural overview which types of discourses are being privileged/excluded in a given debate and context. Subsequently, this "map" of the discursive structures could inform pre-screening of potential participants (i.e., in the form of a questionnaire or an interview) to see what sort of discursive structures they reproduce, which subject/speaker positions they assign or adopt, and which types of knowledge they privilege or exclude. This can build upon existing approaches to "unframing" in deliberative processes (Bellamy and Lezaun, 2017): Discursive mapping prior to deliberative workshop could be used to show participants the "structure" of their own discursive positioning and how they relate to others, thereby exposing, comparing and contrasting different knowledges underpinning "reality inputs" into deliberative processes. Making underpinning knowledges involved in the co-production of objects and subjects explicit could help participatory processes overcome systemic inequalities (Chilvers et al., 2018).

The results of discursive mapping could thus inform the design and facilitation of a deliberative process which (a) includes participants who (re)produce diverse discursive structures, and/or (b) encourages them to recognize and potentially expand the bounds of existing power/knowledge dynamics. The Foucauldian approach iterates that discursive structure is "not so much like a steel web as a spider's"; while we are unable to completely escape its grip, "we are not so trapped as to be immobilized" (Lipschutz, 2014, p. xvi). Elucidating the bounds of a given structure can therefore afford social actors some wriggle room to expand the discursive conditions of possibility (Keller, 2018). Additionally, these sorts of discursive mapping exercises may result in the co-production of diverse discursive templates that can be built upon to facilitate discussion and action on NETs governance in the UK. For example, the sorts of results outlined above could provide the elements of several (complementary or competing) speculative NETs policy narratives which could be used as the basis of participatory processes to deliberate upon different types of NETs governance.

In sum, these results demonstrate that coming to "grips" with the structuring role of discourse has clear benefits for the development of responsible NETs governance: Anticipating how given discursive structures may be coalescing into systems of knowledge that make certain types of governance thinkable and practicable, and elucidating their contingent nature can enable those engaging in the NETs debate to recognize (and potentially expand) the discursive power/knowledge structures they are reproducing. Such structural mapping helps to identify what types of knowledge may be missing in the current debate, and could inform the design of deliberative processes to further "open up" discursive diversity in NETs governance development.

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 human participants were reviewed and approved by Central University Research Ethics Committee (CUREC), Unviversity of Oxford. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

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

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REFERENCES

Bäckstrand, K., Kahn, J., Kronsell, A., and Lövbrand, E. (2010). "The promise of new modes of environmental governance," in *Environmental Politics and Deliberative Democracy: Examining the Promise of New Modes of Governance,* eds K. Bäckstrand, J. Kahn, A. Kronsell and E. Lövbrand (Cheltenham: Edward Elgar Publishing). doi: 10.4337/9781849806411

Bäckstrand, K., and Lövbrand, E. (2006). Planting trees to mitigate climate change: contested discourses of ecological modernization, green governmentality and civic environmentalism. *Glob. Environ. Polit.* 6, 50–75. doi: 10.1162/glep.2006.6.1.50

Bäckstrand, K., and Lövbrand, E. (2016). The road to paris: contending climate governance discourses in the post-copenhagen era. *J. Environ. Policy Plan.* 21, 519–532. doi: 10.1080/1523908X.2016.1150777

Baker, S. E., and Edwards, R. (2012). *How Many Qualitative Interviews is Enough? National Centre for Research Methods Review Paper*. (London: Economic and Social Research Council (ECRC) National Centre for Research Methods (NCRM)).

Bellamy, R. (2016). A sociotechnical framework for governing climate engineering. *Sci. Technol. Hum.* 41, 135–162. doi: 10.1177/0162243915591855

Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nat. Energy* 3, 532–534. doi: 10.1038/s41560-018-0156-6

Bellamy, R., Chilvers, J., and Vaughan, N. E. (2016). Deliberative mapping of options for tackling climate change: citizens and specialists 'open up' appraisal of geoengineering. *Public Underst. Sci.* 25, 269–286. doi: 10.1177/0963662514548628

Bellamy, R., Chilvers, J., Vaughan, N. E., and Lenton, T. M. (2012). A review of climate geoengineering appraisals. *WIREs Clim. Change* 3, 597–615. doi: 10.1002/wcc.197

Bellamy, R., and Lezaun, J. (2017). Crafting a public for geoengineering. *Public Underst. Sci.* 26, 402–417. doi: 10.1177/0963662515600965

Bellamy, R., Lezaun, J., and Palmer, J. (2017). Public perceptions of geoengineering research governance: an experimental deliberative approach. *Glob. Environ. Change* 45, 194–202. doi: 10.1016/j.gloenvcha.2017.06.004

Bemelmans-Videc, M. L., Rist, R. C., and Vedung, E. O. (2010). *Carrots, Sticks, and Sermons: Policy Instruments and Their Evaluation.* New Brunswick and London: Transaction Publishers.

Biermann, F., and Möller, I. (2019). Rich man's solution? Climate engineering discourses and the marginalization of the global south. *Int. Environ. Agreements Polit. Law Econ.* 19, 151–167. doi: 10.1007/s10784-019-09431-0

Boettcher, M. (2019). Cracking the code: how discursive structures shape climate engineering research governance. *Env. Polit*. 29, 890–916. doi: 10.1080/09644016.2019.1670987

Bulkeley, H., Watson, M., and Hudson, R. (2007). Modes of governing municipal waste. *Environ. Plan. A Econ. Space* 39, 2733–2753. doi: 10.1068/a38269

Burchell, G., Gordon, C., and Miller, P. (1991). *The Foucault Effect: Studies in Governmentality.* Chicago, IL: Chicago University Press. doi: 10.7208/chicago/9780226028811.001.0001

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *WIREs Clim. Change* 11:e671. doi: 10.1002/wcc.671

Chilvers, J., Pallett, H., and Hargreaves, T. (2018). Ecologies of participation in socio-technical change: the case of energy system transitions. *Energy Res. Soc. Sci.* 42, 199–210. doi: 10.1016/j.erss.2018.03.020

Clingerman, F., and Gardner, G. (2018). *Playing God: Mutli-faith Repsonses to the Prospect of Climate Engineering*. Highland Park, NJ: Greenfaith.

Clingerman, F., and O'Brien, K. J. (2014). Playing god: why religion belongs in the climate engineering debate. *Bull. Atomic Sci.* 70, 27–37. doi: 10.1177/0096340214531181

Cox, E., and Edwards, N. R. (2019). Beyond carbon pricing: policy levers for negative emissions technologies. *Clim. Policy* 19, 1144–1156. doi: 10.1080/14693062.2019.1634509

Cox, E., Spence, E., and Pidgeon, N. (2020). Incumbency, trust and the monsanto effect: stakeholder discourses on greenhouse gas removal. *Environ. Values* 29, 197–220. doi: 10.3197/096327119X15678473650947

Cox, E. M., Pidgeon, N., Spence, E., and Thomas, G. (2018). Blurred lines: the ethics and policy of greenhouse gas removal at scale. *Front. Environ. Sci.* 6:38. doi: 10.3389/fenvs.2018.00038

Daggash, H. A., Heuberger, C. F., and Mac Dowell, N. (2019). The role and value of negative emissions technologies in decarbonising the UK energy system. *Int. J. Greenhouse Gas Control* 81, 181–198. doi: 10.1016/j.ijggc.2018.12.019

Foucault, M. (2008). *Security, Territory, Population: Lectures at the College De France, 1977 – 78*. New York, NY: Picador.

Fridahl, M., and Bellamy, R. (2018). "Multilevel policy incentives for BECCS in Sweden," in *Bioenergy with Carbon Capture and Storage: From Global Potentials to Domestic Realities,* ed M. Fridahl (Brussels: The European Liberal Forum (ELF)).

Geden, O., and Schenuit, F. (2020). "Unconventional mitigation: carbon dioxide removal as a new approach in EU climate policy," in *SWP Research Paper, 8/2020.* (Berlin: Stiftung Wissenschaft und Politik -SWP- Deutsches Institut für Internationale Politik und Sicherheit).

Gordon, C. (1991). "Governmental rationality: an introduction," in *The Foucult Effect: Studies in Governmentality*, eds G. Burchell, C. Gordon and P. Miller (Chicago, IL: University of Chicago Press), 1–51.

Guest, G., Bunce, A., and Johnson, L. (2006). How many interviews are enough?: an experiment with data saturation and variability. *Field Methods* 18, 59–82. doi: 10.1177/1525822X05279903

Habermas, J. (1987). *The Theory of Communicative Action, Vol. 2, Life World and System*. Boston, MA: Beacon Press.

Habermas, J. (1996). *Between Facts and Norms: Contribution to a Discourse Theory of Law and Democracy*. Cambridge, MA: MIT Press. doi: 10.7551/mitpress/1564.001.0001

Hajer, M. A. (1995). *The Politics of Environmental Discourse: Ecological Modernization and the Policy Process : Ecological Modernization and the Policy Process.* Oxford: Oxford University Press.

Hajer, M. A. (2005). "Coaltions, practices, meaning and environmental politics: from acid rain to BSE," in *Discourse Threory in European Politics,* eds. J. Torfing and D. Howard (Hampshire and New York, NY: Palgrave MacMillan), 297–314. doi: 10.1057/9780230523364_13

Hamilton, S. (2018). The measure of all things? The anthropocene as a global biopolitics of carbon. *Eur. J. Int. Relat.* 24, 33–57. doi: 10.1177/1354066116683831

Hardy, C., Phillips, N., and Harley, B. (2004). Discourse analysis and content analysis: two solitudes? *Qual. Multi Method Res.* 2, 19–22. doi: 10.5281/zenodo.998649

Hester, T. (2018). Legal pathways to negative emissions technologies and direct air capture of greenhouse gases. *Environ. Law Reporter* 5, 10413–10432. Available online at: https://www.law.uh.edu/faculty/thester/Legal%20Pathways%20to%20Broad%20Use%20of%20NETs%20and%20DAC%20by%20Hester.pdf (accessed November 11, 2020).

Honegger, M., and Reiner, D. (2018). The political economy of negative emissions technologies: consequences for international policy design. *Clim. Policy* 18, 306–321. doi: 10.1080/14693062.2017.1413322

Hornridge, A.-K., Keller, R., and Schünemann, W. J. (2018). "Introduction: the sociology of knowledge appraoch to discourse in an interdependent world," in *The Sociology of Knowledge Appraoch to Discourse: Investigating the Politics of Knowledge and Meaning-Making,* eds A.-K. Hornridge, R. Keller and W. J. Schünemann (New York, NY: Routledge), 1–15. doi: 10.4324/9781315170008-1

Hubert, A.-M., and Reichwein, D. (2015) "An exploration of a code of conduct for responsible scientific research involving geoengineering," in *IASS Working Paper & InSIS Occasional Paper* (Potsdam & Oxford). doi: 10.2139/ssrn.3513900

Huttunen, S., Skytén, E., and Hildén, M. (2015). Emerging policy perspectives on geoengineering: an international comparison. *Anthr. Rev.* 2, 14–32. doi: 10.1177/2053019614557958

Jenkins, W. (2016). "Stewards of irony: planetary stewardship, climate engineering and religous ethics," in *Theological and Ethical Perspectives on Climate Engineering: Calming the Storm*, eds F. Clingerman and K. J. O'Brien (New York and London: Lexington Books), 149–164.

Jinnah, S. (2018). Why govern climate engineering? A preliminary framework for demand-based governance. *Int. Stud. Rev.* 20, 272–282. doi: 10.1093/isr/viy022

Karlsson, H., Delahaye, T., Johnsson, F., Kjärstad, J., and Rootz, J. (2017). *Immediate Deployment Opportunities for Negative Emissions with BECCS: A Swedish Case Study*. Available online at: https://arxiv.org/abs/1705.07894 (accessed November 11, 2020).

Keller, R. (2018). "The sociology of knowledge approach to discourse: an introduction," in *The Sociology of Knowledge Approach to Discourse: Investigating the Politics of Knowledge and Meaning-Making*, eds. R. Keller, A.-K. Hornridge and Schünemann (New York, NY: Routledge). doi: 10.4324/9781315170008

Kerchner, B. (2010). "Juridischer diskurs und ökonomisches kalkül: zu foucaults kritik des rechtsstaat," *in Rechtsstaat und Demokratie:Transdisziplinäre Analysen zum Deutschen und Spanischen Weg in die Moderne,* eds D. G. Schulze, S. Berghahn, F. O. Wolf (Münster: Westfälisches Dampfboot).

Kerchner, B. (2011). "Kerchner 2011 vielfalt, komplexität oder intersektionalität: zum einsatz der diskurstheorie in der geschlechterforschung," *in Gender Politik Online*. Available online at: https://www.fu-berlin.de/sites/gpo/pol_theorie/Zeitgenoessische_ansaetze/Vielfalt__Komplexit__t_oder_Intersektionalit__t/index.html (accessed November 11, 2020).

Kerchner, B., and Schneider, S. (2006). *Foucault: Diskursanalyse der Politik, Eine Einführung*. Wiesbaden: VS Verlag für Sozialwissenschaften. doi: 10.1007/978-3-531-90475-7

Kerchner, B., and Schneider, S. (2010). Government, governance, governmentalität. *Femina Polit.* 19, 9–23. Available online at: https://shop.budrich-academic.de/wp-content/uploads/2017/09/1433-6359-2010-2.pdf#page=10 (accessed November 11, 2020).

Lal, R. (2020). The role of industry and the private sector in promoting the "4 per 1000" initiative and other negative emission technologies. *Geoderma* 378:114613. doi: 10.1016/j.geoderma.2020.114613

Leipold, S., Feindt, P. H., Winkel, G., and Keller, R. (2019). Discourse analysis of environmental policy revisited: traditions, trends, perspectives. *J. Environ. Policy Plan.* 21, 445–463. doi: 10.1080/1523908X.2019.1660462

Lenzi, D. (2018). The ethics of negative emissions. *Glob. Sustain.* 1:e7. doi: 10.1017/sus.2018.5

Lenzi, D., Lamb, W. F., Hilaire, J., Kowarsch, M., and Minx, J. C. (2018). Weigh the ethics of plans to mop up carbon dioxide. *Nature* 561, 303–305. doi: 10.1038/d41586-018-06695-5

Lipschutz, R. D. (2014). "Foreword: order! order in the house!," in *Governing the Climate,* eds. J. Stripple and H. Bulkeley (New York, NY: Cambridge University Press).

Litfin, K. T. (1994). *Ozone Discourses : Science and Politics in Global Environmental Cooperation*. New York, NY: Columbia University Press.

Lövbrand, E., and Stripple, J. (2011). Making climate change governable: accounting for carbon as sinks, credits and personal budgets. *Crit. Policy Stud.* 5, 187–200. doi: 10.1080/19460171.2011.576531

Low, S., and Boettcher, M. (2020). Delaying decarbonization: climate governmentalities and sociotechnical strategies from copenhagen to Paris. *Earth Syst. Governance* 5:100073. doi: 10.1016/j.esg.2020.100073

Low, S., and Buck, H. J. (2020). The practice of responsible research and innovation in "climate engineering." *WIREs Clim. Change* 11:e644. doi: 10.1002/wcc.644

McLaren, D., and Markusson, N. (2020). The co-evolution of technological promises, modelling, policies and climate change targets. *Nat. Clim. Change* 10, 392–397. doi: 10.1038/s41558-020-0740-1

McLaren, D. P. (2018). Whose climate and whose ethics? Conceptions of justice in solar geoengineering modelling. *Energy Res. Soc. Sci.* 44, 209–221. doi: 10.1016/j.erss.2018.05.021

McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B., and Markusson, N. O. (2019). Beyond "Net-Zero": a case for separate targets for emissions reduction and negative emissions. *Front. Clim.* 1:4. doi: 10.3389/fclim.2019.00004

Möller, I. (2020). Political perspectives on geoengineering: navigating problem definition and institutional fit. *Glob. Environ. Polit.* 20, 57–82. doi: 10.1162/glep_a_00547

Platt, D., Workman, M., and Hall, S. (2018). A novel approach to assessing the commercial opportunities for greenhouse gas removal technology value chains: developing the case for a negative emissions credit in the UK. *J. Cleaner Prod.* 203, 1003–1018. doi: 10.1016/j.jclepro.2018.08.291

Schneider, L. (2019). Fixing the climate? How geoengineering threatens to undermine the SDGs and climate justice. *Development* 62, 29–36. doi: 10.1057/s41301-019-00211-6

Shepherd, J. (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. London: The Royal Society.

Stielike, L. (2017). *Entwicklung Durch Migration: Eine Postkoloniale Dispositivanalyse am Beispiel Kamerun-Deutschland*. Bielefeld: Transcript Verlag. doi: 10.14361/9783839439807

Stilgoe, J., Owen, R., and Macnaghten, P. (2013). Developing a framework for responsible innovation. *Res. Policy* 42, 1568–1580. doi: 10.1016/j.respol.2013.05.008

Stripple, J., and Bulkeley, H. (2014). *Governing the Climate: New Approaches to Rationality, Power and Politics*. Cambridge, CA: Cambridge University Press. doi: 10.1017/CBO9781107110069

Torfing, J. (1999). *New Theories of Discourse: Laclau, Mouffe and Zizek.* Oxford: Blackwell Publishers.

Waller, L., Rayner, T., Chilvers, J., Gough, C. A., Lorenzoni, I., Jordan, A., et al. (2020). Contested framings of greenhouse gas removal and its feasibility: social and political dimensions. *WIREs Clim. Change* 11:e649. doi: 10.1002/wcc.649

Yeo, A., Legard, R., Keegan, J., Ward, K., McNaughton Nicholls, C., and Lewis, J. (2013). "In-depth interviews," in *Qualitative Research Practice: A Guide for Social Science Students and Researchers,* eds J. Ritchie, J. Lewis, C. McNaughton Nicholls and R. Ormston (Los Angeles, CA: Sage Publications), 177–210.

Young, M. I. (1996). "Democracy and difference: contesting the boundaries of the political," in *Communication and the Other: Beyond Deliberative Democracy,* ed S. Benhabib (Princeton, NJ: Princeton University Press).

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Mapping Multi-Level Policy Incentives for Bioenergy With Carbon Capture and Storage in Sweden

Mathias Fridahl[1], Rob Bellamy[2], Anders Hansson[1] and Simon Haikola[3]*

[1] Department of Thematic Studies, Unit of Environmental Change, The Centre for Climate Science and Policy Research (CSPR), Linköping University, Linköping, Sweden, [2] Department of Geography, University of Manchester, Manchester, United Kingdom, [3] Department of Thematic Studies, Unit of Technology and Social Change, Linköping University, Linköping, Sweden

Bioenergy with carbon capture and storage (BECCS) is considered a key mitigation technology in most 1.5–2.0°C compatible climate change mitigation scenarios. Nonetheless, examples of BECCS deployment are lacking internationally. It is widely acknowledged that widespread implementation of this technology requires strong policy enablers, and that such enablers are currently non-existent. However, the literature lacks a more structured assessment of the "incentive gap" between scenarios with substantive BECCS deployment and existing policy enablers to effectuate BECCS deployment. Sweden, a country with progressive climate policies and particularly good preconditions for BECCS, constitutes a relevant locus for such examinations. The paper asks to what extent and how existing UN, EU, and Swedish climate policy instruments incentivize BECCS research, development, demonstration, and deployment in Sweden. The analysis is followed by a tentative discussion of needs for policy reform to improve the effectiveness of climate policy in delivering BECCS. Drawing on a tripartite typology of policy instruments (economic, regulatory, and informational) and the ability of these instruments to create supply-push or demand-pull, the article finds that: (1) no instruments create a demand-pull to cover operational expenditure; (2) economic instruments provide partial support for research and the capital expenditure associated with demonstration, and; (3) regulatory instruments provide partial clarity on environmental safeguards and responsibilities. A few regulatory barriers also continue to counteract deployment. The article concludes that the existing policy mix requires considerable reform if BECCS is to contribute substantially to the Swedish target for net-zero emissions. Continued effort to dismantle regulatory barriers must be complemented with a strong demand-pull instrument that complements the current focus on supply-push incentives. If unreformed, the existing policy mix will most likely lead to substantial public expenditure on BECCS research, development, and demonstration without leading to any substantial deployment and diffusion.

Keywords: bioenergy with carbon capture and storage (BECCS), governance, incentives, negative emissions, policy instruments, regulation

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Sabine Fuss, Mercator Research Institute on Global Commons and Climate Change (MCC), Germany

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****Correspondence:***
Mathias Fridahl
mathias.fridahl@liu.se

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INTRODUCTION

Achieving the goal of the Paris Agreement, to limit global warming well below 2°C, will require a radical transformation of the world's fossil-fuel-dependent energy systems. In the last decade, bioenergy with carbon capture and storage (BECCS) has become a key mitigation technology in the majority of 2°C scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) (Fuss et al., 2014; IPCC, 2018). Various conceptual BECCS technology systems have been proposed. All of them capitalize on the ability of plants to absorb carbon dioxide (CO_2) from the atmosphere during growth. The biomass is then intended to be used in various operations in which the re-released CO_2 is captured, transported, and stored geologically.

While climate change mitigation scenarios deploy BECCS on a large scale, real world deployment is close to non-existent. Few countries are actively investigating the scope of BECCS deployment (Moe and Røttereng, 2018); Sweden is one of few exceptions. In 2017, a broad majority in the Swedish parliament adopted a net-zero greenhouse gas (GHG) emissions target to be achieved by 2045. Sweden shall also achieve net-negative emissions after 2045. In practice, this is specified as at least an 85% reduction of economy-wide GHG emissions by 2045, compared to 1990 levels, and offset the remaining emissions through so-called supplementary measures including the option to use BECCS. The maximum amount of supplementary measures is, thus, restricted to 15%, which translates into 10.7 million metric tons (Mt) of CO_{2eq}. Because the feasibility of achieving negative emissions remains uncertain, the Government of Sweden appointed a committee in July 2018 to investigate the role that enhanced land-use, land-use change and forestry (LULUCF), BECCS, and verified emission reductions in other countries could play in reducing residual emissions to zero. In January 2020, the committee delivered its final report to the government in which it proposed two indicative targets for BECCS: 1.8 Mt of stored CO_2 by 2030 and 3.0–10.0 $MtCO_2$ by 2045. The delivery of these levels, however, is seen as dependent on reforming existing or implementing new policy instruments capable of providing adequate incentives for businesses to engage in BECCS deployment (GoS, 2020c).

Sweden, with a large modern bioeconomy, has unusually good preconditions for BECCS and is therefore a particularly relevant national case study. In 2018, Sweden emitted 32.3 $MtCO_2$ from biomass-based fuels. This can be compared to the total emissions of GHGs that amounted to 51.8 $MtCO_{2eq}$. While emissions of GHGs have fallen by 27% in the period 1990–2018, CO_2 emissions from biomass-based fuels have increased by 161% (**Figure 1A**). During the same period, the net removals in the Swedish LULUCF sector remained stable at a high level. Net LULUCF removals in 1990 amounted to 34.5 $MtCO_{2eq}$, which had increased to 42.0 $MtCO_{2eq}$ by 2018. Although the inter-annual variation is high and in part linked to events such as storms and wildfires, the trend indicates a slight increase in Swedish net LULUCF removals (SEPA, 2020). Indeed, the share of biomass-based energy supply in Sweden is exceptional among high-income countries (Ericsson and Werner, 2016).

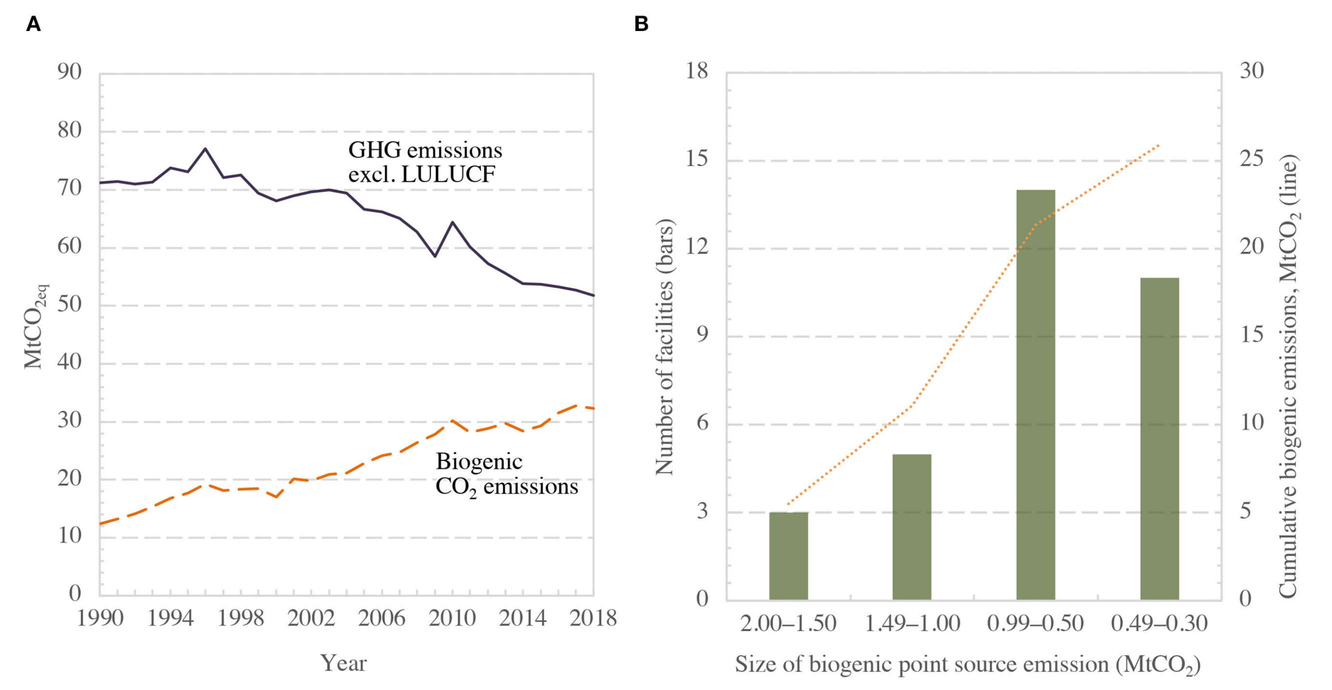

FIGURE 1 | (A) Swedish total territorial emissions of greenhouse gases excluding land-use, land-use change, and forestry (LULUCF), and emissions of biogenic carbon dioxide, 1990–2018. **(B)** Number of facilities in categories of size of biogenic CO_2 point source emissions (bars) and their total cumulative emissions (line). Sources: Statistics Sweden (2020) and SEPA (2020).

A substantial amount is used in the large-scale production of electricity, heat, pulp and paper, biofuels, and cement. As a rule of thumb, Swedish uses a cascade model, e.g., biomass used for energy is typically sourced from waste fractions from the forest industry (Rodriguez et al., 2020).

One example of the Swedish potential for BECCS is provided by a key basic industry in Sweden; the production of pulp. In 2019, biogenic emissions from the 10 largest pulp and paper facilities amounted to 13.0 $MtCO_2$ (SEPA, 2020). Several other large point sources of biogenic CO_2 exist too, such as in the energy sector (including several bioenergy and waste-to-energy facilities) and the chemical industry, including bioethanol production (see **Figure 1B**).

Some of these industries can partly recover the electricity loss for the separation of CO_2 as useful heat. This is particularly applicable to combined heat and power plants (Levihn et al., 2019). One prominent example is the biomass-dedicated boiler at Värtaverket in Stockholm with 0.9 Mt biogenic CO_2 released in 2019 (SEPA, 2020). Others, such as many pulp and paper mills, could utilize excess heat to capture CO_2 (Kuparinen et al., 2019). There are also substantial amounts of biogenic CO_2 emitted from Sweden's many waste incineration plants as well as a few larger point sources from biogas and bioethanol production (Fridahl, 2018). All of the above make Sweden an interesting case for exploring policy incentives for BECCS research, development, demonstration, and deployment (RDD&D).

Thus, with the large Swedish bioeconomy including substantial point sources of biogenic CO_2, it seems feasible that BECCS can be utilized to deliver on making Sweden a net-zero emitter by 2045 and net-negative thereafter. Nevertheless, the character and the extent of the incentive gap between tentative targets for deployment and existing policy enablers remain unclear. This paper, therefore, seeks to systematically map and characterize the incentive gap between a scenario in which BECCS contributes significantly to fulfilling Swedish climate objectives and the extent to which existing UN, EU, and Swedish climate policy instruments are likely to spur BECCS deployment.

It should be noted that Sweden has not committed to a specific level of BECCS or even to BECCS as such. At the time of writing, the proposed intermediary BECCS target for 2030 (GoS, 2020c; SOU, 2020) has not been adopted by Swedish Parliament. The Swedish Government has, however, dedicated funding to the Swedish Energy Agency in the budget bill for 2021, to administer an economic incentive for BECCS. The budget bill, which is currently under deliberation in Parliament, specifies that "[t]he ambition shall be to establish the program for support of operational costs during 2022, to speed up BECCS deployment" (GoS, 2020a: UO21, p. 32). It should also be noted that there is no scientific consensus on what would constitute adequate commitment by Sweden under the Paris Agreement. The incentive gap explored herein, thus, should be understood as a gap between current policy and a *scenario* in which BECCS plays a significant role in fulfilling Swedish climate targets, such as the levels proposed by the public inquiry (GoS, 2020c). The scenario has not been adopted by Parliament and hereinafter is referred to as tentative. If the scenario were to be adopted, it could still be argued to represent an inadequate level of ambition (see, for example, Anderson et al., 2020). This article is relevant against the backdrop of such a scenario. The analysis and conclusions provide a starting point for redesigning the policy instrument mix if and when a policy commitment to BECCS is agreed on.

The article proceeds as follows. The next section provides a background to BECCS in general and our case study country Sweden, outlines the analytical framework applied, and describes the method for data collection. The Findings section maps and discusses incentive structures of international, supranational, and national policy instruments of relevance to BECCS in Sweden. Finally, Concluding discussion section discusses emerging patterns in the existing policy mix and offers a number of recommendations for more effective policymaking in terms of giving BECCS a significant role in fulfilling Swedish climate targets.

ANALYTICAL FOCUS AND METHOD

Analytical Focus

The need for negative emissions provides a new context for policy development. Previous literature on this topic has acknowledged that current policy instruments are often unfit for the delivery of carbon removals. Since CCS installed at a biomass-based operation increases capital and operational expenditure without producing any benefits beyond mitigation, Gough and Upham (2011) have noted that its deployment "depends on clearly regulated limits to CO_2 emissions or on a carbon price" (p. 329). Cost-optimal climate change mitigation scenarios mainly drive the deployment of specific technologies through assumptions on the technologies' mitigation potential, marginal abatement cost curves, and carbon price levels (Keith et al., 2006; van Vliet et al., 2014). This speaks to the issue of the carbon price levels at which BECCS can be incentivized, but not to the issue of the types of policy instruments that can achieve such price levels or what other types of instruments can incentivize BECCS in the absence of a high carbon price. Most low-carbon energy industries face significant market barriers due to the entrenched power of incumbents (Bonvillian and Van Atta, 2011), and the time horizon of venture capital is ill-suited for developing clean-techs that typically require longer periods of trial and error before being able to compete on the market (Gaddy et al., 2017). Thus, given that BECCS provides no added value to end-users, it is unlikely that a state of technological maturity through the prevailing market structure will be reached.

It should be emphasized, as pointed out by Tanzer and Ramírez (2019), that the effectiveness of BECCS in generating negative emissions, from a system-perspective, requires a full accounting of emissions and removals from "cradle-to-grave" (p. 1216). To maximize the climate benefits of BECCS, policy instruments need to minimize climate impact across all steps of technological systems, i.e., from the *production of biomass* as the primary energy source via efficient *capture* technologies, to safe and effective *geological storage*. Effects should even be factored in, e.g., on feedbacks and changed albedo (Tanzer and Ramírez, 2019; Fridahl et al., 2020). Policy making can target all of these aspects. Policy instruments for the sustainable production of biomass-based energy supply have been analyzed at length in the literature (Henders and Ostwald, 2012; Cambero and Sowlati, 2014; Su et al., 2015). Such an analysis will not be reproduced here. This article instead focusses on a substantial gap in the literature: policies for directly incentivizing the capture of CO_2 beyond the achievement of zero emissions. Policies pertaining to geological storage are part of this effort and are common to all CCS, no matter the origin of the CO_2 (fossil or biogenic). These are discussed in detail in the literature on fossil CCS (Bachu, 2008; Liu et al., 2016), the focus herein is on recent developments in storage-related policy or when such instruments lead to competitive dis-/advantages for BECCS vis á vis fossil CCS.

Policy Instruments and Their Evaluation

Public policy involves multiple actors and interconnected phases ranging from agenda setting, via policy formulation and decision making, to implementation and evaluation (Fischer et al., 2007). Policy instruments are defined as "the techniques or means through which states attempt to attain their goals" (Howlett, 2011: p. 22), i.e., the specific part of public policy involving the political tools to reach objectives.

Bemelmans-Videc et al. (2010) have developed a 3-fold typology of policy instruments, which they refer to as economic, regulatory, and informational instruments. Economic instruments involve "the handing out or the taking away of material resources while the addressees are not obligated to take the measures involved" (p. 32). Examples include affecting market processes through taxation, the provision of subsidies, and tradeable emissions permits. Regulatory instruments are measures taken to "influence people by means of formulated rules and directives which mandate receivers to act in accordance with what is ordered in these rules and directives" (p. 31). Examples include direct controls to limit permissible levels of emissions and the specification of mandatory processes or equipment. Informational instruments are "attempts at influencing people through the transfer of knowledge, the communication of reasoned argument, and persuasion" (p. 33). Examples include public information campaigns and appeals to corporate social responsibility.

We further distinguish between the ability of different types of policy instruments to instigate change at different steps in the development and deployment of technologies. Developing technology niches often take time and are marked by multiple failures and slow learning. When niches have been established, the cost of production per unit of output (such as per unit of captured CO_2) often falls dramatically due to economies of scale and incremental learning. This technology phase is therefore typically marked by more rapid seizure of market shares until demand is fulfilled at specific costs (Lehmann and Gawel, 2013; Mercure et al., 2014; Hammond, 2018). As such, the volume of output for a technology through the phases of development, regime introduction, diffusion, and market saturation is often depicted with an S-shaped curve (Rogers, 2003), see **Figure 2**.

Since existing policies are often modeled on existing sociotechnical systems, new technologies developed in niches often find it hard to compete with established technologies in existing regimes. This factor, together with many other dynamics, such as technology and policy lock-in effects including sunk costs, contribute to technology regimes being marked by conservatism and stability (Utterback, 1994; Geels, 2002;

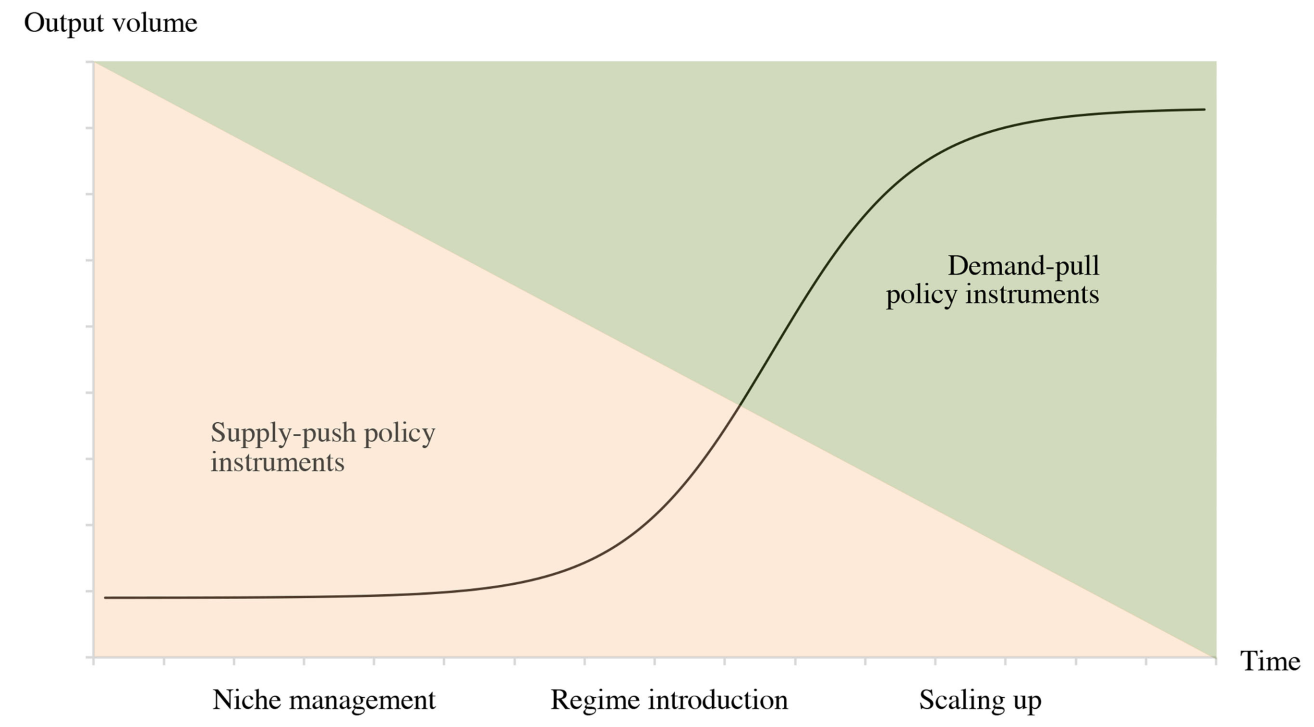

FIGURE 2 | Schematic S-curve for technology development and deployment in existing sociotechnical regimes.

Berkhout et al., 2004; Amars et al., 2017). Transitioning to a low- or net-zero emissions economy is therefore challenging. Political interventions are often required to instigate change in sociotechnical systems, such as by making new climate-friendly technical solutions competitive on existing markets. The effective and efficient use of policy to support specific technologies, such as BECCS, requires a policy mix that is capable of addressing different needs in the development, regime introduction, and diffusion phases. At low levels of technology maturity and industrial expertise, policy makers should target supply-push instruments capable of establishing niches. These may include research grants, support to knowledge centers, and subsidies for pilots and demonstration projects. Instruments capable of instigating a demand-pull are often needed when a technology matures and expertise increases (Hammond, 2018). Such instruments may include taxation or cap-and-trade systems, quota obligations, and certificate trading or systems of fees and dividends. A mix of policy instruments is often recommended to enable overcoming various types of market failures associated with blocking new technical solutions that would contribute to the fulfillment of policy objectives, such as combating climate change (Lehmann and Gawel, 2013; Gawel et al., 2017).

We used the tripartite typology of policy instruments provided by Baumol and Oates (1979) to classify different existing policy instruments at the international, supranational, and national levels. It should be noted that only *direct* incentives were evaluated; the indirect dynamic effects of other types of policy were not considered here. Regulatory instruments were assessed in terms of whether they provide favorable conditions for or raise barriers to BECCS in Sweden. Drawing on Vihma (2012), the legal arrangement was qualitatively evaluated as "soft" (amorphous, non-legally binding recommendations) or "hard" (generating precise, binding, and enforceable obligations) pertaining to BECCS in Sweden (also see e.g., Skjærseth et al., 2006; Karlsson-Vinkhuyzen and Vihma, 2009). Economic and informational instruments were assessed in terms of whether they provided weak, moderate, or strong positive incentives, did not provide incentives or disincentives, or disincentivized BECCS in Sweden. The level of incentivization was qualitatively assessed drawing on frameworks for the difficult but highly relevant *ex-ante* assessments of instrument effectiveness to initiate change at depth and at multiple levels of governance (Herrick and Sarewitz, 2000; Oikonomou et al., 2012). We did not intend to make sharp distinctions between the different levels of incentivization. Indeed, given the "uphill struggle" that faces BECCS innovators (Bellamy and Healey, 2018), it could well be argued that any lack of incentive for BECCS constitutes a disincentive. Instead, we distinguished between levels of incentives to approximate their likely influence on industrial actors or innovators that can drive the RDD&D of BECCS.

The primary scope of the instruments was also assessed, distinguishing between whether the instruments targeted: (1) research, development, demonstration, and/or deployment of BECCS technology and; (2) capture, transport, and/or storage elements of the BECCS technology chain. This allows for identifying gaps in what might represent a more coherent approach to incentivizing BECCS across instrument types and their primary scope, at multiple levels of governance. The analytical framework is summarized in **Table 1**.

TABLE 1 | Summary of the analytical framework to categorize and specify the relevance of economic, regulatory, and informational policy instruments for BECCS RDD&D.

Issue	Instrument type	Analytical category
Governance level	All	The following governance levels are targeted: (1) International, i.e., UN and regional multilateral; (2) Supranational, i.e., the EU, and; (3) National, i.e., Sweden
Scope	All	The instruments are evaluated in terms of their scope, i.e., carbon dioxide: (1) Capture; (2) Transport, and; (3) Storage
Primary intended effect	All	The instruments are evaluated in terms of the change they seek to instigate: (1) Supply-push (research, development, and demonstration); (2) Demand-pull (deployment and diffusion)
Direction of effect	Economic and informational instruments	The instruments are evaluated in terms of providing: (1) Incentives; (2) Neither incentives nor disincentives (lack of incentive), and; (3) Disincentives
	Regulatory instruments	The instruments are evaluated in terms of being: (1) Favorable, or; (2) A barrier
Relevance to BECCS	Economic and informational instruments	Used as a proxy for their importance to BECCS, incentives/disincentives are evaluated as: (1) Weak; (2) Moderate, or; (3) Strong
	Regulatory instruments	The regulations are evaluated as: (1) Soft (unspecific, guiding, facilitative), or; (2) Hard (precise, binding, and enforceable)

After mapping the multi-level landscape for direct incentives of relevance to BECCS in the different RDD&D phases in Sweden, the paper discusses the incentives provided by the aggregate, multi-level policy mix.

Legal Repositories

Empirically, this study focused on three data sources. First, at the international level, it focused on the most central international bodies related to BECCS, i.e., the treaties and decisions of the UN Framework Convention on Climate Change (UNFCCC), the International Maritime Organization (IMO), the Convention on Biological Diversity (CBD), the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), and the Baltic Marine Environment Protection Commission

(HELCOM), as well as the methodological guidelines on GHG inventories of the Intergovernmental Panel on Climate Change (IPCC). All documents were accessed via the UNFCCC and the IMO online repository for treaties and decisions and the IPCC document portal.

Second, at the supranational level, it focused on EU regulations (directly binding), directives (that specify goals to be implemented through domestic laws), and decisions that addressed Sweden or Swedish industry (that are binding on those they address), as well as policy evaluations commissioned by the EU Commission (*ex-post* as well as *ex-ante* evaluations). All documents were accessed via the EU online repository for laws and preparatory acts, EUR-Lex.

Third, at the national level, it focused on Swedish laws and strategies (such as guidelines, goals, and directions agreed on by Parliament) as well as government-commissioned policy evaluations (*ex-post* as well as *ex-ante* evaluations) conducted by the most central government agencies concerned with BECCS (i.e., the Swedish Energy Agency, the Swedish Environmental Protection Agency, and the Geological Survey of Sweden). All documents were accessed via the Swedish Government's online repository for laws and the Swedish Parliament's online repository for bills and other policy-related documents.

For access to all repositories, see "Data Availability Statement" below.

FINDINGS

International Level: UN and Regional Multilateral Cooperation

Sweden has ratified several international agreements of which the UNFCCC, the Kyoto Protocol, and the Paris Agreement are among the most relevant for BECCS. However, some IMO regulations also impact incentives for BECCS, as do guidelines developed by the IPCC and agreed on by the UNFCCC (**Tables 2**, **3**).

Economic Instruments

While the UNFCCC mostly sets out policy goals and principles, the Kyoto Protocol includes a stronger regulatory component: quantified emissions limitation and reduction objectives for developed countries. It also includes three economic instruments to increase the cost effectiveness of meeting the objectives: the Clean Development Mechanism (CDM), Joint Implementation (JI), and Emissions Trading (ET) (UNFCCC, 1998: Articles 12, 6, and 17). The rules regulating the flexible mechanisms under

TABLE 2 | International (UN and regional multilateral) economic policy instruments of direct relevance to BECCS RDD&D in Sweden, in descending order of significance.

Instrument	Effect and scope	Description	Incentives provided
The Paris Agreement to the UNFCCC, Article 6, cooperative approaches (UNFCCC, 2016: 1/CP.21)	Deployment Capture Transport Storage	The 2015 Paris Agreement established a credit-based market mechanism and international trading with so-called "emission reduction outcomes." The rules for operating the mechanism and trading are currently under negotiation. The crediting mechanism to promote mitigation and support sustainable development is likely to start operating in a fashion similar to the CDM. How this mechanism will attract finance and how liquidity is to be maintained at high carbon prices remains unresolved	N/A (rules currently under negotiation)
The Kyoto Protocol to the UNFCCC, Article 17, Emissions trading (UNFCCC, 1998: 1/CP.3)		ET allows developed country Kyoto Protocol members to sell surplus Assigned Amount Units (AAUs) to other countries	Lack of incentive: through a general oversupply of Kyoto Protocol assigned amount units, leading to low prices. However, it puts framework conditions in place for regional emissions trading systems to be used in compliance with Kyoto commitments
The Kyoto Protocol to the UNFCCC, Article 12, the Clean Development Mechanism, CDM (UNFCCC, 1998: 1/CP.3)	Deployment Capture Transport Storage	The CDM, established in 1997 with operational rules agreed on in 2001, is in part an instrument of tradeable emission rights. Developed countries can invest in mitigation activities (CDM projects) in developing countries. Proven emissions reductions, compared to a baseline, generate tradeable emission rights that can be used for developed countries' compliance with their Kyoto Protocol commitments. In 2011, the UNFCCC decided to include CCS in the CDM	Lack of incentive: targets deployment outside Sweden and through an extremely low price on CDM-certified emission reduction credits generated by BECCS, following on a market collapse
The Kyoto Protocol to the UNFCCC, Article 6, Joint Implementation, JI (UNFCCC, 1998: 1/CP.3)	Deployment Capture Transport Storage	JI is similar to CDM but only involves developed country parties. Typically, a country with a mature market economy would use JI to invest in economies in transition	Lack of incentive: through a general oversupply of JI emission reduction units, leading to low prices

TABLE 3 | International (UN and regional multilateral) regulatory and informational policy instruments of direct relevance to BECCS RDD&D in Sweden, in descending order of significance.

Instrument	Type, effect, and scope	Description	Incentives provided
The London Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter, including amendments to Annex 1 [IMO, 1996: LP.4(8); 2006: LP.1(1)]	Regulatory Deployment Transport Storage	The London Protocol, agreed in 1996, regulates sub-seabed disposal of CO_2 (Annex 1) and transboundary movement of CO_2 (Article 6)	Favorable (hard): adopts the 2006 amendment to dispose of CO_2 in sub-seabed storage complexes
Amendment of Article 6 of the London Protocol [IMO, 2009: LP.3(4); 2019: LP.5(14)]	Regulatory Deployment Transport	The London Protocol was amended in 2009 to allow export of CO_2 for disposal provided that an agreement or arrangement has been entered into by the countries concerned. A resolution agreed in 2019 allows for the provisional application of the 2009 amendment until the latter has entered into force	Favorable (hard): allows the provisional application of the 2009 amendment that circumvents the London Protocol's export prohibition. Yet it raises barriers by creating high administrative burdens pending lack of entry into force of otherwise more simplified procedures
The Convention for the Protection of the Marine Environment of the North-East Atlantic [OSPAR], including amendments to Annex 2 and 3 (OSPAR Commission, 1992)	Regulatory Deployment Storage	A regional multilateral convention for cooperation on the protection of the marine environment in the North-East Atlantic. Originally agreed on in 1972 and 1974, substantially updated in 1992, and with amendments of relevance to CCS concluded in 2007, the Convention currently has 16 contracting parties, including the EU	Favorable (hard): allows sub-seabed storage in accordance with the amendment to Annex 1 of the London Protocol (see above, same table) and the CCS-directive (see **Table 5**)
IPCC Guidelines for National Greenhouse Gas Inventories; Developed by the IPCC and adopted with small amendments by the UNFCCC to apply under the Paris Agreement (IPCC, 2006, 2019; UNFCCC, 2019a,b)	Informational (IPCC) Regulatory (UNFCCC) Deployment Capture Transport Storage	Accounting guidelines concluded in 2006, including how to account for emissions avoided though BECCS	Favorable (hard): allows a government to include BECCS in national greenhouse gas inventories and in accounting toward targets N.b., the UNFCCC adopted IPCC 2006 guidelines apply to greenhouse gas inventories only (18/CMA.1). The rules for accounting toward targets are more flexible, but require the application of methodologies and common metrics assessed by the IPCC and transparent reporting thereof (4/CMA.1)
The Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM, 1992)	Regulatory Deployment Storage	A regional multilateral convention for environmental policymaking among countries on the Baltic Sea. Agreed on in 1992, the Convention currently has 10 contracting parties, including the EU	Barrier (hard): prohibits sub-seabed storage in the Baltic Sea. As the EU is a contracting party to the Convention, the convention's prohibition takes precedence over the CCS Directive (see **Table 5**) that would otherwise allow such storage in the northern Baltic Sea
The Convention on Biological Diversity [CBD] (CBD, 2010: X/33)	Regulatory Deployment Capture Transport Storage	Paragraph 8(w) states that "in the absence of science-based, global, transparent and effective control and regulatory mechanisms for geo-engineering, and in accordance with the precautionary approach and Article 14 of the Convention, that no climate-related geo-engineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities"	Barrier (soft): puts a moratorium on climate-related geoengineering activities that may impact biodiversity negatively. BECCS is treated ambiguously as both geoengineering and mitigation "broadly defined" so the moratorium may or may not apply, notwithstanding ongoing evolution around the terminology. Allows research and development, if easily contained to specific sites

the Kyoto Protocol will, however, lose relevance after 2020. For the period after 2020, the objectives of the UNFCCC will largely be operationalized through the Paris Agreement instead of the Kyoto Protocol. However, it is still relevant to ask if the flexible mechanism of the Kyoto Protocol has incentivized BECCS in Sweden. Experience from the Kyoto Protocol is a key in UN deliberations on how to operationalize the market mechanisms developed under the Paris Agreement.

The CDM is an instrument of tradeable emission credits generated from emissions reductions in developing countries. Such emissions reductions are compared to a baseline and generate tradeable certified emission reductions (CERs) credits. CERs can in turn be used by developed countries to comply with their Kyoto Protocol commitments. In 2011, the UNFCCC decided to include CCS in the CDM. Zakkour et al. (2014a) argue that, as CDM involves "issuances of 'credits' against a baseline minus actual emission irrespective if these are negative" (p. 6827), opening up for CCS methodologies means that the CDM can theoretically be used to recognize negative emissions generated through BECCS. However, the focus of the mechanism on implementation in developing countries excludes direct support to BECCS in Sweden. Swedish engagement in CCS CDM projects would be limited to increasing Swedish knowledge about BECCS through engagement in deployment abroad. In addition, no Swedish actors were involved in any such projects abroad. In fact, not one single methodology for a CCS CDM project has, thus far, been approved. Approval is also unlikely to occur in the future for at least two reasons: First, the market for CERs from the CDM collapsed with the decline in interest in the Kyoto Protocol and the EU's restriction on using such emission rights in order to comply with the EU Emissions Trading System (EU ETS, see section "Supranational level: EU policy instruments"). Zakkour et al. (2014b) note that the approval of the CCS CDM rules coincided with the downturn in interest in the CDM. Second, the requirements for the approval of CCS methodologies are unusually strict, involving host country domestic regulations on "site selection and characterization, access rights to storage sites, redress for affected entities and liability" (Dixon et al., 2013, p. 7598). While the need for strict methodologies can be motivated given that CCS technology is less mature than other mitigation technologies, the requirement has likely contributed to limiting interest in engaging in CCS CDM projects.

In addition—in line with the aforementioned EU restrictions to limit use of CERs after 2012 to credits generated from projects registered in least developed countries (LDCs)—the Swedish government has decided to focus on LDCs for its CDM engagement. The potential for BECCS is generally limited in LDCs (Hansson et al., 2019). Thus, even if the CER market would not have collapsed and the CCS methodology requirements would have been less strict, Swedish engagement in CCS CDM projects would probably have been non-existent.

While JI is very similar to the CDM and is unlikely to spur BECCS deployment in Sweden for much the same reasons (Kossoy et al., 2015), ET is a different story. ET is an economic instrument that allows developed country Kyoto Protocol members to sell surplus Assigned Amount Units (AAUs) to other developed countries, for compliance. In theory, ET could incentivize countries to support domestic BECCS deployment if such deployment is understood as a measure to generate surplus AAUs that can be sold and generate income. However, the aggregate surplus was large in the Kyoto Protocol's first commitment period. A large surplus of AAUs was generated from the collapse of the former Soviet Union's industry rather than as an effect of the climate policy itself. This surplus was subsequently labeled "hot air" and could be traded cheaply. Some assessments even suggest that countries pursued strategies of complying through buying cheap hot air mainly from Poland, Romania, and the Czech Republic rather than conducting more expensive domestic mitigation actions (Shishlov et al., 2016; Martínez de Alegría et al., 2017). Under such circumstances, the economic incentive provided by ET for investments in relatively expensive BECCS—to comply with commitments or to generate a tradable AAUs surplus—was very low.

More recently, the Paris Agreement has detailed the objective of the UNFCCC by providing, among other things, a temperature goal: "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC, 2016: Article 2.1.a). The objective is further detailed in Article 4.1: "Parties aim to reach global peaking of greenhouse gas emissions as soon as possible [...] 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" (UNFCCC, 2016). This is clearly relevant for BECCS. However, the rules operationalizing the Paris Agreement are currently under negotiation. The Agreement established a mechanism to promote mitigation and support sustainable development (Article 6.4) that is likely to start operating in a fashion similar to that of the CDM. Whether this mechanism, which is sometimes referred to as the Sustainable Development Mechanism (SDM), will attract funding and how liquidity is to be maintained at high carbon prices—sufficient to drive investments in BECCS—are currently unresolved questions. It is, however, still too early to evaluate how the international carbon market will develop under the Paris Agreement (Honegger and Reiner, 2018).

The Paris Agreement also allows the trading of so-called Internationally Transferred Mitigation Outcomes (ITMOs, Article 6.2), which are similar to ET under the Kyoto Protocol. While ITMOs and the SDM are intrinsically linked, the market for ITMOs involves a broader opportunity for countries to sell surplus emissions reductions that are not credited toward their mitigation pledges under the Paris Agreement. ITMOs opens up a door for countries to sell surplus mitigation outcomes to raise international finance for domestic BECCS expenditure. While there is a cap on the amount of Swedish supplementary measures that can be credited toward target fulfillment (maximum 10.7 $MtCO_{2eq}$, see "Introduction"), there is no cap on the amount of supplementary measures that can be reported or that can be sold as ITMOs.

The international economic climate policy instruments are summarized in **Table 2**.

A key problem pertaining to both ET and ITMOs is how these instruments relate to supranational climate policy. Negative emissions generated by BECCS can currently be seen as falling between the cracks of the main EU climate policy instruments (see section "Supranational level: EU policy instruments"). As such, negative emissions from BECCS cannot be used to comply with EU targets, which makes it infeasible for Sweden (or any other EU Member State) to trade in surplus emissions reductions generated by BECCS.

Regulatory and Informational Instruments

In addition to the economic instruments defined at the UN level, the Paris Agreement is based on a collective, global goal to which Member States voluntarily contribute through so-called Nationally Determined Contributions (NDCs) that are regularly updated. To date, no NDC refers to BECCS. Moreover, Sweden has no NDC of its own. Instead, it adheres to a collective NDC submitted by the EU based on the EU's climate policy goals. Therefore, EU policy on fulfilling EU goals, including Sweden's contribution to this task, is more relevant for understanding Swedish BECCS deployment than what is stipulated in the joint EU NDC (see section "Supranational level: EU policy instruments"). This includes the opportunity for Sweden to sell surplus supplementary measures on an ITMO market since any such surplus would have to first be deducted from other EU Member States' potential underachievement. While the EU can sell surplus ITMOs, it is debatable how this opportunity pertains to Sweden.

Two regional multilateral conventions provide a more relevant regulatory frame for BECCS in Sweden. The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) is aligned with the 2006 amendment to the London Protocol, i.e., allowing for sub-seabed CO_2 storage. The Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention), on the other hand, prohibits sub-seabed CO_2 storage in the Baltic Sea. This—along with legal barriers for sub-seabed CO_2 storage in the southern Baltic Sea introduced by the EU CCS Directive (see **Table 3**)—has led the Swedish committee of inquiry on negative emissions to conclude that CO_2 captured in Sweden will most likely have to be exported, for example to Norway, for sub-seabed storage (GoS, 2020c).

The 2006 amendment of the 1996 London Protocol (to the 1972 IMO Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter) is a more relevant UN regulation. It permitted the previously forbidden sub-seabed disposal of CO_2 within a country's territory (IMO, 1996, 2006). However, Article 6 of the London Protocol prohibits transboundary movement of CO_2 if the intended final use is sub-seabed disposal (IMO, 1996). The Protocol was amended in 2009 to allow the export of CO_2 for disposal "provided that an agreement or arrangement has been entered into by the countries concerned" (IMO, 2009). The rules for operationalizing the amendment by specifying what an "agreement or arrangement" means were adopted in 2013 (IMO, 2013). For permits to be granted, export agreements shall include, for example, a clear distribution of responsibilities, risk and environmental impact assessments, and monitoring schemes. By the end of 2020, however, the amendment had not been ratified by the number of Parties required for it to enter into force. This means that the London Protocol still prohibits export of CO_2 among contracting parties (see e.g., Dixon et al., 2014). Since 2019, however, Parties to the London Protocol can apply the amendment provisionally, providing an opening for CO_2 export (IMO, 2019). Pending entry into force of the amendment to the London Protocol, such export would require a bilateral agreement between the importing country (such as Norway) and the exporter (Sweden) for the amendment to provisionally be applied.

There is also the question as to whether or not BECCS would be affected by decision X/33 of the tenth meeting of the Conference of the Parties to the Convention on Biological Diversity (CBD), in which parties agreed that, "in accordance with the precautionary approach and Article 14 of the Convention, no climate-related geo-engineering activities that may affect biodiversity take place," without adequate scientific understanding and consideration of risks and social impacts. In the CBD's technical report on the matter, BECCS was labeled as both geoengineering and mitigation "broadly defined" (CBD, 2016). Despite this ambiguity, since the decision was made geoengineering terminology has evolved to mainly refer to solar radiation management techniques, while carbon removal methods have formed their own, separate category. At any rate, the moratorium set out by the CBD is in reality an imprecise, non-binding, and non-enforceable, soft regulation which is unlikely to affect BECCS going forward.

The international community also designs accounting guidelines in addition to regulated prohibitions, emission reduction targets, and various economic implementation instruments. These can be understood as regulatory instruments that can have effects on BECCS; if the rules do not allow accounting for negative emissions, they raise barriers for BECCS. All project-based instruments of tradeable emission rights—the CDM, JI, and the Paris Agreement's mechanism—in principle allow[1] accounting for negative emissions to generate credits (Zakkour et al., 2014a). This is because credits are generated from the extent to which emissions reductions deviate from a baseline that would, hypothetically, have been the case without a project intervention. Accounting for negative emissions is principally not prohibited, as long as it is proven that they are additional to any emission reductions that would have occurred in the absence of the project (Zakkour et al., 2014a; Torvanger, 2019).

Both the Kyoto Protocol (Article 5) and the Paris Agreement (Article 13) link national accounting to IPCC methodologies. The 2006 IPCC accounting guidelines state that emissions "of CO_2 from biomass fuels are estimated and reported in the AFOLU [Agriculture, Forestry and Other Land Use] sector," and that "emissions from combustion of biofuels are reported as information items but not included in the sectoral or national totals to avoid double counting" (IPCC, 2006: volume 2, chapter 2, p. 33). However, if a combustion plant is supplied with biofuels, "the subtraction of the amount of gas transferred to long-term storage may give negative emissions. This is correct since if the biomass carbon is permanently stored, it is being removed from the atmosphere" (volume 2, chapter 2, p. 37). The possibility to capture CO_2 from industrial processes has also been acknowledged (volume 3, chapter 1.2.2). The 2019 refinement of the 2006 guidelines further clarify that BECCS should be treated consistently with fossil fuel CCS, and that net emissions, including negative emissions generated by BECCS, should be reported in the energy and/or the industrial processes and product use sectors (IPCC, 2019: volume 1, chapter 8, p. 5).

Under the Paris Agreement, national greenhouse gas inventories are to be based on the 2006 IPCC guidelines

[1]The accounting rules of Article 6 of the Paris Agreement have not yet been agreed on. However, it is likely that the rules will apply a "deviation from baseline" approach allowing the generation of credits from negative emissions. Weather emission removals or sinks shall be explicitly prohibited or not is still, however, under negotiation.

(UNFCCC, 2019b). As a consequence of the different scope that NDCs can have, accounting rules for the fulfillment of NDCs are less rigid and more flexible than under the Kyoto Protocol. Parties to the Paris Agreement are encouraged to use methodologies and common metrics assessed by the IPCC, such as accounting guidelines, and to describe how they have done so. If a NDC takes on a form that makes it hard to use IPCC guidelines, the NDC must contain information on the alternative methodology used (UNFCCC, 2019a).

Thus, accounting rules under the UNFCCC provide favorable regulatory conditions for governments to pursue carbon dioxide removals such as through BECCS. However, this does not translate into incentives to subnational entities or businesses. The international accounting rules establish a foundation for accounting for stored biogenic CO_2 as negative emissions in the event the Swedish government wishes to develop policy incentives for domestic actors to engage with BECCS. Torvanger (2019) has, however, shown that BECCS would benefit from a more standardized accounting and rewarding framework that resolves outstanding issues, especially issues related to sustainability safeguards and carbon cycle dynamics. Although these issues fall outside the scope of this article, it is worth noting that developing effective and at the same time broadly acceptable criteria for sustainable biomass production—a vital component to guarantee negative emissions from BECCS—is challenging for the international community.

Supranational Level: EU Policy Instruments

Sweden joined the EU in 1995. The EU shares competence on the environment with Member States (EU, 2012a). As such, sovereign rights are partly transferred from Sweden to the EU, which makes the EU a supranational union (Wettestad et al., 2012).

The EU has ratified the Paris Agreement and deposited its first NDC with the goal to reduce emissions by at least 40% by 2030 compared to 1990 levels (EU, 2016), within the EU 2030 climate and energy framework. The goal is to be achieved mainly with three instruments: the EU Emissions Trading System (EU ETS) to reduce emissions by 43% compared to 2005 levels, domestic actions in non-EU ETS sectors to reduce emissions by 30% compared to 2005 levels, and no-debit emissions from land use, land use change, or forestry (LULUCF). Thus, the EU's flagship climate policy instrument is the EU ETS, complemented with regulating mandatory emission reduction commitments in the non-ETS and no-debit emissions in the LULUCF sectors through the Effort Sharing Regulation (ESR) and the LULUCF Regulation (EU, 2018c,h,i). The ESR requires Sweden to reduce emissions by 40% in 2030 compared to 2005 levels. A number of related economic policy instruments, mostly designed to subsidize investments, are also notable. These have been established through the EU ETS Directive as well as through other decisions, directives, and regulations. These instruments are all of relevance to BECCS RDD&D in Sweden and will be discussed in more detail below. In 2019, the European Council agreed that the goal shall be revised during 2020, to increase ambition. If the ambition increases, consequential amendments of the EU ETS, ESR, and LULUCF Regulation will have to be adopted.

Economic Instruments

The EU ETS is an instrument of tradeable emission rights called EU Allowance Units (EUAs). The Kyoto Protocol's ET rules formed the basis for the EU ETS, developed to achieve cost-effective compliance with the EU Kyoto commitments (EU, 2003, 2009c, 2018c).

The system is based on allowances rather than credits and would require substantial amendments to allow the generation of new allowances based on negative emissions. Such procedures would also increase the amount of EUAs and create perverse outcomes unless negative emissions do not lead to a stricter cap or a corresponding cancellation of EUAs, e.g., in future auctions. Neither does the EU ETS cover emissions from LULUCF. The political appetite for incorporating LULUCF into the EU ETS has been very low (Ellison et al., 2014). The fact that the EU ETS is an allowance-based system and that attempts to include LULUCF emissions has been considered a dead end politically, which gives a gloomy outlook on agreeing on rules to generate EUAs from BECCS. However, the permanency and certainty of geologically stored CO_2 is much greater than LULUCF sinks, which opens a door for the possibility to integrate BECCS into the EU ETS. The fact that the EU ETS already covers fossil CCS further opens a door for integrating BECCS, as regulation to deal with possible leakage from geological storage has already been adopted (Rickels et al., 2020).

Any emissions from LULUCF activities are reported in the LULUCF sector under the LULUCF Regulation (EU, 2018h). This rationality applies even if the harvested biomass is transported to centralized entities, and emissions are released at point sources in operations where fossil emissions are often covered by the EU ETS, such as cement production. It should be noted, however, that the EU ETS does in fact cover large point sources of biogenic CO_2 if they are mixed with fossil CO_2, such as from pulp and paper production or heat and power production. Installations that exclusively use biomass fuels in their operations are, however, excluded from the EU ETS. Even if a facility using biomass is covered by the EU ETS, emissions from biomass arising at the facility should always be rated as zero. For biofuels and bioliquids, the zero-emissions assumption is only valid if the fuel fulfills the sustainability criteria of the Renewable Energy Directive (EU, 2018e). Black liquor from the pulp and paper industry, however, is treated as a solid biomass instead of a liquid biofuel. Thus, facilities with great potential to deploy BECCS are often already covered by the EU ETS (unless they exclusively use biomass fuels) and account for their biogenic emissions as zero emissions. Sweden has also implemented the so-called opt-in article of the EU ETS Directive (Article 24). The article allows a unilateral opt-in of additional emissions that are not covered by the EU ETS. Sweden has done this for emissions from small installations in the district heating sector. The opt-in provision further improves the scope for incentivizing BECCS through the EU ETS, yet achieving this would require substantial amendments to the existing EU law (Rickels et al., 2020).

Several researchers have, however, noted the failure of the EU ETS to drive innovation, for example of fossil CCS (e.g., Åhman et al., 2018). The most cited reason is the low price for EUAs (Koch et al., 2014). Other reasons include the free allocation of EUAs to installations classified as energy-intensive trade-exposed (EITE) industries at risk of carbon leakage (Nicolaï and Zamorano, 2018). Both steel and cement are EITE industries that are suitable for CCS technology. Combined with an increase in the use of bioenergy in these industries, part of any CO_2 captured at such installations could theoretically be accounted for as negative, i.e., as BECCS. EITE industries are entitled to freely allocated emission permits instead of having to buy them at auction.

The fact that the low and unstable EUA price is currently not strong enough to drive investments in CCS, and that the carbon leakage provides perverse incentives for EITE industries to argue for the unavailability of technical solutions to lower emissions, add to the lack of incentives provided by the EU ETS for developing BECCS. The innovation deficit has also been acknowledged by the EU, which has designed a number of R&D subsidies to complement the EU ETS. The idea behind combining R&D funding schemes with the EU ETS is straightforward: use supply-push R&D instruments to de-risk investments, put new technologies on the shelf, and make them more competitive, and to use demand-pull instruments, such as the EU ETS, to spur the diffusion of these technologies. Some of these R&D subsidies are funded from selling emission permits while others are funded from the core budget (**Table 4**).

In addition, many of the R&D funding sources target a CCS supply-push yet they limit funding to CO_2 of fossil origin. This provides no direct incentives for BECCS although this may indirectly incentivize BECCS through technical overlaps with fossil fuel CCS. Some of the funding sources are open to financing BECCS, such as Horizon 2020 and its successor Horizon Europe, the Connecting Europe Facility (CO_2 transport), and the Innovation Fund, although the eligibility criteria for the latter are still under consideration.

Some funding sources for BECCS R&D and demonstration are available, of which Horizon 2020 (2014–2020) and Horizon Europe (2021–2027) are the most notable for providing large R&D grants to legal entities, such as businesses and universities. Funding is provided in isolation from a supportive policy mix for commercial deployment. This allows BECCS operators to raise revenues to cover operational expenditure and, in that manner, create market pull incentives. Åhman et al. (2018) commenting on the failure of The New Entrants Reserve (NER300) to finance CCS despite targeting such projects, concluded that the low carbon price of the EU ETS failed to create a market pull for fossil CCS. This lack of a market "made investments in CCS unprofitable and highly risky" (Åhman et al., 2018: p. 104) due to high operational expenditure, despite large public co-funding of capital expenditure (see also Gough et al., 2018). In their evaluation of NER300 and the Regulation on European Energy Programme for Recovery (EEPR), the European Court of Auditors (ECA) concurred with the conclusions made by Åhman et al. (2018): "A key factor in the failure of CCS deployment has been the low carbon market price after 2011" (EU ECA, 2018: p. 9). The ECA found that the CCS project applicants assumed that the price for EUAs would be high and rising, thus creating a demand-pull for CCS. This situation for BECCS is even worse given the fact that the weak market pull provided by the EU ETS for fossil CCS is nonexistent for BECCS.

The ECA (2018) also underscored that the failure of EEPR and NER300 to deploy CCS in the EU was, in part, due to complex and inflexible application procedures and, in part, because of a lack of coordination.

The new framework program Horizon Europe is promising in this regard. It is "mission oriented," meaning that it will be oriented around concrete goals to address societal problems, including climate change. Among other things, this is likely to improve links between EU climate goals and research that focuses on the crucial role of demand-pull policy for BECCS. This approach to organizing R&D funding is well-aligned with the recent developments in innovation policy studies. These policy studies underscore the extremely dire need to deliberately steer innovation in directions that harmonize with political goals for societal challenges (Hekkert et al., 2020). The Innovation Fund is also promising in this regard, established in 2018 as the successor to NER300. Based on lessons learned from the failure of NER300, the Innovation Fund will use simpler and more flexible application procedures, will be able to provide more up-front rather than results-based funding, and will be able to cover a larger share of operational expenditure (60% instead of the 50% available under NER300). In preparation for the fourth trading period (2021–2030), the EU ETS has also been reformed to reduce the EUA surplus to strengthen the system's price signal. This provides a better context for capitalizing on the Innovation Fund, from auctioning 450 million EUAs during the trading period, and the Innovation Fund is also mandated to spend unused NER300 funding (EU, 2019a).

Developing infrastructure for BECCS is equally as important as developing a demand-pull policy. One of the challenges with BECCS is to get the whole technology chain in place in parallel. BECCS technology systems are marked by a chicken-and-egg problem. It is meaningless to capture CO_2 for storage if a company has no access to storage sites. Vice versa, developing storage capacity without some type of financial derivatives that obligates actors to future delivery of CO_2 at specific prices is financially extremely risky (Fridahl, 2019). In 2020, the EU acknowledged this problem and awarded the Northern Lights Project the status of a European Project of Common Interest (PCI). A PCI focuses on cross-border infrastructure projects that link European energy systems, in this case, the transport and carbon storage infrastructure in northern Europe, and grants infrastructure developers access to apply for funding from the Connecting Europe Facility (EU, 2019a). Accepting the Northern Lights Project as a PCI creates potential to significantly lower the financial risks of investments for private actors and nation states.

In practice, EU funding sources have not been directed at CCS projects in Sweden, regardless if it is fossil energy, bioenergy, or both. However, the Swedish utility company Vattenfall was granted EEPR funding for a fossil CCS project in Jänschwalde, Germany, which had to be canceled due to public resistance and a legal impasse created through the German government‘s

TABLE 4 | Supranational (EU) economic policy instruments of direct relevance to BECCS RDD&D in Sweden, in descending order of significance.

Instrument	Effect and scope	Description	Incentives provided
Directive on a scheme for greenhouse gas emission allowance trading [EU ETS] (EU, 2003, 2018c)	Deployment Capture Transport Storage	Established in 2003 and operational in 2005, the EU ETS was designed to enhance the cost effectiveness of meeting the EU commitment under the Kyoto Protocol. The fourth trading period commences in 2021, through amendments for the period 2021–2030 (EU, 2018a). Other amendments have been implemented too, and the EU ETS also includes rules for monitoring emissions (EU, 2007, 2018a)	Lack of incentive: lacks a price on CO_2 of biogenic origin and not allowing the offset of CO_2 of fossil origin through BECCS
Regulation on Horizon 2020 (EU, 2013a) and Regulation on Horizon Europe (EU, 2018f)	Research Development Demonstration Capture Transport Storage	Established in 2013, Horizon 2020 is the 8th so-called Framework Programme for Research and Innovation, which is designed to deliver an innovation-friendly environment in Europe. Horizon 2020 provides R&D grants and is open to legal entities, primarily from within the EU. Its successor, Horizon Europe (the 9th Framework Programme), has been provisionally agreed on and will finance R&D and demonstration including BECCS Administered by the European Commission with multiple partners; Timespan: 2014–2020 (Horizon 2020) and 2021–2027 (Horizon Europe)	Incentive (moderate): provides grants to R&D (including BECCS)
Regulation on the Connecting Europe Facility [CEF] (EU, 2013b) and Commission delegated regulation on Project of Common Interest [PCI] (EU, 2019b)	Deployment Transport	Established in 2013, the CEF provides financing for cross-border CO_2 transport infrastructure with a view to the deployment of CCS. Such funding could be used to build transport networks between Swedish biogenic point sources and established offshore storage sites in Norway The 2020 award of the Northern Lights Project, a commercial CO_2 cross border transport connection project in northern Europe, status of a PCI substantially improves the possibility of accessing CEF funding Administered by: The Innovation and Networks Executive Agency; Timespan: 2014–2020	Incentive (moderate): opens for funding for cross-border CO_2 transport networks with a view to the deployment of CCS (including BECCS)
Amendment to Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments [incl. the Innovation Fund] (EU, 2018c, 2019a)	Demonstration Deployment Capture Transport Storage	Established in 2018, the Innovation Fund is designed to support low-carbon transformation as a complement to the market pull provided by the price on CO_2 established through the EU ETS Administrative entity to be determined by the European Commission; Timespan: 2021–2030	N/A. CCS is to be eligible for funding, yet even though the fund has established the framework rules (including eligibility criteria for various types of CCS), detailed specification has not yet been agreed on. By learning from the failure of NER300, the Innovation Fund is likely to become more effective and has the potential to provide a strong incentive for BECCS
Decision on financing of commercial demonstration projects of environmentally safe CO_2 capture and geological storage as well as projects of innovative renewable energy under the EU ETS [NER300] (EU, 2010b)	Demonstration Deployment Capture Transport Storage	Established in 2010, the NER300 was capitalized by 300 million EUAs, monetized to about €2.1bn. NER300 funding can be combined with other EU funding yet requires substantial co-funding. €0.3bn has been dispatched to a CCS project (the White Rose project, a coal-fired power plant adjacent to the Drax power station in North Yorkshire, UK), a project that was abandoned in 2015 after the UK government withdrew its co-funding Administered by the European Investment Bank; Timespan: 2011–2020	Lack of incentive: primarily targets fossil and not biogenic CO_2, and the low price on EUAs in the EU ETS have led to a failure to finance NER300 at economic scales sufficient to provide large CCS co-funding. However, unused NER300 funding will be transferred to the Innovation Fund, which can be used to finance BECCS
Regulation on European Energy Programme for Recovery [EEPR] (EU, 2009e)	Demonstration Capture Transport Storage	Established in 2008 as part of the European Economic Recovery Plan, the EEPR was designed to boost the economy through low-carbon development while increasing energy security. In 2010, the EEPR granted €1.0bn to six CCS demonstration projects (Don Valley Hatfield, UK: ROAD Rotterdam, Netherlands; Belchatow, Poland; Compostilla, Spain; Porto Tolle, Italy; and Jänschwalde, Germany). Only one project has been completed thus far (Compostilla). Four projects were terminated. In 2016, €0.4bn of the €1.0bn had been dispatched Administered by the European Commission; Timespan: 2010–TBD	Lack of incentive: limits co-funding for CCS to coal-fired CHP plants and for transporting CO_2 captured at a steel plant (i.e., excluding BECCS)

(Continued)

TABLE 4 | Continued

Instrument	Effect and scope	Description	Incentives provided
InnovFin Energy Demonstration Projects facility [EDP], European Investment Bank and European Investment Fund in cooperation with the Commission, mandated by Regulation on the financial rules applicable to the general Union budget (EU, 2012b, repealed by: EU, 2018g)	Demonstration Deployment Capture Transport Storage	Established in 2014, the InnovFin EDP was designed to carry risks associated with moving technology, including BECCS, from the pilot phase to demonstration of commerciality. The fund is organized as a loan scheme under Horizon 2020, allowing a higher risk profile than otherwise possible and designed to facilitate the delivery of the EU Strategic Energy Technology Plan. The fund receives unspent NER300 funding as of the end of 2017 and onwards Administered by the European Investment Bank; Timespan: 2014–2020	Lack of incentive: only provides loans or guarantees to bankable projects, i.e., projects that can guarantee sufficient revenues, which, under the current lack of a price on biogenic CO_2 and an inability to sell credits, cannot be guaranteed by BECCS project developers in Sweden

adoption of their own CCS law (Kapetaki et al., 2017). This example shows that regulatory certainty also influences the willingness to invest in technology such as BECCS, and are a complement to R&D funding and policy instruments that create market pull. Nevertheless, the funding likely contributed indirectly to the Swedish capacity for BECCS.

Regulatory and Informational Instruments

While the supranational economic instruments largely do not provide incentives for BECCS, several regulatory instruments do create favorable conditions for deployment. The most notable is the CCS Directive (EU, 2009d). As noted by Duscha and del Río (2017), it "enables CCS within the European Union in general and sets the rules for the geological storage of CO_2" (p. 16). As such, it settles important issues related to, for example, responsibility sharing for storage. The CCS Directive is important because it provides partial clarity on the playing field and thus grants security to investment planners. However, economic incentives are instead supposed to be provided by other instruments. As noted in the above section, the existing economic instruments are not particularly well-designed to incentivize major opportunities for BECCS in Sweden. It should also be noted that the CCS Directive requires any physical leakage of CO_2 from storage to be compensated for by surrendering EU ETS allowances. This is regardless of whether the CO_2 can be considered to be of biogenic or fossil origin.

As also noted in the section "International level: UN and regional multilateral cooperation," biogenic emissions (whether a source or a sink) are reported in the LULUCF sector. Like the CCS Directive, the LULUCF Regulation provides a positive context for BECCS through enhanced regulatory clarity, yet the regulation does not provide any direct economic incentives for deployment.

The above, and other, regulatory instruments originating from the EU are summarized in **Table 5**.

At least three informational instruments also have a bearing on BECCS RDD&D in Sweden: First, the European Commission has also set the goal to make the EU climate-neutral by 2050 (EU, 2018b), with the goal endorsed both by the Parliament and the Council. Through the European Green Deal, the Commission has also proposed to put the climate-neutrality target into law. Although the European Climate Law is still being negotiated (EU, 2020b), the vision and the proposal to manifest the target in law provides a positive framework for BECCS in Sweden. Although there are risks associated with not specifying the climate-neutrality target in a clearly defined emission reduction target and a separate target for negative emissions (McLaren et al., 2019), the Commission has communicated its intension to keep such targets separate and with no backsliding from the previous emission reduction target for 2050 (i.e., at least −80% compared to 1990 levels). However, in the Commission's proposal for a European Climate Law (EU, 2020b), the 2050 target remains unspecified as a net-zero GHG emissions target. While the Commission highlights that "greenhouse gas emissions should be avoided at source as a priority" (EU, 2020b: p. 7), McLaren et al. (2019) argue that distinct targets for emissions reductions and negative emissions are beneficial both in terms of avoiding mitigation deterrence and making more explicit the scale and pace of the investments required to deliver negative emissions. Although the Green Deal and the proposed European Climate Law provide a positive framework for BECCS in Sweden, the latter would benefit greatly from further specification of the 2050 EU target into separate and well-defined emissions reductions and negative emissions targets.

Second, policy objectives defined through the European Commission's Strategic Energy Technology (SET) Plan; an informational instrument providing a strategic vision and rationale for the various EU funds targeting CCS for investments. In 2016, a set of goals were adopted for the period 2020–2030 with a subsequent Implementation Plan for CCS R&D and demonstration activities agreed on in 2017. The goals of the SET Plan are aligned with the Commission's vision for building an Energy Union and its current regulation (EU, 2015a,c, 2017, 2018j). The Energy Union regulation requires Member States to develop a 10 year integrated national energy and climate plan (NECP) and national long-term strategies with a perspective of at least 30 years. The plans and strategies increase transparency and improve the coherence between mid- and long-term planning, on the one hand, and the goals and the actions taken to achieve those goals, on the other hand. Even if this could be viewed as soft regulation or even as an informational policy instrument, it does provide a context for countries to start thinking about negative emissions. The Commission also envisages NECPs that play a more active role under the European Climate Law (EU, 2020b). The law in its current proposal form says that the Commission is to use the information in NECPs to evaluate if the measures taken by Member States are inconsistent with the Union's trajectory for achieving climate neutrality. The Commission

TABLE 5 | Supranational (EU) regulatory and informational policy instruments of direct relevance to BECCS RDD&D in Sweden, in descending order of significance.

Instrument	Type, effect, and scope	Description	Incentives provided
Directive on the geological storage of carbon dioxide (EU, 2009d), with links to the Waste Directive (EU, 2018d) and the Regulation on shipments of waste (EU, 2006)	Regulatory Deployment Storage	Agreed on in 2009, the CCS Directive clarifies rules for the disposal of CO_2. It was implemented in Sweden with the option to prohibit storage under land (due to considerably more complicated procedures). The directive exempts CO_2 that is stored within the EU from being considered as waste. The Waste Directive stipulates that the regulation on shipments of waste applies to CO_2 that is exported for storage outside the EU	Largely favorable (hard): establishes a scheme for sharing responsibility for long-term storage with the state. Barrier: no distinction between fossil and biogenic CO_2; all leakage into water or the atmosphere is to be compensated for by surrendering EU ETS allowance units Some barriers relevant to specific applications also apply: Barrier to developing domestic sub-seabed storage in Sweden (southern Baltic Sea) due to likely leakage into EU-external (Russian) territory, which is prohibited. Barrier by prohibiting export outside EU territory unless the importing country is a member to the European Free Trade Association *and* party to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal
Guidelines on State aid for environmental protection and energy (EU, 2014) mandated by Treaty 2012/C 326/01 on the European Union and the Treaty on the Functioning of the European Union. The expiration date of the guidelines has been prolonged by one year (until 2021) in the wake of the Covid-19 crisis (EU, 2020a)	Regulatory Research Development Demonstration Capture Transport Storage	Establishes a list of exemptions from the general principle of prohibition of state aid for 2014–2021. For CCS, "both operating and investment aid is permitted" (§163). Eligible funding is defined as the gap between cost savings from implementing CCS (e.g., reduced need for EUAs) and additional costs incurred by CCS	Favorable (soft): allows state aid to finance all incremental costs associated with BECCS, i.e., removes a barrier raised by the general rule prohibiting state aid. Barrier: provides no certainty for the period beyond 2021
Decision on the effort of Member States to reduce their greenhouse gas emissions [ESD] (EU, 2009a), and regulation on binding annual emission reductions [ESR] (EU, 2018i)	Regulatory Deployment Capture Transport Storage	Establishes effort sharing for the reduction of emissions not covered by the EU ETS, to meet the EU 2020 and 2030 climate targets	Barrier (hard): does not allow for accounting for negative emissions from BECCS at the national level to comply with the national commitment specified in the ESD for 2020 and the ESR for 2030. However, the domestic Swedish emission reduction target for 2030 (−63% compared to 1990 levels) is substantially more ambitious than what is required of Sweden to comply with its ESR target for 2030 (−46% compared to 1990 levels). Thus, even with full use of supplementary measures to meet its domestic target, Sweden will be able to comply with its EU target without accounting for negative emissions. The barrier raised by the ESD/ESR will thus be less relevant in Sweden. If biogenic CO_2 emissions were included in the EU ETS and BECCS were allowed to generate emissions credits linked to the EUA market (Rickels et al., 2020), the relevance of not allowing negative emissions from BECCS to be accounted for under the ESD/ESR would become irrelevant. If a common accounting system for BECCS was adopted, the ESR Article 5.7 would allow Sweden to sell any surplus or project-based BECCS units to other Member States
Communications on a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (EU, 2018b) and the Commission's proposal for a European Climate Law (EU, 2020b)	Informational RDD&D Capture Transport Storage	Outlines the Commission's vision of a revised long-term (2050) climate goal	Incentive (weak): provides a strategic long-term goal for a climate-neutral Europe, including scenarios that use BECCS to reach this goal. If the proposed European Climate Law was adopted, the vision would be anchored in law with the requisite subsequent amendments of the main EU climate policy instruments. This would substantially increase the significance of the long-term goal

(Continued)

TABLE 5 | Continued

Instrument	Type, effect, and scope	Description	Incentives provided
Decision on monitoring and reporting guidelines for greenhouse gas emissions from CCS (EU, 2010a) and Implementing Regulation on the monitoring and reporting of greenhouse gas emissions pursuant to the EU ETS (EU, 2018a)	Regulatory Deployment Capture Transport Storage	Amends the guidelines for monitoring and reporting emissions covered by the EU ETS with guidelines for how to monitor and report avoided emissions from CCS	Barrier (hard): unclear if it is permitted to deduce biogenic CO_2 from calculated levels of emissions from an installation. Further barrier: requires conservative methodologies to avoid attributing CO_2 of biogenic origin to fossil sources
Communications on the Energy Union (EU, 2015a,b), and The Strategic Energy Technology Plan (EU, 2015c)	Informational Research Development Demonstration Capture Transport Storage	Outlines the Commission's vision of a secure and low-carbon Energy Union, aligned with its SET plan identifying key areas for the R&D of CCS. The SET plan for CCS aligns with the objectives of the EU CCS funding sources (see **Table 4**)	Incentive (weak): provides a strategic, informative umbrella for EU funding directed toward CCS. This would include funding for which BECCS is eligible through CEF and Horizon 2020
Regulation on the governance of the Energy Union and climate action (EU, 2018j)	Regulatory RDD&D Capture Transport Storage	Requires EU Member States to submit national energy and climate plans (NECPs) covering the period 2020–30, biannual reports om progress toward the plans, and national long-term strategies with a perspective of at least 30 years	Favorable (soft): the EU Member States are to provide plans for how they intend to implement the agreed EU energy and climate targets. The Commission reviews the plans and provides recommendations for changes. The Member States are to then take due account of the recommendations or publicly explain why they do not. The first Swedish NECP (GoS, 2020b) affirms that BECCS is part of the long-term strategy for reaching net-zero emissions by 2045
Directive on the promotion of the use of energy from renewable sources (EU, 2009b, 2018e)	Regulatory Deployment Pre- capture (bioenergy)	Establishes targets for the share of renewable energy in each Member State by 2020, including energy from biomass. Revised in 2018 to establish an aggregate 2030 EU target	Favorable (hard): promotes the bioenergy component of BECCS systems with potential effects on the production of bioethanol, electricity, and heat
Communication on supporting early demonstration of sustainable power generation from fossil fuels (EU, 2008)	Informational RDD&D Capture Transport Storage	Establishes a European CCS Demonstration Project Network. Facilitates coordination among first movers, information exchange, increased visibility, and access to financial support	Lack of incentive caused by the focus on fossil CCS

is mandated to issue recommendations for Member States to get into compliance if it identifies inconsistencies. Member States must report how they take due account of these recommendations. The significance of NECPs will be upgraded if this procedure is eventually adopted as part of the European Climate Law.

Sweden, in its first long-term strategy, also restates its intention to potentially develop climate action that is supplementary to emission reductions. The framework allows for using supplementary measures to offset up to 10.7 $MtCO_{2eq}$ residual hard-to-mitigate emissions by 2045, such as emissions from the agriculture and waste sectors, and includes the option to use BECCS (GoS, 2019).

Third is the European CCS Demonstration Project Network (EU, 2008). This network, facilitated by the EU, gathers actors involved in CCS demonstration projects to share information and learning, partly, for policy development purposes. However, the network targets fossil CCS and is therefore less likely to acknowledge the specificities of policy for BECCS.

National Level: Swedish Policy Instruments

The Swedish climate law (GoS, 2017d) requires each successive Swedish government to propose a climate policy implementation plan, including policy instruments, and to relate how the instruments contribute to achieving the goal of net-zero emissions by 2045 and negative emissions thereafter. Thus, Sweden has a nationally regulated target, and it is the responsibility of each successive national government (in the period 2020–2045) to design instruments to meet this target.

Economic Instruments

Two of the oldest climate policy instruments in Sweden have been discussed by Börjesson et al. (2017): "[t]he carbon dioxide (CO_2) tax on fossil fuels introduced in 1991 and renewable electricity certificates of 2003 represent two important political incentives behind the significant increase in bioenergy" (p. 18). Both are economic instruments.

The carbon tax is an instrument of tax on households and firms. Established in 1991 at SEK 250 (€26) per $MtCO_2$ in general and SEK 63 (€7) per $MtCO_2$ for industry (nominal values, October 2017 exchange rates), it increased to SEK 1120 (€116) per $MtCO_2$ in 2016. In 2016, industry was still entitled to some tax reductions, but these had almost completely expired in 2018. The tax is adjusted annually along with the Consumer Price Index. In addition, an annual increase of 2% is added to the tax level to account for GDP developments (GoS, 2016; Börjesson et al., 2017).

At these levels, the tax could be expected to incentivize substantial amounts of BECCS in Sweden. However, the tax includes several exemptions, including taxation on biogenic CO_2 emissions. Even if the tax provided incentives to avoid biogenic CO_2, it would only incentivize reductions toward zero emissions; negative emissions are not rewarded through taxation. Brännlund et al. (2014) have also shown that before the introduction of the EU ETS, the ability of the carbon tax to decarbonize the pulp and paper industry was unusually low; pulp and paper was the only industry in Sweden in 1991–2004 that did not achieve an absolute decoupling of economic growth and emissions.

The tax, however, has in part incentivized the development of the Swedish bioeconomy in terms of increasing the share of bioenergy in the production of electricity and heat and in shifting from fossil fuels to biofuels for transportation (Börjesson et al., 2017). To some extent, a reduced tax for non-road mobile machinery used in the agriculture and forestry sectors has also likely contributed to the development of the bioeconomy. This tax reduction is one of few that remained in force after 2018 on the rationale that these sectors face unusually strong international competition (GoS, 2016).

It should also be noted that since 2011, industries covered by the EU ETS do not pay any carbon tax in Sweden. Given that the carbon price in the EU ETS is substantially lower than the tax, the incentive for these installations to shift from fossil fuels to bioenergy is lower than for entities outside the EU ETS.

The Swedish Renewable Energy Certificates system is a special form of instrument for tradeable emission rights. Each MWh of produced renewable energy generates a certificate that can be sold on a common Norwegian and Swedish market. The buyers are usually electricity producers and other actors (e.g., heavy industry) with a liability to own certificates in a given proportion to their electricity production or consumption. The system is designed to support investments in renewable electricity production but is not directly proportional to emission reductions, thus the certificates cannot be linked to other emissions trading schemes in which one unit usually corresponds to one tCO_2. The price for a certificate in Sweden averaged €3.1 MWh^{-1} in 2016 (SEA NWRED, 2017).

Some electricity installations fueled with bioenergy receive certificates. In 2016, certificates were granted for 1,967 GWh from biofuel and peat. This is not insignificant; it amounts to 16.8% of the total certificates generated in 2016. Yet the allocation is not based on emission levels but on a predefined list of eligible electricity production types and their production volume. Therefore, the system rewards the expansion of biofuel for electricity, thus increasing the potential for BECCS. Nevertheless, it does not reward negative emissions as such in its current form.

Two recent instruments, the Climate Leap Program (*Klimatklivet*) and the Industrial Leap scheme (*Industriklivet*) subsidize investments. The Climate Leap Program, established in 2015, allows municipalities, organizations, and businesses to apply for funding for immediate and direct local climate benefits (GoS, 2015b). In other words, this program prioritizes direct emission reductions over R&D and actions resulting in indirect climate benefits. R&D with high investment risks and high potential for emission reductions, is not supported.

The Industrial Leap scheme, established in 2017, is a pledge to provide 300 m SEK (€31 m) annually from 2018 to 2040 to mitigate process-related industrial emissions. The fund subsidizes much needed R&D and demonstration. It acknowledges that Swedish process-related emissions remain high and stable and that reducing them requires technological leaps that are both expensive and risky. Biorefineries, a sector with potential for BECCS, are eligible for funding.

The pulp and paper industry, however, was originally not eligible for funding from the Industrial Leap. This raised concerns that partly led to adjustments in 2019. Parallel to reinforcing the Industrial Leap to a total of 600 mSEK (€52 m) annually in 2020–2022 and thereafter 400 mSEK (€41 m) annually until 2027, the directive was amended with an appropriation for negative emissions through BECCS or direct air CO_2 capture and storage (GoS, 2017c). The appropriation is limited to 100 mSEK (€10 m) in 2019–2022 and 50 mSEK (€5 m) in 2023–2027 but the appropriation opens the Industrial Leap for applications from the pulp and paper industry.

The Industrial Leap is thus, in part, promising for incentivizing R&D and demonstration of BECCS and could potentially be used to raise required co-funding for companies seeking EU funding from the Innovation Fund (see "Supranational level: EU policy instruments"). However, the fund is imperfect in that long-term funding is not secured upfront. By mid-2020, 1.8 bnSEK (€0.19 bn) of the total 6.9 bnSEK (€0.72 bn) pledged for 2018–2040 had been secured. The promise of future funding cannot be guaranteed unless the current government capitalizes the fund upfront and designs a mechanism to protect the funding from future government interventions.

Finally, several funds are available to support R&D of relevance to BECCS. These funds are complementary to EU funding, such as Horizon 2020 and Horizon Europe, and are governed through the decrees on which instructions to governmental line agencies rest (GoS, 2008, 2015a, 2017b). The most notable decrees relate to public R&D support within the field of energy (to a large part administered by the Swedish Energy Agency) and within the fields of environment, agricultural sciences, and spatial planning (to a large extent administered by the Swedish Research Council, Formas). These funding sources support not only technical development but also policy development, capacity building, and the exploration of social preconditions for deployment. As such, they build the general capacity to understand preconditions for BECCS in Sweden and the capacity to develop hardware. The Swedish economic climate policy

TABLE 6 | National (Swedish) economic policy instruments of direct relevance to BECCS RDD&D, in descending order of significance.

Instrument	Effect and scope	Description	Incentives provided
Decree on support to actions for decreasing the industry's process-related emissions, and negative emissions [The Industrial Leap] (GoS, 2017c)	RDD&D Capture Transport Storage	Aims to reduce process-related emissions from Swedish industry	Incentive (moderate): partly provides funding for BECCS. Most of the annually dedicated funding, however, targets process-related fossil emissions
Decrees on public support to R&D (GoS, 2008, 2015b, 2017b)	Research Development Demonstration Capture Transport Storage	Regulates public support targeted for R&D and demonstration activities, generally within the fields of energy, the environment, and planning	Incentive (weak): provides grants to R&D and demonstration and to building capacity not only to develop technology but also to understand the preconditions for deployment
Decree on support to local climate investments [The Climate Leap] (GoS, 2015c)	Deployment Capture Transport Storage	Aims to reduce emissions locally, open to all legal entities, prioritizes projects with the highest potential for emission reduction per invested Swedish krona	Lack of incentive: provides small-scale grants focused on direct emission reductions
The electricity certificates law (GoS, 2011)	Deployment Capture Transport Storage	Aims to incentivize renewables by regulating the issuance and use of certificates generated from renewable electricity production. The tradeable certificates are used by power producers to fulfill quota obligations proportional to a share of their electricity production and use	Lack of incentive: focuses on rewarding renewable electricity production with no reward for capturing biogenic CO_2. However, the system does provide incentives for the expansion of biomass-based electricity production
The energy tax law (including the carbon tax) (GoS, 1994)	Deployment Capture Transport Storage	Regulates tax on electricity and fuel (including a tax on carbon in specific fuels). It specifies, e.g., tax levels, the carbon content of different fuels, and tax exemptions	Lack of incentive: does not cover biogenic CO_2 (and, if it was covered in the future, no incentives are provided for emission reductions beyond zero)

instruments of relevance to BECCS are summarized in **Table 6**.

Other economic climate policy instruments exist too, such as subsidies for solar cells and RDD&D investments in fossil-free transports, as well as a bonus-malus system to penalize high-emitting and reward low-emitting vehicles. However, these are unlikely to have any substantial, direct impact on BECCS in Sweden.

Regulatory and Informational Instruments

The long-term (2045) goal is complemented by mid-term goals for emission reductions in the non-ETS sectors. Emissions in the non-ETS sectors are to be reduced by at least 63% in 2030 and by at least 75% in 2040, compared to 1990 levels. LULUCF is explicitly not included nor is international transportation (bunker fuels). Thus, even though LULUCF is covered by the new EU regulation and can be used in accounting to meet the Swedish 2030 EU target, it is already decided that it will not be used to meet the domestic target (GoS, 2017a,d).

The Swedish climate policy framework also specifies that the intermediary targets for 2030 and 2040 can be met by using a maximum of 8 and 2% of so-called supplementary measures, respectively. Such actions include BECCS, international offsetting, and net LULUCF uptake (even though LULUCF is not covered as a whole, an aggregate increase in net uptake can be accounted for as a supplementary measure). The framework also specifies that the 1990 non-ETS emissions were 46.7 $MtCO_{2eq}$, meaning that if no other supplementary measures are used to meet the goal, BECCS will be limited to 3.7 $MtCO_2$ in 2030 and to 0.9 $MtCO_2$ in 2040. Any additional BECCS will not be allowed to be applied toward meeting intermediary goals. This regulation makes sense from a precautionary perspective; the targets should be based on known mitigation potentials and should be independent of loopholes or unproven technologies, yet the regulation also caps the amount of BECCS that Sweden can use to meet its target. In this manner, the regulation can influence future discussions on the level of state spending on BECCS RDD&D. The regulation may act as a barrier to BECCS, not only because it limits the share of allowed BECCS but also because this share declines in the mid-term (i.e., from 2030 to 2040) before it increases again by 2045. The uncertainty of the Swedish climate policy framework would be repealed if the proposal by the Swedish committee of inquiry on negative emission is adopted and specifies BECCS targets for 2030 and 2045, respectively, and assumes roughly linear upscaling (GoS, 2020c).

The climate policy framework also specifies that the share of allowed supplementary measures, including the option to use BECCS, will likely have to increase in the long term, beyond 2045, to achieve net-negative emissions. Although the climate policy framework also fails to quantify goals for net-negative emissions after 2045, setting quantified goals for long-term net-negative emissions would provide greater certainty for near-term expenditure on BECCS or other negative emission technologies, it sets out a clear long-term direction for greater significance for BECCS beyond 2045. In view of the clarity of the long-term trajectory, the disincentive provided by a mid-term decline in how much BECCS will be allowed to contribute to Swedish climate policy objectives is relatively weak.

The favorable regulatory environment is more positive in terms of the Swedish policy mix that targets the deployment of storage infrastructure. The Swedish potential for geological storage is primarily found offshore, in the Baltic Sea. As such, instruments targeting offshore storage are the most relevant. The existing policy mix consists primarily of three instruments: The Directive on Geological Storage of CO_2 (GoS, 2014), the Continental Shelf Law (GoS, 1966), and the Environmental Code (GoS, 1998). The Environmental Code also provides clarity on requirements for building and operating a piped transport network, complemented by the Law on Certain Pipelines (GoS, 1978).

Although clarity is provided, which provides a positive context as it increases the predictability of the market conditions for BECCS (Jänicke, 2017), this positive context is undermined, albeit for good reasons, by the administrative burden bestowed on actors wanting to open new storage facilities. The Continental Shelf Act demands authorization, which for storage of more than 0.1 $MtCO_2$ within the Swedish economic zone must be tested and, if accepted, granted by the Land and Environment Court. The EU Commission must be notified of draft applications and has the opportunity to submit comments. As a final step, the Government of Sweden is to approve or decline applications. Authorization is required both to examine potential storage and for actual storage. Simplified procedures apply to sites intended for storage of <0.1 $MtCO_2$ for research purposes. The juridical interpretation of the law has proven more ambiguous than the law itself, creating uncertainties around expected outcomes even if the legal requirements appear to have been fulfilled at the time of application for authorization (Stigson et al., 2016).

The Swedish regulatory and informational climate policy instruments of direct relevance to BECCS are summarized in **Table 7**.

CONCLUDING DISCUSSION

Even though BECCS is considered a key mitigation technology in almost all 1.5°C and most 2°C compatible climate change mitigation scenarios (Fuss et al., 2014; IPCC, 2018), there is a significant gap between BECCS deployment and the capacity of this technology to deliver on those scenarios. This implementation gap has been described as the result of an incentive gap between the tentative targets for BECCS deployment and existing policy enablers. To characterize this incentive gap, this paper mapped incentives provided by existing climate policy instruments for BECCS research, development, demonstration, and deployment (RDD&D) in Sweden. Sweden was chosen as a case study country because of its particularly high theoretical potential for BECCS.

The overall trends in the composition of policy instruments across different levels of governance are summarized as follows: A number of patterns were observed with respect to the prevalence of different types of policy instruments and their effects at different levels of governance using the tripartite typology of policy instruments, and an understanding of the relevance of

TABLE 7 | National (Swedish) regulatory and informational policy instruments of direct relevance to BECCS RDD&D, in descending order of significance.

Instrument	Type, effect, and scope	Description	Incentives provided
The climate policy framework, including the climate law (GoS, 2017a,d)	Regulatory RDD&D Capture Transport Storage	The Climate Act links the Government's climate policy to the long-term climate goal defined by Parliament (2045 and beyond), demands continuous implementation plans, and mandates an independent council to review the implementation plans in light of the long-term policy objective	Favorable (soft): allows for BECCS to contribute to fulfilling Swedish climate policy objectives. The positive framing is weakened by a cap on the amount of BECCS allowed to comply with the 2045 target and by establishing an intermediate decline in the allowed use of BECCS
Decree on geological storage of CO_2 (GoS, 2014)	Regulatory Deployment Storage	Regulates storage above a total of 0.1 $MtCO_2$, including provisions on, e.g., ex-ante modeling of geological properties, the purity and pressure of the CO_2 injected, monitoring, and responsibility sharing	Favorable (hard): allows for and provides clarity on rules for prospecting for geological storage of CO_2. Barrier: cumbersome application processes
The environment code (GoS, 1998)	Regulatory Deployment Transport Storage	Aims to support sustainable development in Sweden and regulates, e.g., permit approval and reporting requirements for storage sites above a total of 0.1 $MtCO_2$; requires environmental considerations in building infrastructure; mandates national administration to issue fees for costs incurred; and mandates the government to issue decrees related to the storage of CO_2	Favorable (hard): provides clarity on rules for dumping CO_2 in geological formations in Sweden and environmental considerations for the construction of pipelines
The continental shelf law (GoS, 1966)	Regulatory Deployment Storage	Regulates the exploration and utilization of the seabed and the sub-seabed within the Swedish economic zone, including the issuance of permits for exploring the sub-seabed as a CO_2 storage site	Favorable (hard): allows for and provides clarity on rules for the geological storage of CO_2 on the Swedish continental shelf. Barrier: cumbersome authorization
The certain pipelines law (GoS, 1978)	Regulatory Deployment Transport	Regulates the issuance of concessions required for the pipe-bound transportation of liquid or gaseous fuels longer than 20 km, including CO_2 intended for storage	Favorable (hard): allows for and provides clarity on rules for pipe-bound transport of CO_2

TABLE 8 | Incentives/disincentives for BECCS RDD&D across different levels of governance.

	Economic			Regulatory		Informational		
	Incentive	Neither incentive nor dis-incentive	Dis-incentive	Favorable	Barrier	Incentive	Neither incentive nor dis-incentive	Dis-incentive
International	0	4	0	4	2	1	0	0
Supranational	2	5	0	4	2	2	1	0
National	2	3	0	5	0	0	0	0
Total, all levels	4	12	0	13	4	3	1	0

The category "Neither incentive nor disincentive" also includes the few instruments whose effects on BECCS are yet to be assessed pending ongoing policy processes. For instruments that have both incentivizing and disincentivizing effects, the overriding effect is counted and reported in the table.

policy instruments for generating a supply-push or demand-pull across the RDD&D phases of BECCS (see **Table 8**).

It is clear from the analysis that a large number of regulatory instruments actively govern BECCS RDD&D in Sweden. The majority of these instruments are so-called "hard," i.e., precise, binding, and enforceable instruments that provide a mostly favorable regulatory environment. Some exceptions to this rule exist and have notable international and supranational legal barriers and unclarities. Overall, however, the multi-level regulatory regime would allow for RDD&D of the full BECCS technology chain; the existing regulatory barriers are unlikely to substantially impede BECCS RDD&D. Although the regulatory instruments rarely explicitly inhibit BECCS RDD&D, they do not provide the incentives necessary for widespread deployment, nor do they coerce action. Instead, the EU and Swedish regulatory instruments generate high transaction costs, e.g., transaction costs related to permit application to explore and operate CO_2 storage sites and transaction costs related to trade export agreements. This increases the urgency for economic incentives to cover costs, not only the costs of technology investments and operation but also the transaction costs associated with regulatory compliance.

The analysis also identified an almost equal number of economic instruments of relevance to BECCS. The pattern was less positive than the regulatory regime. Most economic instruments of potential relevance to BECCS, at all levels of governance, were found to neither provide incentives nor disincentives for BECCS. All of the economic instruments that do provide incentives target research, development, and demonstration. As such, they cover at least a substantial part of the supply-push needs. However, there is a complete lack of demand-pull instruments for BECCS deployment.

This may appear to make perfect sense; the maturity of the full BECCS technology chain has thus far not been demonstrated. It would therefore seem logical to focus economic policy efforts on technology development and demonstration. The problem for BECCS is that individual components of the technology chain are already relatively well-developed. Additional supply-push instruments that do not initiate any demand-pull are therefore likely to lead to well-developed components of the technology chain. In some cases, the available funding may even serve to demonstrate the full chain yet fail to spur more widespread deployment. As pointed out by de Coninck et al. (2010), even fossil fuel CCS is prone to end up in the technology "valley of death" between the public funding of R&D and more widespread private funding of deployment on established markets. Fossil CCS faces this risk despite existing economic instruments that provide incentives for reducing the emissions of fossil-based CO_2. This study confirms the concern raised in previous research (Fridahl, 2017; Torvanger, 2019): demand-pull instruments for capturing and storing CO_2 of biogenic origin are completely lacking, at least in the EU and in Sweden.

Only a few relevant informational instruments could be identified, all of which are inter- or supranational and almost all target action by governments. These informational instruments are mostly supportive, e.g., by allowing to the countries to account for negative emissions in compliance with commitments. As yet, however, relevant informational instruments do little to provide deployment incentives for industrial actors. Given that BECCS provide no added private value to consumers, and hence are unlikely to seem attractive for commercial companies, the gap between prospective policy objectives and their delivery requires substantial incentives to be bridged.

In its current form, therefore, there is no question that the policy mix will fail to incentivize more widespread BECCS deployment. The present study found a number of key implications for policymaking in this area if BECCS RDD&D is to be successfully incentivized.

First, there is a need to introduce new economic instruments that can incentivize BECCS at all levels of governance, either through reforming existing instruments, such as the EU ETS, or by designing new instruments, such as the proposed Swedish reversed auctions dedicated to BECCS. Other policy alternatives include certificates or negative emission refund schemes (Pour et al., 2018). Such demand-pull instruments would complement existing supply-push instruments as well as complement calls for new RDD&D funding streams that target either specific aspects of BECCS, such as new bio-feedstocks, or negative emissions technologies in general (Lomax et al., 2015; Burns and Nicholson, 2017; Cox and Edwards, 2019). The potential for capturing biogenic CO_2 in Sweden and the Swedish proximity to Norwegian storage sites (Kjärstad et al., 2016), combined with the long storage permanence associated with the geological storage of CO_2 compared to many other forms of negative emissions (Fridahl et al., 2020), improves the likelihood that economic instruments that target BECCS will result in tangible and substantial contributions to addressing climate change. Among the several options available for the design of economic instruments, Parson and Buck (2020) argue that public procurement is the most appropriate form of instrument to incentivize negative emissions. According to Parson and Buck (2020), procurement allows for better control of the volume of CO_2 removed from the atmosphere in the event that global warming is eventually limited and carbon dioxide removals, if unmitigated, cause problematic global cooling. Based on this argument, however, other instruments, e.g., quota obligations and certificate trade or cap-and-trade systems, could provide the state with a similar control, as the level of quota obligations, or the cap, can be adjusted. Even subsidy schemes or fees and dividends can be designed to retain control over the volumes of BECCS that the instruments seek to effectuate (Fridahl, 2019). In any case, public procurement options ought to allow enough security for investments and ought to incentivize BECCS relatively expeditiously. This is also an option that would interfere relatively little with the existing climate policy mix designed to incentivize emission reductions rather than removals.

Second, there is a need to amend regulatory instruments that raise deployment barriers at international and supranational levels, i.e., to remove regulatory barriers. Regulatory harmonization across levels of governance, a process that has clearly already been started by reforming UN and other multilateral regulation to harmonize with EU regulation, must continue. There is also scope to continue lowering the supranational regulatory barriers, e.g., to sort out unclarities regarding the leakage of biogenic CO_2 from geological storage sites under the CCS Directive. These would complement calls for clearer frameworks for licensing sub-soil access for CO_2 storage (Cox and Edwards, 2019).

Third, there is scope to introduce informational instruments at all levels. In pursuit of supporting BECCS, it may be particularly useful to initiate networks intended for sharing experience and fostering mutual learning (Fridahl and Johansson, 2017) and to organize lobby power to balance the power of conservative policy networks in incumbent sociotechnical regimes (Normann, 2017).

Fourth, given that incentives are lacking on international and supranational levels, and that actions on these levels are beyond the direct control of national governments, countries that are serious about assigning a limited role to BECCS within their mitigation portfolio should act proactively and independently to pursue RDD&D activities. Waiting for an international carbon price to reach levels sufficient to incentivize BECCS is certainly the wrong approach. The technology may turn out to be a technological dead-end for reasons difficult to foresee from the present vantage point. As Mazzucato (2018) argues, in the pursuit of clean-tech innovations, national governments must look beyond the "market-fixing" approach of previous decades and dare instead to pursue "market shaping" and "market cocreating." The Swedish government has a better opportunity than most to play an active role in supporting the domestic RDD&D of BECCS, bearing the risk for the companies willing to be involved, and thus contributing valuable lessons about the global potential for negative emissions.

There is another key factor that depends on the incentivization of BECCS, however. The incentivization of BECCS must be done responsibly to determine whether and to what extent BECCS diffusion is feasible and desirable, socially speaking (Bellamy, 2018). After all, BECCS, like any other technology, is not simply a technical artifact but one that is dependent on—and inseparable from the social contexts in which it would reside. In the United Kingdom, for example, research has shown significant public opposition to the technology if BECCS was incentivized with guaranteed price premiums. The public was opposed to using a system in which companies using biomass boilers to produce electricity and heat would be guaranteed a price premium if they ran their installations with BECCS (Bellamy et al., 2019). Understanding the industrial actors' perspectives, or BECCS acceptance, is also an important social context. Investigations of the large-scale emitters of biogenic CO_2 in Finland and Sweden have, in addition to the policy aspects raised in this paper, revealed challenges to, e.g., process integration, trade-offs between various firm-specific sustainability goals, willingness to become a first mover, and beliefs in the responsibility to mitigate climate change. The results indicate that these firms often seem unwilling to decrease biogenic CO_2 emissions if such investments crowd out investments intended to fulfill other sustainability targets (Rodriguez et al., 2020). This means that broad societal participation is necessary in the evaluation of which negative emission technologies might be used, the selection of policy instruments for bringing these technologies to development, and the design of governance principles that reflect the diverse values and interests of key actors in society.

In conclusion, at the dawn of the 2020s, the existing climate policy mix is unfit for the purpose of incentivizing BECCS deployment. If unreformed, the existing policy mix will most likely lead to substantial public expenditure on BECCS research, development, and demonstration without leading to any substantial deployment and diffusion. Even if there is scope to reform existing regulatory instruments and to initiate new informational instruments, the incentive gap between the tentative targets for BECCS and existing policy enablers is largely characterized by a complete lack of economic demand-pull instruments. There is therefore an urgent need for future research to characterize alternative demand-pull policy instrument pathways, and to formally evaluate these pathways in terms of their potential to deliver net-negative emissions through a variety of means in technically effective and socially responsible ways.

If supported by the Swedish government and adopted by Parliament, the proposed Swedish negative emission strategy (GoS, 2020c) would shift the Swedish policy mix in the direction suggested herein. Mid-term reversed auctions would then be used to instigate a limited but long-term state-led demand for BECCS by 2030. This would allow for testing both the willingness of the industry to deliver BECCS and the societal response to such delivery. In line with socially robust policy development, the design of an instrument to generate demand in the longer and grander 2045 perspective would require both actor-specific feedback and policy development in the EU and internationally. In addition, the proposed strategy would task the Swedish Energy Agency with leading a much-needed knowledge and policy network on CCS including BECCS. If combined with new demand-pull policy instruments developed in the EU, this proposal would go a long way toward closing the incentive gap for BECCS deployment in Sweden.

Although this article has focused on Sweden, the findings are relevant for all EU Member States that are interested in using BECCS for target fulfillment, yet that have not developed a strong demand-pull for BECCS as part of their national climate policy mix. While several EU Member States have shown an interest in BECCS, to the best of our knowledge, no EU Member State has as yet adopted such a policy. If this holds true, the findings of this article can be used as a departure point for policy making in interested EU Member States and supranationally in the Union itself.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: The datasets analyzed for this study can be found in the online document repositories for the UNFCCC (https://unfccc.int/documents), the IMO (https://docs.imo.org), the CBD (https://www.cbd.int/cooperation/about/documents.shtml), the OSPAR (https://www.ospar.org/meetings/archive), the HELCOM (https://helcom.fi), and the IPCC (https://www.ipcc.ch/documentation), as well as the EU online repository for laws and preparatory acts, EUR-Lex (eur-lex.europa.eu), and the Swedish government's online repository for laws, the Swedish Code of Statues (https://svenskforfattningssamling.se/english.html) and the Swedish Parliament's repository for bills, communications, reports, and other central policy documents (riksdagen.se/en/documents-and-laws).

AUTHOR CONTRIBUTIONS

MF designed the research and collected the data. MF and RB conducted the analysis and wrote the majority of the article. AH and SH contributed as critical reviewers, discussants, and as authors of specific sections of the paper. All authors contributed to the article and approved the submitted version.

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REFERENCES

Åhman, M., Skjærseth, J. B., and Eikeland, P.O. (2018). Demonstrating climate mitigation technologies: an early assessment of the NER 300 programme. *Energy Policy* 117, 100–107. doi: 10.1016/j.enpol.2018.02.032

Amars, L., Fridahl, M., Hagemann, M., Röser, F., and Linnér, B.-O. (2017). The transformational potential of nationally appropriate mitigation actions in tanzania: assessing the concept's cultural legitimacy among stakeholders in the solar energy sector. *Local Environ.* 22, 86–150. doi: 10.1080/13549839.2016.1161607

Anderson, K., Broderick, J. F., and Stoddard, I. (2020). A factor of two: how the mitigation plans of 'climate progressive' nations fall far short of Paris-compliant pathways. *Clim. Policy* 20, 1290–1304. doi: 10.1080/14693062.2020.1728209

Bachu, S. (2008). Legal and regulatory challenges in the implementation of CO_2 geological storage: an alberta and Canadian perspective. *Int. J. Greenhouse Gas Control* 2, 259–273. doi: 10.1016/j.ijggc.2007.12.003

Baumol, W. J., and Oates, W. E. (1979). *Economics, Environmental Policy and the Quality of Life.* Englewood Cliffs, NJ: Prentice Hall

Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nat. Energy* 3, 532–534. doi: 10.1038/s41560-018-0156-6

Bellamy, R., and Healey, P. (2018). 'Slippery slope' or 'uphill struggle'? Broadening out expert scenarios of climate engineering research and development. *Environ. Sci. Policy* 83, 1–10. doi: 10.1016/j.envsci.2018.01.021

Bellamy, R., Lezaun, J., and Palmer, J. (2019). Perceptions of bioenergy with carbon capture and storage in different policy scenarios. *Nat. Commun.* 10:743. doi: 10.1038/s41467-019-08592-5

Bemelmans-Videc, M.-L., Rist, R. C., and Vedung, E. O. (2010). *Carrots, Sticks, and Sermons: Policy Instruments and their Evaluation.* London: Transaction Publishers.

Berkhout, F., Smith, A., and Stirling, A. (2004). "Socio-technological regimes and transition contexts," in *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy*, eds B. Elzen, F.W. Geels, and K. Green (Cheltenham and Northampton: Edward Elgar Publishing), 48–75.

Bonvillian, W. B., and Van Atta, R. (2011). ARPA-E and DARPA: applying the DARPA model to energy innovation. *J. Technol. Transf.* 36:469. doi: 10.1007/s10961-011-9223-x

Börjesson, P., Hansson, J., and Berndes, G. (2017). Future demand for forest-based biomass for energy purposes in Sweden. *For. Ecol. Manage.* 383, 17–26. doi: 10.1016/j.foreco.2016.09.018

Brännlund, R., Lundgren, T., and Marklund, P.-O. (2014). Carbon intensity in production and the effects of climate policy: evidence from Swedish industry. *Energy Policy* 67, 844–857. doi: 10.1016/j.enpol.2013.12.012

Burns, W., and Nicholson, S. (2017). Bioenergy and carbon capture with storage (BECCS): the prospects and challenges of an emerging climate policy response. *J. Environ. Stud. Sci.* 7, 527–534. doi: 10.1007/s13412-017-0445-6

Cambero, C., and Sowlati, T. (2014). Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives – a review of literature. *Renew. Sustain. Energy Rev.* 36, 62–73. doi: 10.1016/j.rser.2014.04.041

CBD (2010). *Decision Adopted by The Conference Of The Parties To The Convention on Biuological Diveristy at its Tenth Meeting: x/33. Biodiversity and Climate Change*. Montreal, QC: UN Convention on Biological Diveristy.

CBD (2016). *CBD Technical Series No. 84: Update on Climate Geoengineering in Relation to The Convention on Biological Diversity: Potential Impacts and Regulatory Framework*. Montreal, QC: UN Convention on Biological Diversity.

Cox, E., and Edwards, N. R. (2019). Beyond carbon pricing: policy levers for negative emissions technologies. *Climate Policy* 19, 1144–1156. doi: 10.1080/14693062.2019.1634509

de Coninck, H., De Best-Waldhober, M., and Groenenberg, H. (2010). "Regulatory and social analysis for the legitimation and market formation of carbon dioxide (CO_2) capture and storage technologies," in *Developments and Innovation in Carbon Dioxide (CO_2) Capture and Storage Technology,* ed M.M. Maroto-Valer (Cambridge: Woodhead Publishing), 64–92.

Dixon, T., Garrett, J., and Kleverlaan, E. (2014). Update on the london protocol – developments on transboundary CCS and on geoengineering. *Energy Proc.* 63, 6623–6628. doi: 10.1016/j.egypro.2014.11.698

Dixon, T., Leamon, G., Zakkour, P., and Warren, L. (2013). CCS projects as kyoto protocol CDM activities. *Energy Proc.* 37, 7596–7604. doi: 10.1016/j.egypro.2013.06.704

Duscha, V., and del Río, P. (2017). An economic analysis of the interactions between renewable support and other climate and energy policies. *Energy Environ.* 28, 11–33. doi: 10.1177/0958305X16685456

Ellison, D., Lundblad, M., and Petersson, H. (2014). Reforming the EU approach to LULUCF and the climate policy framework. *Environ. Sci. Policy* 40, 1–15. doi: 10.1016/j.envsci.2014.03.004

Ericsson, K., and Werner, S. (2016). The introduction and expansion of biomass use in Swedish district heating systems. *Biomass Bioenergy* 94, 57–65. doi: 10.1016/j.biombioe.2016.08.011

EU (2003). *Directive 2003/87/EC Establishing A Scheme for Greenhouse Gas Emission Allowance Trading Within the Community, Oj L 275*. Brussels: The European Union.

EU (2006). *Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on Shipments of Waste, Oj L 190*. Brussels: The European Union.

EU (2007). *Commission Decision of 18 July 2007 Establishing Guidelines for the Monitoring and Reporting of Greenhouse Gas Emissions Pursuant to Directive 2003/87/EC of The European Parliament and of the Council (C(2007) 3416), Oj L 229*. Brussels: The European Union.

EU (2008). *Communication From the Commission, Supporting Early Demonstration of Sustainable Power Generation From Fossil Fuels (COM(2008) 13 FINAL)*. Brussels: The European Union, Commission.

EU (2009a). *Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the Effort of Member States to Reduce Their Greenhouse Gas Emissions to Meet the Community's Greenhouse Gas Emission Reduction Commitments up to 2020, Oj L 140/136*. Brussels: The European Union.

EU (2009b). *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy From Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC, Oj L 140/16*. Brussels: The European Union.

EU (2009c). *Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 Amending Directive 2003/87/EC So as to Improve and Extend the Greenhouse Gas Emission Allowance Trading Scheme of the Community, Oj L 140/63*. Brussels: The European Union.

EU (2009d). *Directive 2009/31/EC on the Geological Storage of Carbon Dioxide and Amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC And Regulation (EC) No 1013/2006, Oj L 140*. Brussels: The European Union.

EU (2009e). *Regulation (EU) No 663/2009 of the European Parliament and of the Council of 13 July 2009 Establishing a Programme to Aid Economic Recovery by Granting Community Financial Assistance To Projects in the Field of Energy, Oj L 200/31*. Brussels: The European Union.

EU (2010a). *Commission Decision C (2010) 3310 Amending Decision 2007/589/EC As Regards the Inclusion of Monitoring and Reporting Guidelines for Greenhouse Gas Emissions From the Capture, Transport and Geological Storage of Carbon Dioxide, Oj L 155*. Brussels: The European Union Commission.

EU (2010b). *Commission Decision C (2010) 7499 Laying Down Criteria and Measures for the Financing of Commercial Demonstration Projects That Aim at the Environmentally Safe Capture and Geological Storage of CO2 as Well as Demonstration Projects of Innovative Renewable Energy Technologies Under the Scheme for Greenhouse Gas Emission Allowance Trading Within the Community Established By Directive 2003/87/EC of the European Parliament and of the Council*. Brussels: The European Union Commission.

EU (2012a). *Consolidated Version of the Treaty on the Functioning of the European UNION, Oj C326/47"*. Rome: The European Union.

EU (2012b). *Regulation (EU, Euratom) No 966/2012 of the European Parliament and of the Council of 25 October 2012 on the Financial Rules Applicable to the General Budget of the Union and Repealing Council Regulation (EC, EURATOM) No 1605/2002, Oj L 298*. Brussels: The European Union.

EU (2013a). *Regulation (EU) No 1291/2013 of the European Parliament and of the Council of 11 December 2013 Establishing Horizon 2020 - the Framework Programme for Research and Innovation (2014-2020) and Repealing Decision No 1982/2006/EC, Oj L 347/104*. Brussels: The European Union.

EU (2013b). *Regulation (EU) No 1316/2013 of the European Parliament and of the Council of 11 December 2013 Establishing The Connecting Europe Facility, Amending Regulation (EU) No 913/2010 and Repealing Regulations (EC) No 680/2007 and (EC) No 67/2010, Oj L 348*. Brussels: The European Union.

EU (2014). *Communication From the Commission, Guidelines on State Aid for Environmental Protection and Energy 2014-2020 (2014/C 200/01), Oj C 200*. Brussels: The European Union, Commission.

EU (2015a). *Communication From the Commission, a Framework Strategy for a Resilient Energy Union With a Forward-Looking Climate Change Policy (COM/2015/080 FINAL)*. Brussels: The European Union, Commission.

EU (2015b). *Communication From the Commission, a Roadmap For Moving to A Competitive Low Carbon Economy in 2050 (COM/2011/0112 FINAL)*. Brussels: The European Union, Commission.

EU (2015c). *Communication From the Commission, Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation (C(2015) 6317 FINAL)*. Brussels: The European Union, Commission.

EU (2016). *Council Decision 2016/1841 on the CONCLUSION, on Behalf of the European Union, of the Paris Agreement Adopted Under the United Nations Framework Convention on Climate Change, Oj L 282/1*. Rome.

EU (2017). *THE Strategic Energy Technology (Set) Plan*. Brussels: The European Union.

EU (2018a). *Commission Implementing Regulation (EU) 2018/2066 Of 19 December 2018 on the Monitoring and Reporting of Greenhouse Gas Emissions Pursuant to Directive 2003/87/EC of the European Parliament and of the Council and Amending Commission Regulation (EU) No 601/2012. Oj L 334*. Brussels: The European Union.

EU (2018b). *Communication From the Commission, A Clean Planet for ALL: A European Strategic LONG-TERM Vision for A Prosperous, Modern, Competitive and Climate Neutral Economy (COM/2018/773 FINAL)*. Brussels: The European Union Commission.

EU (2018c). *Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 Amending Directive 2003/87/EC to Enhance COST-EFFECTIVE Emission Reductions and Low-Carbon Investments, and Decision (EU) 2015/1814, Oj L 76*. Brussels: The European Union.

EU (2018d). *Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste, Oj L 150*. Brussels: The European Union.

EU (2018e). *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy From Renewable Sources, Oj L 328*. Brussels: The European Union.

EU (2018f). *Proposal for a Regulation of the European Parliament and of the Council Establishing Horizon Europe – the Framework Programme for Research and INNOVATION, Laying Down Its Rules for Participation and Dissemination, COM/2018/435 FINAL*. Brussels: The European Union.

EU (2018g). *Regulation (EU, Euratom) 2018/1046 of the European Parliament and of the Council of 18 July 2018 on the Financial Rules Applicable to the General Budget of the UNION, Oj L 193*. Brussels: The European Union.

EU (2018h). *Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the Inclusion of Greenhouse Gas Emissions and Removals From Land USE, Land Use Change and Forestry in the 2030 Climate and Energy Framework, Oj L 156/1*. Brussels: The European Union.

EU (2018i). *Regulation (EU) 2018/842 on Binding Annual Greenhouse Gas Emission Reductions By Member States From 2021 to 2030 Contributing to Climate Action to Meet Commitments Under the Paris Agreement and Amending Regulation (EU) No 525/2013, Oj L 156/26*. Brussels: The European Union.

EU (2018j). *Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, Oj L 328/1*. Brussels: The European Union.

EU (2019a). *Commission Delegated Regulation (EU) 2019/856 Of 26 February 2019 Supplementing Directive 2003/87/EC of the European Parliament And of the Council With Regard to the Operation of the Innovation Fund, Oj L 140/6*. Brussels: The European Union.

EU (2019b). *Commission Delegated Regulation (EU) 2020/389 Of 31 October 2019 Amending Regulation (EU) No 347/2013 of the European Parliament and of* *the Council as Regards the Union List of Projects of Common Interest. Oj L 74*. Brussels: The European Union.

EU (2020a). *Communication From the Commission Concerning the Prolongation and the Amendments of the Guidelines on Regional State Aid For 2014-2020. C 224*. Brussels: The European Union.

EU (2020b). *Proposal for A Regulation of the European Parliament and of the Council Establishing the Framework for Achieving Climate Neutrality and Amending Regulation (EU) 2018/1999 (European Climate Law), COM(2020) 80 FINAL*. Brussels: The European Union.

EU ECA (2018). *Demonstrating Carbon Capture and Storage and Innovative Renewables at Commercial Scale in the EU: Intended Progress Not Achieved In The Past Decade*. (Luxembourg: European court of Auditors.

Fischer, F., Miller, G. J., and Sidney, M. S. (Eds.). (2007). *Handbook of Public Policy Analysis: Theory, Politics, and Methods*. Boca Raton; London; New York, NY: CRC Press.

Fridahl, M. (2017). Socio-political prioritization of bioenergy with carbon capture and storage. *Energy Policy* 104, 89–99. doi: 10.1016/j.enpol.2017.01.050

Fridahl, M. (ed.). (2018). *Bioenergy with Carbon Capture and Storage: From Global Potentials to Domestic Realities*. Brussels: European Liberal Forum.

Fridahl, M. (2019). *"Incitamentsstrukturer för Bioenergi Med Koldioxidavskiljning och -Lagring i Sverige och Europeiska Unionen: Underlagsrapport till Klimatpolitiska Vägvalsutredningen (M 2018:07)"*. Linköping: Linköping Univeristy and Stockholm Environment Institute

Fridahl, M., Hansson, A., and Haikola, S. (2020). Towards indicators for a negative emissions climate stabilisation index: problems and prospects. *Climate* 8:75. doi: 10.3390/cli8060075

Fridahl, M., and Johansson, L. (2017). An assessment of the potential for spurring transformational change through nationally appropriate mitigation actions (NAMAs). *Environ. Innov. Soc. Trans.* 25, 35–46. doi: 10.1016/j.eist.2016.11.003

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., et al. (2014). Betting on negative emissions. *Nat. Clim. Chang.* 4, 850–853. doi: 10.1038/nclimate2392

Gaddy, B. E., Sivaram, V., Jones, T. B., and Wayman, L. (2017). Venture capital and cleantech: the wrong model for energy innovation. *Energy Policy* 102, 385–395. doi: 10.1016/j.enpol.2016.12.035

Gawel, E., Lehmann, P., Purkus, A., Söderholm, P., and Witte, K. (2017). Rationales for technology-specific RES support and their relevance for German policy. *Energy Policy* 102, 16–26. doi: 10.1016/j.enpol.2016.12.007

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Res. Policy* 31, 1257–1274. doi: 10.1016/S0048-7333(02)00062-8

GoS (1966). *LAG (1966:314) Om Kontinentalsockeln [The Continental Shelf LAW]*. Stockholm: Government of Sweden, Swedish Code of Statues (SFS).

GoS (1978). *LAG (1978:160) Om Vissa Rörledningar [LAW on Certain Pipelines]*. Stockholm: Government of Sweden, Swedish Code of Statues (SFS).

GoS (1994). *LAG (1994:1776) Om Skatt På Energi [the Energy Tax Law]*. Stockholm: Government of Sweden, Swedish Code of Statues (SFS).

GoS (1998). *Miljöbalk (1998:808) [the Environmental Code]*. Stockholm: Government of Sweden, Swedish Code of Statues (SFS).

GoS (2008). *FÖRORDNING (2008:761) Om Statligt Stöd Till Forskning Och Utveckling Samt Innovation Inom Energiområdet [Decree on Public Support to Research and Development as Well as Innovation Within the Field of ENERGY, Including Amendments Until 2018:1036]*. Stockholm: Government of Sweden, the Swedish Code of Statutes (SFS).

GoS (2011). *LAG (2011:1200) Om Elcertifikat [the Electricity Certificates LAW]*. Stockholm: Government of Sweden, Swedish Code of Statues (SFS).

GoS (2014). *Förordning (2014:21) Om Geologisk Lagring Av Koldioxid [Decree on Geological Storage of Carbon Dioxide, Including Amendments Until 2016:1190]*. Stockholm: Government of Sweden, the Swedish Code of Statutes (SFS).

GoS (2015a). *Förordning (2015:208) Om Statligt Stöd Till Forskning Och Utveckling Samt Innovation [Decree on Public Support to Research and Development as Well as INNOVATION, Including Amendments Until 2018:880]*. Stockholm: Government of Sweden, the Swedish Code of Statutes (SFS).

GoS (2015b). *FÖRORDNING (2015:517) Om Stöd Till Lokala Klimatinvesteringar [Decree on Support to Local Climate INVESTMENTS, Including Amendments Unrtil 2017:815]*. Stockholm: Government of Sweden, the Swedish Code of Statutes (SFS).

GoS (2015c). *Förordning Om Stöd Till Lokala Klimatinvesteringar, Svensk Författningssamling 2015:517 [Regulation of Support to Local Climate Investments, Swedish Statues 2015:517]*. Stockholm: Government of Sweden, the Swedish Code of Statutes (SFS).

GoS (2016). *En Klimat- Och LuftvåRdsstrategi för Sverige, Del 1, Sou 2016:47 [A Climate and Clean Air Strategy For Sweden, Part 1, Sou 2016:47]*. Stockholm: Government of Sweden, Government Official Reports (SOU).

GoS (2017a). *ETT Klimatpolitiskt Ramverk för Sverige, Regeringens Proposition 2016/17:146 [A Climate Policy Framework for Sweden, Government Proposition 2016/17:146]*. Stockholm: The Government of Sweden, Ministry of Energy and the Environment.

GoS (2017b). *Förordning (2017:195) Om Stöd Till Forskning Och Utveckling Samt Innovation Inom Miljö, Areella Näringar Och Samhällsbyggande [Decree on Public Support to Research and Development as Well as Innovation Within the Field of Environment, Agricultural Sceinces, and Spatial Planning, Including Amendments Until 2018:914]*. Stockholm: Government of Sweden, the Swedish Code of Statutes (SFS).

GoS (2017c). *Förordning (2017:1319) Om Statligt Stöd Till Åtgärder För Att Minska Industrins Processrelaterade Utsläpp Av Växthusgaser Och För Negativa Utsläpp [Decree On Support to Actions for Decreasing the Industry's Process Related Emissions and for Negative Emissions]*. Stockholm: Government of Sweden, the Swedish Code of Statutes (SFS).

GoS (2017d). *Klimatlagen, Svensk Författningssamling 2017:720 [the Climate LAW, Swedish Statues 2017:720]*. Stockholm: Government of Sweden, the Swedish Code of Statutes (SFS).

GoS (2019). *Rapportering Enligt förordning (EU) 2018/1999 Om Styrningen Av Energiunionen Och Av Klimatåtgärder: Sveriges långsiktiga Strategi för Minskning Av Växthusgasutsläppen*. Stockholm: Government of Sweden, The Ministry of Environment.

GoS (2020a). *Budgetpropositionen För 2021 [Proposed Budget For 2021]. Proposition (BILL) 2017/18:1*. Stockholm: Government of Sweden.

GoS (2020b). *Sweden's Integrated National Energy and Climate Plan*. Stockholm: Government of Sweden, The Ministry of Infrastructure.

GoS (2020c). *Vägen Till En Klimatpositiv Framtid: Strategi Och Handlingsplan för Att NÅ Negativa Utsläpp Av VäXthusgaser Efter 2045, Sou 2020:4 [The Pathway to a Climate-Positive Future: Strategy and Action Plan for Achieving Negative Greenhouse Gas Emissions After 2045, Sou 2020:4]*. Stockholm: Government of Sweden, Government Official Reports (SOU).

Gough, C., Garcia-Freites, S., Jones, C., Mander, S., Moore, B., Pereira, C., et al. (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C. *Glob. Sustain.* 1:e5. doi: 10.1017/sus.2018.3

Gough, C., and Upham, P. (2011). Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gas Sci. Technol.* 1, 324–334. doi: 10.1002/ghg.34

Hammond, G. P. (2018). "System characterisation of carbon capture and storage (CCS) systems," in *Biomass Energy With Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*, eds C. Gough, P. Thornley, S. Mander, N. Vaughan, and A. Lea-Langton (Hoboken, NJ: John Wiley & Sons), 129–162.

Hansson, A., Fridahl, M., Haikola, S., Yanda, P., Pauline, N., and Mabhuye, E. (2019). Preconditions for bioenergy with carbon capture and storage (BECCS) in sub-Saharan Africa: the case of Tanzania. *Environ. Dev. Sustain.* 22, 6851–6875. doi: 10.1007/s10668-019-00517-y

Hekkert, M. P., Janssen, M. J., Wesseling, J. H., and Negro, S. O. (2020). Mission-oriented innovation systems. *Environ. Innov. Soc. Trans.* 34, 76–79. doi: 10.1016/j.eist.2019.11.011

HELCOM (1992). *Convention on the Protection of the Marine Environment of the Baltic Sea Area, Including Amendments to Annexes Adopted by the Helsinki Commission In 2000, 2001, 2003, 2007 and 2013*. Helsinki: The Baltic Marine Environment Protection Commission.

Henders, S., and Ostwald, M. (2012). Forest carbon leakage quantification methods and their suitability for assessing leakage in REDD. *Forests* 3, 33–58. doi: 10.3390/f3010033

Herrick, C., and Sarewitz, D. (2000). Ex post evaluation: a more effective role for scientific assessments in environmental policy. *Sci. Technol. Hum. Values* 25, 309–331. doi: 10.1177/016224390002500303

Honegger, M., and Reiner, D. (2018). The political economy of negative emissions technologies: consequences for international policy design. *Clim. Policy* 18, 306–321. doi: 10.1080/14693062.2017.1413322

Howlett, M. (2011). *Designing Public Policies: Principles and Instruments.* London; New York, NY: Routledge.

IMO (1996). *The London Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other matter. Lc Prot 1996.* London: International Maritime Organization.

IMO (2006). *Notification of Amendments to Annex 1 to the London Protocol 1996. LC-LP.1/CIRC.5.* London: International Maritime Organization.

IMO (2009). *Report of the 4TH Meeting of the Contracting Parties to the London PROTOCOL. Lc 31/15.* London: International Maritime Organization.

IMO (2013). *Report of the 8TH Meeting of the Contracting Parties to the London PROTOCOL. Lc 35/15.* London: International Maritime Organization.

IMO (2019). *Resolution LP.5(14) On the Provisional Application of the 2009 Amendment to Article 6 of the London Protocol.* London: International Maritime Organization.

IPCC (2006). *IPCC Guidelines for National Greenhouse Gas Inventories, prepared by the National Greenhouse Gas Inventories Programme*, eds H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe. Hayama: The Institute for Global Environmental Strategies (IGES).

IPCC (2018). *Global Warming Of 1.5 °C: an IPCC Special Report on the Impacts of Global Warming Of 1.5 °C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge: Intergovernmental Panel on Climate Change.

IPCC (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 1, General Guidance And Reporting*, eds E. Calvo Buendia, K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, N. S, A. Osako, Y. et al. Hayama: The Institute for Global Environmental Strategies (IGES).

Jänicke, M. (2017). The multi-level system of global climate governance – the model and its current state. *Environ. Policy Govern.* 27, 108–121. doi: 10.1002/eet.1747

Kapetaki, Z., Hetland, J., Le Guenan, T., Mikunda, T., and Scowcroft, J. (2017). Highlights and lessons from the EU CCS demonstration project network. *Energy Proced.* 114, 5562–5569. doi: 10.1016/j.egypro.2017.03.1696

Karlsson-Vinkhuyzen, S. I., and Vihma, A. (2009). Comparing the legitimacy and effectiveness of global hard and soft law: an analytical framework. *Regul. Govern.* 3, 400–420. doi: 10.1111/j.1748-5991.2009.01062.x

Keith, D. W., Ha-Duong, M., and Stolaroff, J. K. (2006). Climate strategy with Co_2 capture from the air. *Clim. Change* 74, 17–45. doi: 10.1007/s10584-005-9026-x

Kjärstad, J., Skagestad, R., Eldrup, N. H., and Johnsson, F. (2016). Ship transport—a low cost and low risk CO_2 transport option in the Nordic countries. *Int. J. Greenhouse Gas Control* 54, 168–184. doi: 10.1016/j.ijggc.2016.08.024

Koch, N., Fuss, S., Grosjean, G., and Edenhofer, O. (2014). Causes of the EU ETS price drop: recession, CDM, renewable policies or a bit of everything?—New evidence. *Energy Policy* 73, 676–685. doi: 10.1016/j.enpol.2014.06.024

Kossoy, A., Peszko, G., Oppermann, K., Prytz, N., Klein, N., m., et al. (2015). *State and Trends of Carbon Pricing 2015.* Washington, DC: World Bank.

Kuparinen, K., Vakkilainen, E., and Tynjälä, T. (2019). Biomass-based carbon capture and utilization in kraft pulpmills. *Mitig. Adapt. Strateg. Glob. Change* 24, 1213–1230. doi: 10.1007/s11027-018-9833-9

Lehmann, P., and Gawel, E. (2013). Why should support schemes for renewable electricity complement the EU emissions trading scheme? *Energy Policy* 52, 597–607. doi: 10.1016/j.enpol.2012.10.018

Levihn, F., Linde, L., Gustafsson, K., and Dahlen, E. (2019). Introducing BECCS through HPC to the research agenda: the case of combined heat and power in Stockholm. *Energy Rep.* 5, 1381–1389. doi: 10.1016/j.egyr.2019.09.018

Liu, L.-C., Li, Q., Zhang, J.-T., and Cao, D. (2016). Toward a framework of environmental risk management for CO2 geological storage in china: gaps and suggestions for future regulations. *Mitig. Adapt. Strateg. Glob. Change* 21, 191–207. doi: 10.1007/s11027-014-9589-9

Lomax, G., Lenton, T. M., Adeosun, A., and Workman, M. (2015). Investing in negative emissions. *Nat. Clim. Chang.* 5, 498–500. doi: 10.1038/nclimate2627

Martínez de Alegría, I., Fernández-Sainz, A., Alvarez, I., Basañez, A., and del-Río, B. (2017). Carbon prices: Were they an obstacle to the launching of emission abatement projects in Spain in the Kyoto protocol period? *J. Clean. Prod.* 148, 857–865. doi: 10.1016/j.jclepro.2017.01.154

Mazzucato, M. (2018). Mission-oriented innovation policies: challenges and opportunities. *Indus. Corp. Change* 27, 803–815. doi: 10.1093/icc/dty034

McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B., and Markusson, N. O. (2019). Beyond "Net-Zero": a case for separate targets for emissions reduction and negative emissions. *Front. Clim.* 1:4. doi: 10.3389/fclim.2019.00004

Mercure, J.-F., Pollitt, H., Chewpreecha, U., Salas, P., Foley, A. M., Holden, P. B., et al. (2014). The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector. *Energy Policy* 73, 686–700. doi: 10.1016/j.enpol.2014.06.029

Moe, E., and Røttereng, J.-K. S. (2018). The post-carbon society: rethinking the international governance of negative emissions. *Energy Res. Soc. Sci.* 44, 199–208. doi: 10.1016/j.erss.2018.04.031

Nicolaï, J.-P., and Zamorano, J. (2018). Windfall profits under pollution permits and output-based allocation. *Environ. Resour. Econ.* 69, 661–691. doi: 10.1007/s10640-016-0096-1

Normann, H. E. (2017). Policy networks in energy transitions: the cases of carbon capture and storage and offshore wind in Norway. *Technol. Forecast. Soc. Change* 118, 80–93. doi: 10.1016/j.techfore.2017.02.004

Oikonomou, V., Flamos, A., Zeugolis, D., and Grafakos, S. (2012). A qualitative assessment of EU energy policy interactions. *Energy Sourc. Part B Econ. Plann. Policy* 7, 177–187. doi: 10.1080/15567240902788996

OSPAR Commission (1992). *The Convention for the Protection of the Marine Environment of the North-East Atlantic, as Amended on 24 JULY 1998, Updated 9 MAY 2002, 7 February 2005 and 18 MAY 2006, and With Amendments To Annexes II and III Adopted at Ospar 2007*. London: The Oslo and Paris Conventions (OSPAR) Commission.

Parson, E. A., and Buck, H. J. (2020). Large-scale carbon dioxide removal: the problem of phasedown. *Glob. Environ. Politics* 20, 70–92. doi: 10.1162/glep_a_00575

Pour, N., Webley, P. A., and Cook, P. J. (2018). Potential for using municipal solid waste as a resource for bioenergy with carbon capture and storage (BECCS). *Int. J. Greenhouse Gas Control* 68, 1–15. doi: 10.1016/j.ijggc.2017.11.007

Rickels, W., Proel, ß, A., Geden, O., Burhenne, J., and Fridahl, M. (2020). *The Future of (Negative) Emissions Trading in the European Union*. Kiel: Kiel Institute for the World Economy.

Rodriguez, E., Lefvert, A., Fridahl, M., Grönkvist, S., Haikola, S., and Hansson, A. (2020). Tensions in the energy transition: Swedish and finnish company perspectives on bioenergy with carbon capture and storage. *J. Clean. Prod.* doi: 10.1016/j.jclepro.2020.124527. [Epub ahead of print].

Rogers, E. M. (2003). *Diffusion of Innovations.* New York, NY: The Free Press.

SEA and NWRED (2017). *En Svensk-Norsk Elcertifikatsmarknad: Årsrapport För 2016 [The Swedish-Norwegian Electricity Certificate Market: Annual Report 2016]*. Eskilstuna and Oslo: The Swedish Energy Agency and the Norwegian Water Resources and Energy Directorate.

SEPA (2020). *Utsläpp i siffror [Emissions in numbers]* [Online]. *Stockholm: Swedish Environmental Protection Agency.* Available online at: http://utslappisiffror.naturvardsverket.se (accessed May 27, 2020).

Shishlov, I., Morel, R., and Bellassen, V. (2016). Compliance of the parties to the Kyoto protocol in the first commitment period. *Clim. Policy* 16, 768–782. doi: 10.1080/14693062.2016.1164658

Skjærseth, J. B., Stokke, O. S., and Wettestad, J. (2006). Soft law, hard law, and effective implementation of international environmental norms. *Glob. Environ. Politics* 6, 104–120. doi: 10.1162/glep.2006.6.3.104

SOU (2020). *VäGen Till En Klimatpositiv Framtid [The Pathway to a Climate-Positive Future]*. Stockholm: Statens Offentliga Utredningar

Statistics Sweden (2020). *Miljöräkenskaperna [The Environmental Accounts]*. Stockholm: Statistics Sweden. Available online at: http://www.statistikdatabasen.scb.se (accessed May 27, 2020).

Stigson, P., Haikola, S., Hansson, A., and Buhr, K. (2016). Prospects for Swedish acceptance of carbon dioxide storage in the Baltic Sea: learning from other energy projects. *Greenhouse Gas. Sci. Technol.* 6, 188–196. doi: 10.1002/ghg.1585

Su, Y., Zhang, P., and Su, Y. (2015). An overview of biofuels policies and industrialization in the major biofuel producing countries. *Renew. Sustain. Energy Rev.* 50, 991–1003. doi: 10.1016/j.rser.2015.04.032

Tanzer, S. E., and Ramírez, A. (2019). When are negative emissions negative emissions? *Energy Environ. Sci.* 12, 1210–1218. doi: 10.1039/C8EE03338B

Torvanger, A. (2019). Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement. *Clim. Policy* 19, 329–341. doi: 10.1080/14693062.2018.1509044

UNFCCC (1998). *Cop3: Report, Addendum 1 (including The Kyoto Portocol), Kyoto 1997. FCCC/CP/1997/7/ADD.1*. Bonn: The UN Framework Convention on Climate Change.

UNFCCC (2016). *Cop21 Report (Addendum 1), Paris 2015. FCCC/CP/2015/10/ADD.1*. Bonn, Germany: United Nations Framework Convention on Climate Change.

UNFCCC (2019a). *Decision 4/CMA.1: Further Guidance in Relation to the Mitigation Section of Decision 1/CP.21. FCCC/PA/CMA/2018/3/ADD.1*. Bonn, Germany: United Nations Framework Convention on Climate Change.

UNFCCC (2019b). *Decision 18/CMA.1: MODALITIES, Procedures and Guidelines for the Transparency Framework for Action and Support Referred to in Article 13 Of The Paris Agreement. Fccc/PA/CMA/2018/3/ADD.2*. Bonn, Germany: United naTions Framework Convention on Climate Change.

Utterback, J. M. (1994). *Mastering the Dynamics of Innovation: How Companies Can Seize Opportunities in the Face of Technological Change*. Boston, Mass.: Harvard Business School Press.

van Vliet, J., Hof, A. F., Mendoza Beltran, A., van den Berg, M., Deetman, S., den Elzen, M. G. J., et al. (2014). The impact of technology availability on the timing and costs of emission reductions for achieving long-term climate targets. *Clim. Change* 123, 559–569. doi: 10.1007/s10584-013-0961-7

Vihma, A. (2012). "Analyzing soft law and hard law in climate change," in *Climate Change and the Law,* eds E. J. Hollo, K. Kulovesi, and M. Mehling (Dordrecht; Heidelberg; New York, NY; London: Springer), 143–164.

Wettestad, J., Eikeland, P. O., and Nilsson, M. (2012). EU climate and energy policy: a hesitant supranational turn? *Glob. Environ. Politics* 12, 67–86. doi: 10.1162/GLEP_a_00109

Zakkour, P., Kemper, J., and Dixon, T. (2014a). Incentivising and accounting for negative emission technologies. *Energy Proced.* 63, 6824–6833. doi: 10.1016/j.egypro.2014.11.716

Zakkour, P., Scowcroft, J., and Heidug, W. (2014b). The role of UNFCCC mechanisms in demonstration and deployment of CCS technologies. *Energy Proced.* 63, 6945–6958. doi: 10.1016/j.egypro.2014.11.728

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The Discourse and Reality of Carbon Dioxide Removal: Toward the Responsible Use of Metaphors in Post-normal Times

Noel Castree[1,2]*

[1] *School of Communication, University of Technology Sydney, Sydney, NSW, Australia,* [2] *Department of Geography, University of Manchester, Manchester, United Kingdom*

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Edited by:
Oliver Geden,
German Institute for International and Security Affairs (SWP), Germany

Reviewed by:
Shinichiro Asayama,
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Manjana Milkoreit,
Purdue University, United States

Correspondence:
Noel Castree
noel.castree@uts.edu.au

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There's little doubt that a variety of CDR techniques will be employed worldwide in the decades and centuries to come. Together, these techniques will alter the character and functioning of the biosphere, hydrosphere, cryosphere, pedosphere, and atmosphere. More locally, they will have immediate impacts on people and place, within diverse national state contexts. However, for the moment CDR exists more in the realm of discourse than reality. Its future roll-out in many and varied forms will depend on a series of discussions in the governmental, commercial, and civic spheres. Metaphor will be quite central to these formative discussions. Metaphors serve to structure perceptions of unfamiliar phenomena by transferring meaning from a recognized "source" domain to a new "target" domain. They can be employed in more or less felicitous, more or less noticeable, more or less defensible ways. Metaphors help to govern future action by framing present-day understandings of a world to come. To govern metaphor itself may seem as foolhardy as attempting to sieve water or converse with rocks. Yet by rehearsing some old lessons about metaphor we stand some chance of responsibly steering its employment in unfolding debates about CDR techniques and their practical governance globally. This Perspective identifies some key elements of metaphor's use that will require attention in the different contexts where CDR techniques presently get (and will in future be) discussed meaningfully. Various experts involved in CDR development and deployment have an important, though not controlling, role to play in how it gets metaphorized. This matters in our age of populism, rhetoric, misinformation, and disinformation where the willful (mis)use of certain metaphors threatens to depoliticize, polarize, or simplify future debates about CDR. What is needed is "post-normal" discourse where high stakes decisions made in the context of epistemic uncertainty are informed by clear reasoning among disparate parties whose values diverge.

Keywords: discourse, metaphor, CDR, NETs, wicked problems, anticipatory semantics, discursive windows

> Discourses interest us not for their own sake but insofar as they comprise sites for the making of meaning .... The question is not whether material objects exist but how they become meaningful for us ... and thereby influence our actions. Epstein (2008: 8)

At long last, anthropogenic climate change—a key component of the emerging Anthropocene—is beginning to make itself fully felt in the realms of collective human decision making. The reality of global warming is now widely acknowledged, as is the significant future threat it poses; the massive inadequacy of current mitigation measures is no secret and denied only in fringe circles; meanwhile, in the relevant research communities (if not always the political community), talk of far-reaching "sustainability transitions" is now a common-place. The next 25 years could (and should) be game-changing for people and planet, even if few are talking seriously (yet) about a revolution in human affairs. Mitigation and adaptation measures will need to be ramped-up hugely. But they will need to be accompanied by a range of carbon dioxide removal (CDR) techniques designed to sequester greenhouse gases. Without them, global average temperature could make life in many parts of the future world distinctly inhospitable for millions of people, quite aside from its deleterious impacts on terrestrial and marine ecology.

In this context, a number of vitally important questions arise about CDR techniques, which range from biomass energy with carbon capture and storage (BECCS) through bio-char burial and afforestation to direct air capture and sequestration. This collection of papers is designed to begin to answer these questions. We are at an early stage in rolling-out CDR on a large scale. While some techniques are familiar (e.g., tree planting), others are novel and yet to be properly tested in real world settings (e.g., ocean alkalinization). The variety of possible techniques means that governing CDR responsibly will be complex, even within a single country. The perceived urgency of "tackling climate change" since the 2015 Paris Agreement was signed may propel rapid experimentation in the development, trialing, and implementation of certain CDR techniques. There are practical questions that have to be answered about public consultation, rules and regulations, planning permissions, and so on (e.g., see Fajardy et al., 2019, writing in this journal). But it's important not to lose sight of the discursive issues: how we *talk* about CDR requires close attention just as much as the material interventions gathered together under the CDR label. We have already seen this in discussions of solar radiation management (SRM) since around 2010. For some commentators, even to consider the *possibility* of SRM risks moral hazard, well before field- trials of things like stratospheric aerosol injection. The talk we talk affects whether and how we walk the proverbial walk.

It may seem foolhardy to talk about the governance of discourse, even in an informal sense of collectively monitoring and adjusting our language as we proceed. Words and their meanings, deployed in various communicative contexts, seem to elude social control: they evolve organically over time within and across whole societies. However, in this paper I want to focus on *metaphors* not language in general (for reasons to be explained). In addition, while I will make a set of general points about how CDR may in future be metaphorized, it's important to recall that some communicative contexts are more consequential than others. Trying to steer the use of metaphor in these contexts (e.g., public consultation exercises, reports commissioned by governments, or peer review articles) is a broadly viable proposition, whereas governing metaphor use in a wider society is probably not[1]—at least for the addressees of this article (namely, researchers interested in the technical, social, and environmental dimensions of CDR). My main concern in what follows is that ongoing discussions of CDR in the expert community and beyond become suitably "post-normal"—if not always, then as often as possible. That is, discussions should be attuned to the complex, high-stakes, urgent, value-based and uncertain character of CDR interventions seen as a family of specific, local/regional measures to be implemented over time across our variegated globe. Such discussion easily exceeds the language typically used by specialists to depict developments in science and technology.

Conventional uses of metaphor, I will suggest, could easily become barriers to post-normal discourse. While experts in linguistics and communication well understand the pervasive, necessary but often problematic character of metaphorical representation, people in the political, commercial, and civic spheres are often apt to use metaphor in partial, rhetorical, unthinking, manipulative, or strategic ways. This could hamper the sort of sophisticated, well-considered representations of CDR techniques that will help their implementation be as socially legitimate as it can reasonably be. Experts involved in the journey of CDR techniques from drawing board to actuality have a particular role to play in using metaphor well. This is especially important at a time when populist rhetoric, post-truth discourse, "alternative facts," fake news, and similar maladies afflict the public and political spheres worldwide.

While experts do not—and cannot—ultimately have a *determining* role in shaping public understanding of CDR, they arguably have a responsibility to counter manifestly deficient understandings of the technologies in question. Deficiency is not just a question of factual inaccuracy but also relates to the meanings conveyed through particular constellations of words. In the present case, the meanings can relate to (i) the practical efficacy of certain CDR techniques, (ii) to their wider knock-on effects socially and environmentally, and (iii) to the underlying rationale for their deployment in the first place. The unwary can easily elide metaphor use in these related but distinct contexts where questions of fact and value bleed into each other.

CDR ON THE CUSP OF IMPLEMENTATION: ANTICIPATORY SEMANTICS AND METAPHOR

As the COVID-19 pandemic reminds us, language is a necessary tool in any effort to devise suitable forms of action. New socio-environmental problems, or new ways of addressing familiar

[1]That said, through laws and, over time, changing customs, societies do quite successfully govern language as the success of feminist and anti-racist arguments demonstrates in many countries across the world. Such governance responses tend to emerge out of widespread social discontent anchored in inequality, disrespect, or injustice.

problems, call forth "anticipatory semantics:" that is, efforts to describe, explain, and evaluate situations so as to elicit, and justify, one or more practical responses intended to achieve (or avoid) certain future probabilities.[2] In the case of the coronavirus, military language has been prevalent (e.g., COVID-19 is an "enemy" and healthcare professionals are "heroes" working on "the front line" to protect the public). Likewise, social distancing and lock downs have been frequently depicted as necessary "circuit breakers." This sort of language serves to structure interactions between politicians and publics in a crisis situation. CDR is also being framed in the context of emergency: the last 3 years have seen scientists, activists, and others talk loudly of a looming "climate crisis" (Greta Thunberg being the personification of this). But, for better or worse, this second emergency is normally seen as less pressing than the first, even if the long-term threat it poses will be equally existential for many people and non-humans.

Presently, at the global level CDR is entering policy discourse because of (i) the very challenging Paris Agreement goal to keep average global temperature to a 2 degree Celsius rise or less, and (ii) the fact that CDR is built-into various scenarios prepared by the Intergovernmental Panel on Climate Change. Increasingly also called "negative emissions technologies" (NETS), CDR techniques will now start to feature meaningfully in national policy discussions about future plans for energy supply, nature conservation, transportation and more besides. People like me, and the other contributors to this special issue, can shape these discussions through our own language, advice, and interventions beyond the university's walls. But politicians, business people, civil servants, and citizens will have their say too. Parliamentary debates, white papers, United Nations meetings, company strategic plans, and public consultations are just some of the places where CDR techniques will be considered by a range of interlocutors, quite aside from their representation in the news media. A linguistic meshwork will emerge, with plenty of cross-referencing. As noted, while some techniques are scarcely new (and were never designated "CDR" in the past), others are novel. This means that present day discussions will, in very material ways, shape their journey from research through development and demonstration to deployment in specific situations. In short, the discourse of CDR is poised to shape the practice of CDR, whereas only in future will the discourse-practice relationship be much more symmetrical. One very recent example of this is a study of public perceptions of CDR (Cox et al., 2020). Since the perceptions do not wholly precede the process of studying them, the terms and phrases deployed by the researchers to *elicit* perceptions have a *performative* quality. In turn, expressed perceptions will inform CDR research and policy "downstream." So it is that "saying" structures the field of "acting" in a somewhat one-sided process of co-production that may, but only later on, become more balanced and bi-directional (cf. Jasanoff, 2006).

Close and critical scrutiny of the language used to depict environmental phenomena and issues is hardly a new thing (e.g., see Dryzek, 1997).[3] But it remains relevant and hugely important, especially during "discursive windows." These are periods when the descriptive, explanatory, and evaluative terms that will define an emerging issue-field get established. Windows is a fairly apt metaphor here: the issues end-up being seen through a frame of a certain size and shape, whose glass is variously tinted, clear, or opaque to viewers depending on their angle of vision. The window is constructed by dominant actors or many actors of roughly equal influence, again depending on the context.[4] For instance, in the lead up the UK Brexit referendum, the window was sufficiently large that Leavers and Remainers could be seen and heard by millions of people (see Charteris-Brown, 2019). Windows can be altered in time, but typically get fashioned in the first few years of a problem or issue coming to light [for instance, see Brown's 2016 analysis of how "sustainable development" has been progressively depoliticized since the mid-1980s in an attempt by some to "fix" its public meaning consistent with ongoing consumerism]. In the present case, CDR is the "issue," seen in relation to an array of other issues, like decarbonizing energy supply and reducing atmospheric temperature rises. Co-existing and overlapping discursive windows will likely emerge globally and in country-specific contexts. Discursive windows are usually established before what are called "policy windows" get opened: these are periods when sets of actions about new or existing issues or phenomena are instituted (see Rose et al., 2020). Windows can be re-opened and even demolished. This fact is well-illustrated by the vicissitudes of nuclear power in many countries, variously seen as an un/acceptable means of addressing the triple challenge of energy security, energy affordability, and climate change.

That I have referred to the language of CDR in metaphorical terms is very fitting because I want to focus on metaphor in the rest of this article. Metaphor, I contend, can be especially central to anticipatory semantics as discursive windows take shape. There are two obvious reasons why. First, all language is extensively metaphorical: metaphors are not, despite what some people may think, merely linguistic "devices" employed now and then for effect. They are part of the fabric of language, even—according to Lakoff and Johnson's (2003) classic study—the fabric of *thought*. Second, when confronted with new issues, situations or phenomena people are inevitably tempted to draw direct comparison between the familiar and the novel. In the present case, the very terms CDR and NETs have a strongly metaphorical quality, as well signifying techniques which *themselves* invite metaphorical description. This has already been evident in

[2] Anticipatory semantics are important within systematic and formalized processes of "anticipatory governance," where institutions are consciously adapted or designed to prevent or realize a future state of affairs seen as likely or un/desirable.

[3] In many social science and especially humanities disciplines, a major focus on language, imagery and representation occurred during the 1980s and 90s. This "cultural turn" was sometimes presented as "social constructionism," since when there has been a neo-realist and neo-material (re)turn in disciplines like my own, human geography. Regardless of the vagaries of academic fashion, the close scrutiny of language to render the world meaningful and to shape action has never not mattered. A recent example of the value of discursive analysis, again in my own discipline, is provided by Adams (2020). He looks at water and its management as a partial product of its linguistic framing rather than the framing "reflecting" pre-existing meanings awaiting discovery and accurate representation.

[4] I adapt the notion of "discursive window" from the notion of a "policy window," first deployed by political scientists studying how policy agendas get built and instituted by competing political actors over time (e.g., see Kingdon, 1984).

commentary within the expert community before and after the signing of the 2015 Paris Agreement (see Haikola et al., 2019). I now explore metaphor and CDR/NETs under four headings ("The nature and use of metaphor;" "The language of inclusivity and power;" "The dangers of metaphor;" and "Toward post-normal metaphor use"). While experts in the analysis of metaphor will find my observations fairly basic, this Perspective is addressed to those whose expertise is directly related to CDR/NETs. Keener awareness of language use among the latter—in peer review journals, in discussions with environmental journalists, in citizen juries and in community planning fora, for instance—might help improve wider discussions of CDR techniques as their discursive window gets fashioned by many actors. We cannot afford to be casual or hasty in our use of metaphor when the stakes are so very high. So far, expert discussion has fallen prey to rather polarizing metaphors (see Haikola et al., 2019).

THE NATURE AND USE OF METAPHOR

Metaphor involves depicting one thing in terms of another. It's a linguistic convention designed to convey meaning, just as analogy, simile, hyperbole, alliteration, and metonymy are linguistic devices. Metaphor can be used rhetorically, that is to make a point or argument through exaggeration or special emphasis. But metaphor need not be used rhetorically, and—as a linguistic device—it is also not, as noted, only utilized now and then. "The frequency of metaphors," notes Larson (2011: 4), "should not be surprising." Yet metaphors are not all of a piece. For instance, Newmark (1980), in his study of translation between languages, long ago identified several kinds of metaphor: namely, dead, stock, clichéd, and original metaphors. In the pragmatics of communication, the role of these metaphors is variable and contingent. For our purposes, the broad distinction between established and novel metaphors is less important than their *prominence* in specific situations In English, roughly one in every fifteen words is metaphorical. In that sense, metaphors are thoroughly ordinary. However, in some situations, certain metaphors loom large and clamor for attention. In the present context, we might say that as discursive windows take shape some metaphors can be especially potent in framing objects and issues. For those promoting them, these metaphors have the virtue of being memorable (sometimes strikingly so) and convenient.

Take SRM. In their paper, "Metaphors we die by?," Nerlich and Jaspal (2012) examined early newspaper reporting of "geoengineering" (between 1988 and 2010). They revealed the prominence of metaphor in handling the novelty and controversial character of SRM. For instance, a frequent and arresting metaphor was SRM as a "sunscreen," another was SRM as "medicine" administered to a sick "patient" (the Earth). Both metaphors were linked to the notion of a "climate catastrophe." This link, Nerlich and Jaspal suggested, was unlikely to permit widespread support among publics worldwide, and would put many risk-averse politicians off too (even as it drew attention to the need for drastic climate action). This is because they implied it might be "too late" to do other things to address climate change, creating feelings of defeat and fatalism and/or a reluctant reliance on technocrats armed with "last ditch" solutions. That is, however apt the metaphors were seen to be among geoengineering proponents, they were more likely than not to be unpersuasive and risked crowding out other ways of framing SRM.

As the SRM example shows, metaphors involve abstraction. They often "thingify" phenomena or issues by depicting them in terms of a known and well-defined object. This means metaphors are often poor at attending to relationships and entanglements among issues, problems or entities. Metaphors are also both cognitive and normative-cum-affective. They have a *descriptive* quality, linking "source" and "target" domains of reference through literal denotation. Indeed, a claim to some sort of descriptive accuracy or rough adequacy is implicit in virtually all metaphors. But they are also *evaluative*, often generating a positive or negative emotional reaction among their intended audiences. For instance, "sunscreen" is normally seen as good because it's intended to avoid the "bad" of skin cancer, making it (implicitly) "rational" to apply it. Meanwhile, in the field of conservation biology, the notion of "invasive species" is deeply loaded (see Larson, 2005, among others), having friend-enemy associations that are not necessarily apt when dealing with ecological entanglements. The socially accepted normative status of the source domain is thus used to shape normative intentions toward the emerging target domain.

The examples of sunscreen and invasive species remind us that prominent metaphors often work through *chains of implicit semantic association and connotation*. While ostensibly associating one thing or issue to *another* thing or issue, in reality metaphors often conjure-up a whole *set* of unspoken cognitive, normative, and affective references sedimented in our language. These references become quite important when key metaphors are employed repeatedly and rhetorically to define a new issue or object. Key metaphors tend to dominate the discursive space—for instance, the more we use the language of NETs to think about climate change mitigation, the more we are invited to think of a global numbers game where we need to get below a baseline GHG concentration figure by "sucking" gases out of the atmosphere. This is consistent with long-standing discourse about a single envelope of intermixed GHGs (denominated in PPM) in need of global management. Meanwhile, other metaphors operate in less overt ways by virtue of the more "neutral" comparison between the source and target domains. For instance, climate researchers have quite successfully introduced the notion of a "carbon budget" into global discussions about climate policy since around 2005 (see Lahn, 2020). In Anglophone popular culture, the word "budget" is less loaded than the word "negative." Yet at some level it is still normative-affective, conjuring a complex set of economic associations and connotations about responsibility, taking, borrowing, and debt. Its semantic work is real but fairly quiet or surreptitious. Together, the notions of "negative" and "budget"—both signifying numerical targets and amounts—remind us about another key element of prominent metaphors: namely, they tend to work in clusters. That does not mean each metaphor is wholly consistent with the others being used. But a corollary of the above mentioned pervasiveness of metaphor in social discourse is that metaphors come in groups by the time a discursive window is fashioned. The smaller the groups, the more constrained the hermeneutics of the issue in question are likely to be in the public domain. The more contested the issue, the more likely the principal metaphors are to polarize perspectives on it.

In sum, metaphors are pervasive in discourse but for many issues a selection of metaphors become prominent. They involve abstraction, are both cognitive and normative-affective, implicitly signify wider chains of meaning, and work in duos, trios, and clusters—though with some metaphors ultimately more influential than others as discursive windows get opened and gradually constructed.

CDR, NETs AND THE LANGUAGE OF INCLUSIVITY AND POWER

In the twenty-first century, there's a tendency for advanced science and technology to create new processes and objects which society is subsequently tasked with governing (ethically, legally, and practically). The leap-frogging developments in the world of academic and commercial genetics are a case in point. "Responsible research and innovation" (RRI) is now the mantra among many governments and scientists in order to avoid technology losing its societal moorings (e.g., it was a major focus of the EU Horizon 2020 funding programme from 2014). While some CDR/NETs techniques appear to be familiar and are framed as "natural," others are new and, given the ambitious 2015 Paris goals, are being discussed *before* their development and possible roll-out on a large scale. This is why the language used in discussion will matter so much. Even if some of the techniques are not "hi-tech" compared to say, driverless vehicles, CDR/NETs are being advanced by various scientists in the name of a scientifically defined "climate problem" (or crisis) and the related problem of national energy supply and security (since "decarbonization" is now an imperative). This not only gives "experts" a prominent role in framing CDR/NETs; it also lends legitimacy to the idea that CDR/NETs should be considered seriously in the political, commercial, and civic domains. The experts stand to be first-movers, setting the terms for broader discussion, even if—in the end—many others in the civic, commercial, and governmental domains will shape the discursive and policy windows. While there has yet to be a truly public debate about CDR/NETs, we have already seen that a few trained specialists have the key voices so far (e.g., Kevin Anderson, Glen Peters, and Klaus Lacker). Metaphor has been integral to their messages (e.g., see Anderson and Peters, 2016; Lackner et al., 2016).

If certain metaphors will probably loom large in the debates to come, we might ask: what are some of the dangers attending to their use? To answer this question we need to anticipate the likely contexts of future discussion. The terms CDR and NETs encompass disparate measures, so much so that some have asked whether it's at all sensible to consider them together—notwithstanding their common aim to reduce GHG emissions in light of the Paris Agreement targets (Bellamy and Geden, 2019). Even so, it's likely that several measures will be aggregated in global debates (especially in the United Nations) and that national level discussions will also ensue (for instance, recall that the mid-1990s controversy over field testing genetically modified crops caused the British New Labor government to instigate a consultation across England, Northern Ireland, Scotland, and Wales). More locally, just as fracking has sparked community opposition in the UK, USA and elsewhere, so certain proposals to test specific CDR/NETs are likely to spark strong local interest in rural and peri-urban areas, or in coastal areas adjacent to proposed experiments in marine geoengineering. The local debates are much more likely to attend to the specific details of certain CDR/NETs techniques than are national and global debates (which will tend to focus on general questions of principle, size and scope, referenced to strategic climate, and energy goals). But the local debates are also likely to be discursively framed by these prior global and national discussions, often coming later in the "window making" process. Throughout, a common denominator is that discussions of most (if not necessarily all) CDR/NETs in many (if not all) venues will have a *deliberative* character. In other cases, conflict will arise or people will be silenced, rendered passive or ignored in various ways. By and large, the latter cases will arise more often in countries with weak or non-existent histories of democratic rule. Yet in erstwhile democracies, social media, the decline of deference to certified experts and other forces are often conspiring to render deliberation a process of heat without much light among interlocutors.

The reasons why CDR/NETs are likely to spark societal debate are not difficult to fathom. First, the combined *scale* of CDR/NETs needed to meet the Paris goals is such that countries will need to consider each other's rights and responsibilities in the process. Second, the *speed* at which GHG removal techniques will need to be deployed means wide consultation will again be necessary across the globe. Avoidance of such consultation may be a sign of power and special interests in play, perhaps through labeling some CDR/NETs techniques in ways that conceal their significance for ecology and people. Third, within specific countries the immediate *knock-on effects* of large-scale deployment (e.g., of biomass with carbon capture and storage on agricultural land for food) will likely oblige governments to consult citizens in many cases. In several situations, the effects might be perceived as worse than the impacts of unabated climate change. In other cases, government or commercial actors may want to downplay the effects in order to get CDR/NETs projects actioned. Fourth, we live in an *age of protest* where, in democracies as well as more autocratic states, people routinely express their right to be considered and heard. Witness Extinction Rebellion, among many others. When CDR/NETs deployment significantly impacts peoples' local environment—be the people wealthy second-homers in rural Germany, campesinos in Mexico or aboriginal Australians—then we might expect some sort of debate to ensue between stakeholders (be it by design or through oppositional action).

In this context, metaphor can serve the process of deliberation more or less well. Deliberation can be judged according to its quality and range. *Quality* is a question of how sophisticated debate is and whether interlocutors are truly listening to each other. One of the paradoxes of the present is that we live in "an information age" inhabited by more university graduates than ever before, yet where the quality of public debate about important issues is typically low. The Brexit issue in the UK demonstrated this graphically: an exceedingly complex, high-stakes question ("stay or leave?") was answered using sound bites and simplistic slogans by antagonists between 2016 and 2019. The misuse of social media, strong bias in some news reporting organizations (notably Fox News) and the rise of some populist politicians (notably, Donald Trump, Jair Bolsinaro, Boris Johnson, and Vladimir Putin) have also created a "post truth" environment where mutual trust and common ground seem in short supply as misinformation proliferates. Many political theorists advocate for special deliberative measures (e.g., citizen juries, public consultations, consensus conferences) in order to improve shared understanding, to build trust, to clarify reasoning, to facilitate subsequent decision making and to legitimize action. Such measures can address the need to be inclusive of perspectives, that is to build a sufficient *range* of values and arguments into debate so that mainstream or elite perspectives are not assumed to be the best or only starting point. Yet many critics in social science (e.g., Wilson and Swyngedouw, 2014) believe we now live in a "post-political" age where debate is stymied or stage-managed such that "radical" or "alternative" political axioms and goals are not given a proper hearing and remain on the social margins.

Clearly, what counts as a "properly political" debate it itself a political question, the answer to which will be inflected by existing social power relationships. Relatedly, there is no "model" of "good deliberation" that can rise above all contexts as a standard-setter.[5] Even if there was, profound questions arise about how far good deliberation can be instituted in our deeply imperfect world. Even so, we can identify some broad threats that unthinking, special-interest driven, rhetorical, or very strategic metaphor use can pose to rich and inclusive dialogue about CDR/NETs. When realized, the threats might limit understanding, obscure complexity, marginalize some voices and precipitate weakly justified actions that lack legitimacy among those they affect.

THE DANGERS OF CONVENTIONAL METAPHOR USE

The quality of global, national, and local-scale discussion of CDR/NETs techniques—from the research and development phase through to long-term, large-scale deployment—will be strongly conditioned by the principal metaphors employed to characterize them in the next few years (unless we were to somehow forgo use of prime metaphors, something I will consider briefly near the end of this article). This much is obvious when we reflect back on AIDS—the so-called "gay disease"—as it became a matter of medical, governmental, and public concern during the 1980s. In her influential book on AIDs and metaphor, Sontag (1989) showed how the notions of a "plague," a "cancer," and "polluted" bodies served to stigmatize gay people in the USA and beyond. The discursive window, she demonstrated, became quite hard to reopen and reframe thereafter. Analogously, the risk is that poor metaphor use—we might even say the employment of major metaphors, *period*—will crowd-out richer ways of discussing the nature and implications of CDR/NETs. As we will see in the next section, by "richer" I do not simply mean "empirically accurate" to the techniques in question, but also inclusive of value-based, socially contingent, situated appraisals of these techniques relative to climate change and related challenges.

Given the context in which the CDR/NETs issue has risen to prominence, the risks are clear enough and all involve undue simplification of cognitive, normative, and affective complexity and diversity:

Risk 1: Narrow Abstraction and Fetishization Through Conventional Metaphors

Already, it's evident that CDR/NETs risk being narrowly framed in terms of material-physical phenomena (e.g., altering the alkinity of ocean water) and their contribution to an overarching goal of reducing GHG concentrations. Metaphors such as "sinks" and "capture" provide noun or verb-based references to source domains that conjure-up well defined images of removal and containment. Greenhouse gases, and the global atmosphere more broadly, risk being objectified as discrete entities that CDR/NETs can materially manage. While this circumscription may seem factually appropriate—after all, anthropogenic climate change *is* occurring and GHG concentrations *are* rising—it screens-out a whole set of ontological, causal and normative connections between the "problem" at hand and CDR/NETs as putative "solution." A recent paper about SRM and new agricultural biotechnology highlights the problem of narrow abstraction and the fetishization of phenomena. Inspired by the analytical tradition of Frankfurt School critical theory, Gunderson et al. (2020) focus on the language of technology assessment. They identify four potential problems, namely that (i) the political economic determinants of a given technology are hidden; (ii) the technology may conceal chronic social-ecological contradictions; (iii) the technology may reproduce existing, unjust social conditions; and (iv) the technology may be used for more rational or emancipatory ends in different social conditions but these possibilities are occluded. While metaphor is not the focus on their paper, prime metaphors can underpin all four problems of invisibilization.

Risk 2: Urgency and Global Risk Trump Other Concerns Through Evocative Metaphor

As Nerlich and Raspal's study of SRM discourse showed, the connection of simple metaphors about CDR/SRM to other metaphors that evoke crisis, emergency, and calamity is very possible in the immediate future. One of these other metaphors is the "ticking clock," another is "climate debt" and still another

[5] Chilvers and Kearns (2020) outline the cutting-edge of approaches to reflexive, democratic public consideration of science and technology, but the reality is their "gold standard" will simply be infeasible in many parts of the world.

is "climate overshoot." These metaphors are very good indeed at triggering an emotional response. But often, as noted above, it's a negative and de-motivating one (fear and anxiety are as likely to eventuate as a radical, proactive mentality). The metaphors have frequently been employed by geoscientists who are alarmed at chronic foot-dragging among the world's governments. They are also routinely used by environmental NGOs like Greenpeace and by public figures such as David Attenborough, Naomi Klein, Bill McKibben, and George Monbiot. While it may seem as if these metaphors are scientifically validated (i.e., evidentially determined), there is in fact a "gap" between "is" and "ought" that can only be bridged by contestable and revisable judgements about whether, how widespread and how urgent a global "emergency" actually is (Hulme et al., 2020). Anxiety over how to somehow close the gap has been evident in conservation biology for years regarding the global loss of biodiversity (Robbins and Moore, 2013). Without in any way wanting to undermine the serious implications of climate research, it's possible to imagine using less dramatic, less globally-referenced, and less climate-centric metaphors to represent the de/merits of various CDR/NETs projects at different spatial scales. One obvious point to make here is that not every project will, in reality, be equally "necessary" in order to tackle to "climate crisis," regardless of what some proponents may say. Another is that some projects could legitimately be metaphorized with reference to primarily local concerns rather than generalized global risks. At this scale, the metaphors might more helpfully refer to livelihoods, rights, cultural traditions, and environmental quality issues. Community protests against fracking projects in the UK and beyond have already demonstrated this: the protestors reframed fracking so that it was no longer represented (narrowly) in terms of risk (posed to the environment) and energy security at the national scale.

Risk 3: CDR/NETs Metaphorized as "Environmental" Interventions That Are Required of "Society"

Directly linked to the previous two risks is a third one: that metaphors be hitched to the society-nature dualism in ways that make CDR/NETs appear as an environmental *requirement* of certain societies. This is not to say that, as whole, the GHG removal techniques are not urgently needed. But metaphors about CDR/NETs such as their capacity to "restore balance," "cool the planet," or "take the foot off the accelerator" can serve to distract attention from the equally important need for conventional mitigation measures, for far-reaching adaptation measures and, more broadly for structural changes to fossil-fueled, capitalist economies worldwide. In other words, the field of societal "requirements" is potentially wide-open, with some countries and social strata needing to make bigger contributions than others. So-called "environmental imperatives" involve contestable social appraisals of the nature, level, and distribution of risk and do not reside "objectively" in changing natural systems where the precautionary principle is required to be observed. For instance, in some quarters "dead-lineism" is currently hypostatizing these appraisals as if mandated by the "environmental crisis" (see Asayama et al., 2019). In reality, these appraisals can be realized through a range of possible actions that can be metaphorized every bit as much as CDR/NETs can be.

Risk 4: Natural CDR/NETs Delegitimize Some "Artificial" Ones Through Binary Metaphorizing

As Bellamy and Osaka (2020) have recently pointed out, a heuristic distinction between natural and artificial CDR/NETs is taking hold. Broadly, it corresponds to low-tech and high-tech interventions, with few of the latter yet fully developed. As the case of afforestation indicates, "natural" interventions can broadly do what the living world might do if left to its own devices, whereas artificial ones are more-or-less "unnatural." In turn, the distinction invites certain metaphors to be attached to these broad groupings of techniques or to specific techniques within them. For instance, natural CDR/NETs can be framed as "rebalancing" a world knocked off-track through reckless human behavior. Meanwhile, some artificial approaches can be framed as "playing God" through uncontrolled experiments in Earth System management. Yet, as Bellamy and Osaka note, where to place the natural-artificial boundary is not that obvious. Meanwhile, many ostensibly "natural" techniques could, on closer inspection, involve highly artificial components (such as planting non-native trees *en masse* in anticipation of moving ecological belts on a warming planet). Metaphor can too easily be used to "fix" the meanings of certain CDR/NETs across the natural-artificial divide, in the process simplifying matters unduly.

TOWARD POST-NORMAL METAPHOR USE

We live in post-normal times, which—riffing on the notion of "post-normal science" (Funtowicz and Ravetz, 1993)—is to say that our's is an era where high-stakes decisions must be taken urgently but where (i) uncertainty about possibly profound outcomes is large so that (ii) decisions must be based as much on value commitments as on robust knowledge. Acting now in anticipation of a hard-to-understand but potentially very threatening future is becoming normalized—even if it's our great grand-children who might suffer the largest burdens or reap the rewards of our hopefully timely, considered actions. We need anticipatory discourse adequate to this challenge. The four risks identified above would, should they be realized, be reflective of a "normal" use of metaphor. That is, prime metaphors here help interlocutors to *make points*, or *assert claims*, by simplifying complexity in ways that seem intuitive and persuasive because referenced to familiar objects and acts. But in our post-normal times, we need language that is more adept at handling the material and semiotic knottiness of the issues, covering both cognitive and normative issues with sophistication. To complicate the complexity, CDR/NETs interventions will need to be understood in their specific local and national context but also discussed more abstractly in wider considerations of intergovernmental action to tackle climate change. In each case, metaphor will have an important role to play—just as it will in any major proposal for new infrastructure or for systemic changes to a society referenced to mitigation and adaptation imperatives.

In post-normal discourse about CDR/NETs, metaphors would be employed in the service of rounded analyses of the issues, perhaps in the form of extended and even competing *narratives*. The traditional language of science and technology can only be one part of such analyses, not the main part. In rich narratives, metaphors do not short-circuit complexity but help, rather, to reveal it. It may seem to trivialize the issues by emphasizing "story-telling." But textured narratives about CDR/NETs in the near and longer-term future will help to capture the tangle of pros and cons, and the wider implications of the various "natural" and "artificial" techniques should we choose to forgo or employ them.[6] As we saw earlier, metaphors are never only about the things or issues they seemingly make literal reference to. They implicate things beyond the ostensible semantic targets (Seligman and Weller, 2019). Post-normal metaphor use in a narrative context would help to open-up consideration of how CDR/NETs involve questions of, to give a few examples, energy supply, rights to land and water, cultural histories of resource use, food supply, the rights of future generations, group identities, and more besides. It would make a virtue of chains of hermeneutic association and connotation. It would be "knowing" in its employment of metaphor and dominant metaphors would be looked upon with suspicion because of their potential for reductionism. For example, metaphors that highlight the environmental merits of CDR/NETs would be complemented by others that point to its possible negative knock-on effects or uncertain outcomes. In each case, the major epistemic uncertainties prevailing mean that the metaphors would need to be explicit about the relative value judgements written into them.

To talk metaphorically about metaphor, in post-normal discourse great efforts would be made to attend to the dynamic (often frayed) "tapestry" of life not merely the separate "threads." "Metaphor scenarios" would be the norm (Musolff, 2016) and rarely would a CDR/NETs project, or groups of them, be treated in abstraction from a plethora of entanglements. This form of discourse is demanding because, as with any advanced form of analysis, it requires people to hold in their heads many arguments (based on contestable values) and evidential claims. Post-normal discourse is designed to enable rich "communicative reason," albeit in a world chock-full of inequality that (i) denies interlocutors a level communicative platform and (ii) fosters nefarious, self-interested communicative acts insensitive to the common good. It is geared toward inclusive, well-justified decision making about practical action. The expert community can play its part here by using metaphor sensitively and by being explicit about the value judgements animating them.

The way I have depicted things so far, we need skillful use of metaphor to allow more *holistic* and *integrative* forms of understanding that might highlight tensions and contradictions. But, useful as that is, it's *not*, in fact, sufficient. It implies that using *more* metaphors, connecting to *more* elements of reality, is the next discursive step as we anticipate a world with CDR/NETs in it. But the challenge is to grapple with *alternate realities*, both present and future. A "one world" ontology commits us to using metaphor to point to a myriad of issues and phenomena so as to foster some sort of consensus about reality both present and future. Yet humans' capacity for interpretive difference, and alternative ways of living practically, makes "deep pluralism" something to be reckoned with locally, nationally, and globally. Post-normal metaphor use could and should be used to foster *dissonance* about the ontological, affective and value-dimensions of CDR/NETs (see Veland et al., 2018). This would push against the claimed "post-political" tendencies of our time. Different metaphor scenarios will say as much about the people presenting them as about the material realities being referred to in discourse.

This is acutely obvious in ostensibly post-colonial settings in the Anglophone world. For instance, consider a recent study of proposed dam and lock removals along the Upper Mississippi River Gorge in Minnesota (Koban, 2020). Like any local CDR/NETs proposal of reasonable scale, the removals will make a real difference to both people and environment in the region. Koban shows that there are not, in far, shared metaphors or "best metaphors" that can unite disputants over the river restoration plan and the subsequent management of a more "natural Mississippi" (likewise, see Morehouse and Cigliano, 2020 on ice retreat in northern Canada and beyond). In fact, in indigenous cultures "things" are usually not compared to other things but, instead, regarded as *substantively connected* (for an example of such constitutive relationality, see Stewart-Harawira, 2020). Here metaphor in the Anglophone sense reaches its limits, even when used sensitively. This said, the notion of a *kaleidoscope* of perspectives on ostensibly the same river does, perhaps, help us to see the bridging potential of metaphor to acknowledge cognitive and normative incommensurability *en route* to some of sort of accommodation that permits action on the ground.

This mention of limits takes me to the logical conclusion of the analysis. While, according to Lakoff and Johnson (2003), metaphor is unavoidable, for CDR we should perhaps press for the avoidance of prime metaphors of any kind. However, adeptly handled by some, they risk debasement by others and will doubtless serve to simplify complicated issues even if several are in play. One can speculate as to why. Whether one takes a socio-historical or evolutionary approach to language, it is plausible to suggest that humans now operate beyond the physical range to which our inherited vocabularies were adapted. Our metaphors, at least in the West, seem to reflect a disappearing world where relevant objects and activities were close by and broadly manageable in practice. We need to frame CDR in the richest and widest possible ways (economic, moral, aesthetic, and beyond), even when the technical efficacy of one or other technique is the most pressing matter at hand.

CONCLUSION

In his classic essay "Politics and the English language," Orwell (1946) reminded his readers that language is far too important in its effects to be used carelessly or unthinkingly. He strongly disputed "the half-conscious belief that language is a natural growth and not an instrument which we shape for our

[6]There is a growing interest in narrative as a communicative device in various areas of practice-relevant environmental research. See, for instance, Moezzi et al. (2017). However, in the basic sense of "story telling" narratives can be one sided, partial and simplistic. In the present context, for example, Asayama and Ishii (2017) highlight one sidedly optimistic CDR narratives in several Japanese newspapers between 2006 and 2013.

own purposes." Likewise, I've argued here that close, critical attention to metaphor could trigger rich debates about key issues relating to CDR/NETs. Equally, it can be used to facilitate more shallow discussions. But who, in the end, will shape metaphor for the purposes of the many not the few? Clearly, in the discursive life of CDR/NETs, people in the expert community—scientists, technicians, consultants, marine and landscape planning academics, and so on—will have a key role to play. This is because they enter the story early on, as evidenced in recent years by the inclusion of CDR/NETs in the IPCC's future climate scenarios (see Beck and Mahony, 2018). They thereby possess quite a lot of discursive power, providing words, images, and storylines that will shape subsequent understandings of the realities of projects to lock-up GHGs in long-term storage. If metaphors can serve to govern our thoughts and actions then we must work hard to govern our use of metaphor. Science and technology, be it "green" or more hi-tech, is profoundly reliant on metaphor in many acts of communication. The best venues to test and challenge these metaphors are deliberative ones where mini-publics, working with thoughtful people in planning, policy studies, and Science & Technology Studies, can have their own say in light of local and national concerns.[7]

As RRI rises up the agenda in many parts of the world (see Low and Buck, 2019; and the special issue of *Science, Technology & Society* 25, 2), we might reflect on the fact that our responsibilities to people reside, in large part, in language first of all. This is why social scientists and humanists, along with technical experts at the CDR/NETs coal-face, must become deeply aware of the politics and potency of their words in our post-normal times. The words, rightly, will signify things that go beyond science and technology strictly speaking. A balance between clarity and sophistication will be needed. The forces of populism, misinformation, fake news, propaganda, and Manichean thinking may otherwise threaten the quality of discourse about major infrastructural decisions relating to people and planet. The problem is that is certain key communicative domains, such as tabloid journalism, social media platforms and even parliaments, mature communication is not welcome and "normal" discourse is ill-suited to advance human interests.

[7] Haikola et al. (2019) study news media and science media reporting of BECCS, especially from 2013 to 2018. They show how a very few interlocutors in the world of science, by and large, dominated the fairly small amount of discussion about BECCS. The discussion, at that early stage, was generally about the ill/logic for turning to BECCS on a large scale in the future. Haikola et al. conclude that the discursive window has evolved toward a sullen acceptance that BECCS are "risky but necessary." They also conclude that post-normal discourse tends to be temporary, linking it to the pressures to debate BECCS exerted by the Paris meeting of the parties to the UNFCCC in 2015. I am not so sure. Since BECCS have not yet enjoyed widespread and truly public discussion, it is possible that the window will be shaped many times again in different countries. The potential for "normal" discourse about the post normal question of CDR/NETS is high and to be avoided.

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

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

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REFERENCES

Adams, P. C. (2020). Language and groundwater: symbolic gradients of the Anthropocene, *Ann. Am. Assoc. Geogr*. doi: 10.1080/24694452.2020.1782724

Anderson, K., and Peters, G. (2016). The promise of negative emissions-response. *Science* 354, 714–715. doi: 10.1126/science.aal2610

Asayama, S., Bellamy, R., Geden, O., Pearce, W., and Hulme, M. (2019). Why setting a climate deadline is dangerous. *Nat. Clim. Change* 9, 570–572. doi: 10.1038/s41558-019-0543-4

Asayama, S., and Ishii, A. (2017). Selling stories of techno-optimism? The role of narratives on discursive construction of carbon capture and storage in the Japanese media. *Energy Res. Soc. Sci.* 31, 50–59. doi: 10.1016/j.erss.2017.06.010

Beck, S., and Mahony, M. (2018). The politics of anticipation: the IPCC and the negative emissions technologies experience. *Glob. Sustain.* 1, 1–8. doi: 10.1017/sus.2018.7

Bellamy, R., and Geden, O. (2019). Govern CO_2 removal from the ground up. *Nat. Geosci.* 12, 874–879. doi: 10.1038/s41561-019-0475-7

Bellamy, R., and Osaka, S. (2020). Unnatural climate solutions?. *Nat. Clim. Change* 10, 98–99. doi: 10.1038/s41558-019-0661-z

Brown, T. (2016). Sustainability as empty signifier. *Antipode* 48, 115–133. doi: 10.1111/anti.12164

Charteris-Brown, J. (2019). *Metaphors of Brexit.* London: Palgrave.

Chilvers, J., and Kearns, M. (2020). Remaking participation in science and democracy. *Sci. Technol. Hum. Values* 45, 347–380. doi: 10.1177/0162243919850885

Cox, E., Spence, E., and Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nat. Clim. Change* 10, 744–749. doi: 10.1038/s41558-020-0823-z

Dryzek, J. (1997). *The Politics of the Earth.* Oxford: Oxford University Press.

Epstein, C. (2008). *The Power of Words in International Relations.* Cambridge, MA: MIT Press.

Fajardy, M., Patrizio, P., Daggash, H. A., and Mac Dowell, N. (2019). Negative emissions: priorities for research and policy design. *Front. Clim.* 1:6. doi: 10.3389/fclim.2019.00006

Funtowicz, S., and Ravetz, J. (1993). Science for the post-normal age. *Futures* 31, 735–755. doi: 10.1016/0016-3287(93)90022-L

Gunderson, R., Stuart, D., and Petersen, B. (2020). Materialized ideology and environmental problems. *Eur. J. Soc. Theory* 23, 389–410. doi: 10.1177/1368431019839252

Haikola, S., Hansson, A., and Anshelm, J. (2019). From polarization to reluctant acceptance: BECCS and the post-normalization of the climate debate. *J. Integr. Environ. Sci.* 16, 45–69. doi: 10.1080/1943815X.2019.1579740

Hulme, M., Lidskog, R., White, J. M., and Standring, A. (2020). Social scientific knowledge in times of crisis. *WIRES Clim. Change* 11:e656. doi: 10.1002/wcc.656

Jasanoff, S. (2006). *States of Knowledge*. New York, NY: Routledge.

Kingdon, J. (1984). *Agendas, Alternatives and Public Policies*. Boston, MA: Little Brown.

Koban, J. (2020). Ecological restoration or healing?: conflicting ontologies and missed opportunities in public debates surrounding Mississippi River Gorge restoration. *Environ. Commun.* 14, 582–559. doi: 10.1080/17524032.2019.1696854

Lackner, K., Aines, R., Atkins, S., Atkisson, A., Barrett, S., Barteua, M., et al. (2016). The promise of negative emissions. *Science* 354:714. doi: 10.1126/science.aal2432

Lahn, B. (2020). Changing climate change: the climate budget and the modifying work of the IPCC. *Soc. Stud. Sci*. doi: 10.1177/0306312720941933

Lakoff, G., and Johnson, M. (2003). *Metaphors We Live By*. Chicago: Chicago University Press.

Larson, B. (2005). The war of the roses. *Front. Ecol. Environ.* 3, 495–500. doi: 10.1890/1540-9295(2005)003[0495:TWOTRD]2.0.CO;2

Larson, B. (2011). *Metaphors for Environmental Sustainability*. New Haven, CT: Yale University Press.

Low, S., and Buck, H. J. (2019). The practice of responsible research and innovation in 'climate engineering.' *WIRES Clim. Change* 11:e644. doi: 10.1002/wcc.644

Moezzi, M., Janda, K., and Rotmann, S. (2017). Using stories, narratives, and storytelling in energy and climate change research. *Energy Res. Soc. Sci.* 31, 1–10. doi: 10.1016/j.erss.2017.06.034

Morehouse, H., and Cigliano, M. (2020). Cultures and concepts of ice: listening for other narratives in the anthropocene. *Ann. Am. Assoc. Geogr*. doi: 10.1080/24694452.2020.1792266

Musolff, A. (2016). *Political Metaphor Analysis: Discourse and Scenarios*. London: Bloomsbury Academic.

Nerlich, B., and Jaspal, R. (2012). 'Metaphors we die by? Geoengineering, metaphors, and the argument from catastrophe. *Metaphor Symbol* 27, 131–147. doi: 10.1080/10926488.2012.665795

Newmark, P. (1980). The translation of metaphor. *Babel* 26, 93–100. doi: 10.1075/babel.26.2.05new

Orwell, G. (1946). Politics and the English language. *Horizon* 13, 252–265.

Robbins, P., and Moore, S. (2013). Ecological anxiety disorder, *Cult. Geogr*. 21, 3–19. doi: 10.1177/1474474012469887

Rose, D., Mukherjee, N., Simmons. B. I., Tew, E. R., Robertson, R. J., Vadrot, A. B. M., et al. (2020). Policy windows for the environment: tips for improving the uptake of scientific knowledge. *Environ. Sci. Policy* 113, 47–54. doi: 10.1016/j.envsci.2017.07.013

Seligman, A., and Weller, R. (2019). *How Things Count As The Same*. Oxford: Oxford University Press.

Sontag, S. (1989). *Illness as Metaphor and AIDS and Its Metaphors*. New York, NY: Doubleday.

Stewart-Harawira, M. W. (2020). Troubled waters: maori values and ethics for freshwater management and New Zealand's fresh water crisis. *WIRES Water* 7:e1464. doi: 10.1002/wat2.1464

Veland, S., Scoville-Simonds, M., Gram-Hanssen, I., Schorre, A. K., El-Khoury, A., Nordbø, M. J., et al. (2018). Narrative matters for sustainability the transformative role of storytelling in realizing 1.5°C futures. *Curr. Opin. Environ. Sustain.* 31, 41–47. doi: 10.1016/j.cosust.2017.12.005

Wilson, J., and Swyngedouw, E. (2014). "Seeds of dystopia: post-politics and the return of the political," in *The Post-Political & Its Discontents*, eds E. Swyngedouw and J. Wilson (Edinburgh: Edinburgh University Press), 1–15.

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Supply Chain Driven Commercialisation of Bio Energy Carbon Capture and Storage

*Jonathan Klement[1], Johan Rootzén[1,2], Fredrik Normann[1] and Filip Johnsson[1]**

[1] Department of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden, [2] Department of Economics, Gothenburg University, Gothenburg, Sweden

Pulp mills, as large biogenic CO_2 point sources, could adopt Bio Energy Carbon Capture and Storage (BECCS) through retrofitting carbon capture. These existing carbon sources constitute a great potential to roll out BECCS on commercial scale. Yet, despite political targets for negative emission production in Sweden, no incentive schemes were thus far enacted. While previous proposals focus on governmental compensation, the aim of this work is to set BECCS into the supply chain of a wide array of consumer products and thereby find alternative or complementary, business-driven, ways to incentivise BECCS when applied to the pulp and paper industry. In this work, we assess a "value proposition" for low-carbon products in supply chains linked to the pulp and paper industry. By projecting the costs and negative emissions related to BECCS from the pulp mill to typical consumer products, as exemplified by three case study products, we show how BECCS can substantially reduce the carbon footprint of the consumer products, while only marginally increasing their cost. Additional price premiums could shorten the payback period of the initial investment in BECCS. The developed business case presents how actors along the supply chain for pulp and paper products can collectively contribute to securing financing and to mitigating investment risks. The results challenge the private sector, i.e., the companies along the pulp-and-paper supply chain to commit considerable investments also in the case without or with too weak direct political incentives. We conclude by discussing the governance implications on corporate and public level to enable the collaborative "bottom-up" adoption of BECCS.

Keywords: negative emission technologies (NET), commercialisation, low carbon innovation, BECCS, corporate governance, value proposition, pulp and paper industry

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****Correspondence:***
Filip Johnsson
filip.johnsson@chalmers.se

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INTRODUCTION

Limiting the average global temperature increase to "well below 2°C" requires a move to net-zero emissions of greenhouse gases by around 2050. In addition to massive decarbonisation in all sectors, this will require the application of negative-emission technologies (NETs), which enable Carbon Dioxide Removal (CDR) from the atmosphere (IPCC, 2018; Luderer et al., 2018; Kaya et al., 2019). CDR could contribute to offsetting hard-to-mitigate emissions, compensating for an emission overshoot, reducing uncertainty in earth system development or limiting the overall costs of climate change mitigation (Fuss et al., 2018; Rogelj et al., 2018; Bednar et al., 2019; Geden et al., 2019).

While previous research largely focused on the global potential and technical development of NETs, in order to reduce costs and improve performance (supply-side), there has been less emphasis on the adoption of NETs (demand-side) (Nemet et al., 2018). This is why many studies have called for research, investments and demonstration projects to embark on the scaling up of NETs (Fuss et al., 2018; van Vuuren et al., 2018). Fuss et al. (2018) discuss the path to negative emissions, suggesting to start with NETs that are immediately available including nature based approaches like afforestation, reforestation and soil carbon sequestration, while developing technology based approaches with more reliable, long term geological storage, like Bio-Energy Carbon Capture and Storage (BECCS) and Direct Air Capture and Storage. Indeed, BECCS is the NET that has hitherto received the most attention (Minx et al., 2018; The Royal Society, 2018; Rickels et al., 2019), but even though the Carbon Capture and Storage (CCS) technology can be seen as mature (Bui et al., 2018; IEA, 2020), actual practical implementation falls short of previous expectations (IEA, 2019).

As main barrier to CDR, studies bring forward their minor role in the political debates (Geden et al., 2019; Fuss et al., 2020) and the lack of political will to engage and lead the development of NETs and the surrounding governance structures (Fuss et al., 2016; Peters and Geden, 2017; Fridahl and Bellamy, 2018; Geden et al., 2019). For CCS and specifically BECCS this translates to a lack of economic incentives (Fridahl and Lehtveer, 2018; Nemet et al., 2018); legal uncertainties, e.g., related to storing CO_2 (Heffron et al., 2018); unclear CO_2 accounting rules for captured biogenic emissions (Zakkour et al., 2014; Torvanger, 2019); and accordingly, a lack of interest from the private sector, due to the unclear market potential (Platt et al., 2018).

UN, European as well as Swedish policies have thus far failed to incentivise BECCS, yet removed legal barriers to its implementation (Fridahl and Bellamy, 2018; Heffron et al., 2018; Rickels et al., 2020). However, the EU and Sweden plan the deployment of NETs in order to reach their carbon neutrality targets for 2050 and 2045, respectively, combining both nature-based approaches and technology-based approaches. The minor role of CDR in the EU is so far focused on nature based NETs with slight non-nature-based CDR aspirations (Geden and Schenuit, 2020), yet without existing plans to incentivise BECCS or the like (Rickels et al., 2020). The Swedish climate policy framework places an emphasis on negative emissions after 2045. An extensive strategy and action plan, developed for the government, published in early 2020, suggests the deployment of a minimum of 1.8 Mt CDR though BECCS by 2030 and 3–10 Mt CO_2 in 2045 (Klimatpolitiska vägvalsutredningen, 2020). To incentivise BECCS deployment the plan suggests reverse auctioning, allowing installations to bid for the minimum acceptable compensation per stored tonne of CO_2. However, final decisions are yet to be taken (*cf.* Bellamy et al., 2021).

Proposals on how to create a demand for NETs have considered different forms of carbon pricing (Nemet et al., 2018; Zetterberg et al., 2019; Rickels et al., 2020), liabilities to provide negative emission certificates if fossil CO_2 is emitted (Zetterberg et al., 2019), carbon utilisation as a niche market (Nemet et al., 2018), the "Sustainable Development Mechanism" under the Paris agreement (Honegger and Reiner, 2018), and connecting the co-benefits of NETs to other fields of policymaking (Cox and Edwards, 2019). However, with the exception of Platt et al. (2018), who assessed different business models for negative emissions and associated revenues, and Bellamy and Geden (2019), who called on policy makers to support NETs emerging "bottom-up" at the company or regional level, the role of the private sector in creating a demand for NETs remains largely unexplored.

The prevailing perspective, as discussed above, limits BECCS incentives to governmental compensation of actors that could directly deploy BECCS. With this study we want to challenge this perspective of BECCS deployment as sole political task. Instead we formulate BECCS as an innovation initiative within companies' own supply chains. This calls for Corporate Governance which involves multiple stakeholders (stakeholder approach) and lays an emphasis on the firms contribution to society (political Corporate Social Responsibility) (Scherer and Voegtlin, 2020). Existing decarbonisation initiatives in energy-intensive industries show the importance of this perspective as innovation driver in companies (Knoop et al., 2019).

In the present study, the aim was to explore the prospects for the pulp and paper industry (PPI) to adopt BECCS. The PPI processes large volumes of biomass and pulp mills could be retrofitted with a capturing plant. The PPIs annual BECCS potential was estimated to 60 $MtCO_2$ in Europe (Jönsson and Berntsson, 2012) and 20 $MtCO_2$ in Sweden (Hansson et al., 2017; Rootzén et al., 2018). The Swedish PPI, the largest pulp producer in Europe (CEPI, 2017) with CO_2 emissions that are mainly of biogenic origin (97%) (Rootzén et al., 2018), is used as a case study. However, currently no BECCS plant is in operation within the Swedish PPI and the industry is reluctant to drive BECCS adoption since they do not see a suitable and profitable business case (Rodriguez et al., 2020).

The actors in the PPI do not see a market demand for negative emissions (Rodriguez et al., 2020) and as basic material producer it will be difficult for the PPI to create a market for more expensive pulp produced with BECCS. Therefore, we argue that the supply chain needs to be included to assess the market potential. Our analysis thus presents the impact on carbon footprint and costs that BECCS has on consumer products, i.e., end-use products of pulp and paper production, exemplified by three case study products. The customers' willingness-to-pay for these products could be increased, rewarding the climate change mitigation, as discussed in more detail below. Hence, we also analysed the effects on the involved actors of introducing a price premium on the products' retail prices. The price premium, higher than the additional cost, could create a revenue stream to incentivise BECCS adoption. The revenue can be used to compensate for risk-taking and to shorten the payback period of the original BECCS investment.

With the new perspective we present a vision for BECCS commercialisation which could be applied as an alternative or complementary to political incentives, i.e., a way forward to private-sector demand-pull. We discuss proactive corporate governance as innovation driver and how low carbon products could be a core of the BECCS business model.

METHOD

A pulp mill operator who decides to integrate carbon capture in the pulp mill will increase the production costs and will need to increase the price of pulp to recoup the investment. However, at the same time, negative emissions are "created." This work proposes that the negative emissions are attributed to the product—the pulp—and that these emission reductions and their associated costs can be transferred through the supply chain so that the end-products of the pulp can be sold at a corresponding higher price. We refer to pulp associated with net-negative CO_2 emissions as "CDR pulp."

Consumer products that use such "CDR pulp" could allow for the introduction of a price premium. This is because a value proposition for a product is multi-dimensional (Rintamäki and Kirves, 2017), and can be increased by improvements to the sustainability performance (Lacoste, 2016; Bangsa and Schlegelmilch, 2020). These include, as examples, lowering the carbon footprint and contributing to the development of BECCS as such. The revenue of the price premium could contribute to de-risking and incentivising the commitment to BECCS.

BECCS in Pulp Production

The sulphate pulping process is deemed most suitable for a BECCS retrofit (Jönsson and Berntsson, 2012). Pulp fibres are thereby obtained by dissolving the non-fibre material of pulpwood, which is thereafter combusted to generate energy. This combustion and a chemical cleaning are the main CO_2 sources in a sulphate pulp mill, both emitting CO_2 of biogenic origin (*cf.* Onarheim et al., 2017a). The retrofitting potential was studied in several techno economic analyses (Möllersten, 2002; Hektor and Berntsson, 2007, 2009; Hektor, 2008; McGrail et al., 2012; Jönsson et al., 2013; Garðarsdóttir et al., 2014, 2018; Hedström, 2014; Onarheim et al., 2017a,b; Skagestad et al., 2018; Kuparinen et al., 2019; Nwaoha and Tontiwachwuthikul, 2019).

As a reference for BECCS retrofitting in sulphate pulp mills, we use the recent techno-economic evaluations carried out by Onarheim et al. (2017a,b) and Skagestad et al. (2018) (see **Appendix A** for a comparison of the studies and their assumptions). The basis for our analysis are their estimates of negative emissions produced per air dry tonne of pulp (*negative emissions per ADt of pulp*) and the corresponding cost for capture, compression, transport and storage (*additional costs per ADt of pulp*). We take the average of those technical set-ups in which more than 60% of the total emissions are captured (resulting in an average capture rate of 70%, see **Supplementary Table 2**) and assume an allocation of costs and negative emissions to all the produced pulp. The cost of pulp production increases then by $Cost_{BECCS,pulp}$= 110 EUR (range, 75–170 EUR) per air-dried tonne, and per air-dried tonne of pulp $E_{BECCS,pulp}$= 1.6 tonnes (range, 1.4–2.3 tonnes) of biogenic CO_2 emissions can be captured (combining stand-alone pulp mills and integrated pulp and paper mills). The corresponding cost for negative emissions would be approximately 70 EUR per tonne of captured and stored biogenic CO_2. This is significantly higher than the carbon prices in the emissions trading systems currently in force (e.g., the *EU Emissions Trading Scheme*; *EU* ETS).

In the subsequent discussions and analysis we assume that CO_2 emissions of biogenic origin during the production, i.e., the wood combusted in pulp mills, are carbon-neutral (O'Sullivan et al., 2016), assuming a managed forest landscape that maintains or increases the carbon stock (Cintas et al., 2016). Correspondingly, all captured and stored biogenic emissions are assumed to be negative emissions, i.e., reducing the CO_2 concentration in the atmosphere. Additionally, we assume no leakage in transport and storage.

BECCS on the Consumer Product Level

This section describes how we estimate the pass-through of negative emissions and costs throughout the supply chain of pulp, from the pulp mill to the retailing of the consumer product. Three case products are selected. They represent three of five end-use categories that use sulphate pulp and that are produced in large volumes (for a characterisation of paper grades and their supply chain see **Appendix B**):

- Paperboard packaging (Case: *Liquid packaging board*);
- Corrugated board packaging (Case: *Moving boxes*);
- Graphical wood-free paper (Case: *Hardcover book*);
- Wrapping paper; and
- Tissue paper.

The negative emissions associated with each tonne of pulp ($E_{BECCS,pulp}$) and the corresponding cost ($Cost_{BECCS,pulp}$), as presented in the previous section, provide the basis for the analysis. However, during paper production, non-fibrous materials (e.g., fillers, coatings, and chemical additives) can be added to the pulp fibres. For the packaging material and tissue paper, fillers were not usually added, whereas for graphical paper and other papers the shares of fillers increased (Suhr et al., 2015). In addition, pulp is measured as having 10% moisture content, while paper has 6% moisture content (Suhr et al., 2015). Assuming that no fillers are added to the paper, we used the following adjusted estimates in the analysis:

- The amount of negative emissions per mass unit paper, E_{BECCS}, is assumed to be equal to 1.7 tonnes of negative emissions per air-dried tonne of paper (with a range of 1.5–2.4 tCO_2/t paper).
- The cost increase per mass unit paper produced, $Cost_{BECCS}$, is assumed to be equal to 117 EUR per air-dried tonne (with a range of 85–180 EUR).

The carbon footprint reduction Δ_{CFP} (g captured and stored biogenic CO_2) is calculated based on the mass of virgin sulphate paper in the products m_{Paper} (g paper) and the amount of negative emissions, i.e., captured biogenic emissions per mass unit paper, denoted as E_{BECCS} (g captured and stored biogenic CO_2/g paper).

$$\Delta_{CFP} = E_{BECCS} * m_{paper} \quad (1)$$

Similarly, the cost impact Δ_{cost} (EUR) is calculated based on the cost increase per mass unit of produced paper, denoted as

$Cost_{BECCS}$ (EUR/g paper).

$$\Delta_{cost} = Cost_{BECCS} * m_{paper} \tag{2}$$

The cost and amount of negative emissions are calculated under a *ceteris paribus* assumption, relating both to the current retail price and the carbon footprint. Furthermore, perfect cost pass-through of the additional cost to the end-consumer is assumed.

Revenues and Profits Linked to a Price Premium on Consumer Products

We assume that that a "buyers' coalition" consortium or a vertical joint venture of actors is formed to share the financial and entrepreneurial risks among the actors along the supply chain and connect the investment in BECCS directly to the consumer products. Thus, while the pulp mill company will have to make the investment in the CCS plant, the remaining partners along the supply chain will have to make binding commitments to purchase a certain volume of CDR pulp.

Including an additional price premium to the buyers' coalition consortium set-up [compare supply chain pricing (Voeth and Herbst, 2006)], a break-even analysis for the case of liquid packaging board is performed. We assume a pulp mill with 700,000 tonnes capacity, use the CAPEX and OPEX estimates of Onarheim et al. (2017a,b) and Skagestad et al. (2018) (**Supplementary Table 2**), and the revenues from price premiums of 1 cent and 4 cents (EUR, before taxes) on the retail price of single consumer liquid packaging board products. The investigated premiums are chosen randomly, but in an actual implementation they could be linked to insights about the respective willingness-to-pay by consumers of different products. Nevertheless, from a practical point of view a premium of 1 cent is the lowest possible price increase of a single product.

For this calculation, we furthermore assume a risk and revenue allocation of 60% to the pulp/paper producer and 40% to the other actors, e.g., the paper-converting and paper-using companies or other transaction costs, although the design of the corresponding partnerships is a matter for agreement. The assumption means that 0.6 cent/package out of the 1 cent price premium reaches the pulp mill. Without this risk sharing the break-even point could even be reached earlier than presented here. However, we introduced risk and revenue sharing to include potential interests of the members of the buyers' coalition, i.e., the consortium of pulp producer, paper converter and paper user, who ensure this payment. If they do not have other costs, they could therefore also earn a profit once they had achieved sufficient sales to cover the guaranteed payment. The remaining 40% could be understood as a buffer to the required market size that they need to provide, i.e., if there is only one partner between the pulp mill and customers that partner only needs to sell 60% of the products with the premium to cover the payment. In a real-life case, the principle applied for risk and revenue sharing along the supply chain needs to be negotiated.

Selection and Analysis of the Case Study Products

The case study products were selected to cover the different paper grades, as well as to represent a variety of end-use categories, with varying cost and price structures and end-use purposes.

The basis for the product analysis is an understanding of the supply chain processes, from production to retail stages, and their contributions to the cost composition and the carbon footprint of the consumer product.

The carbon footprint of a product (E), i.e., the sum of emissions (e) caused by the processes and inputs (j) over the life-stages of the product (Wiedmann and Minx, 2008), is calculated as follows:

$$E = \sum_j e_j \; [gCO_2e]$$

As retrofitting BECCS in pulp mills does not change the physical properties of the pulp or the biomass sourcing, the processes in the use and end-of-life phases are assumed to remain unchanged. The baseline for the carbon footprint for the investigated products is, therefore, evaluated by consulting the relevant Life Cycle Assessment (LCA) studies on a cradle-to-gate basis.

Similarly, the cost composition of the consumer product is estimated based on available market statistics on key processes and inputs, deriving from the retail price. Thus, the retail price of the product (C) is assumed to reflect the cost (c) of the processes and inputs (k) involved in the production and sale of the product.

$$C = \sum_k c_k \; [EUR]$$

In the following section, the selected case study products are introduced. The ambition here is to provide a magnitude estimate of the changes related to the cost composition and the carbon footprint of the selected consumer product rather than exact values. A detailed description of the current carbon footprint and cost composition are provided in **Appendix C**.

(A) Case: Liquid packaging board—Oat drink

The first case product is a 1-litre aseptic oat drink in a carton package made of liquid packaging board, which is sold for 1.70 EUR. The carbon footprint estimation is based on an assessment made by CarbonCloud (2019), combined with data describing the climate impact arising from the production of an oat drink obtained from Florén et al. (2013) and data on packaging from Markwardt et al. (2017). We assume the usage of 100% virgin sulphate pulp in the production of the liquid packaging board.

(B) Case: Corrugated board packaging—Moving boxes

In the second case, we investigate a set of corrugated board boxes, with a total weight of 1.87 kg, which are sold as a set of two moving boxes for 2.99 EUR. The carbon footprint estimate is based on an assessment carried out by the European Federation of Corrugated Board Manufacturers (FEFCO, 2019) using data from their European database, focusing on the paper production and conversion (FEFCO, 2018). Corrugated board is a composite of an outside layer of paper (called "liner") and an internal layer of paper (called "fluting"), which is corrugated and glued to the outside layers. In line with FEFCO (2018), we assume that the moving boxes are made of corrugated boards that comprise 9.5% virgin sulphate paper (Kraftliner).

(C) Case: Graphical wood-free paper—Hardcover book

The third case product is a hardcover book with 300 pages, comprising inner sheets and an outside cover. We assume a retail price of 13 EUR, corresponding to the average prices for entertainment books in Sweden and Germany (Börsenverein des Deutschen Buchhandels, 2015; Wikberg, 2018). The carbon footprint estimation is based on an assessment performed by Pihkola et al. (2010), corresponding to conditions in Finland. These conditions give the mass share of the different paper grades as: 17% cover, 79% inner sheets, 2% end paper, and 2% jacket. The book weighs 500 g (after 28% maculature), of which 100 g are softwood sulphate pulp and 220 g are hardwood sulphate pulp, with the remainder comprising binders and fillers.

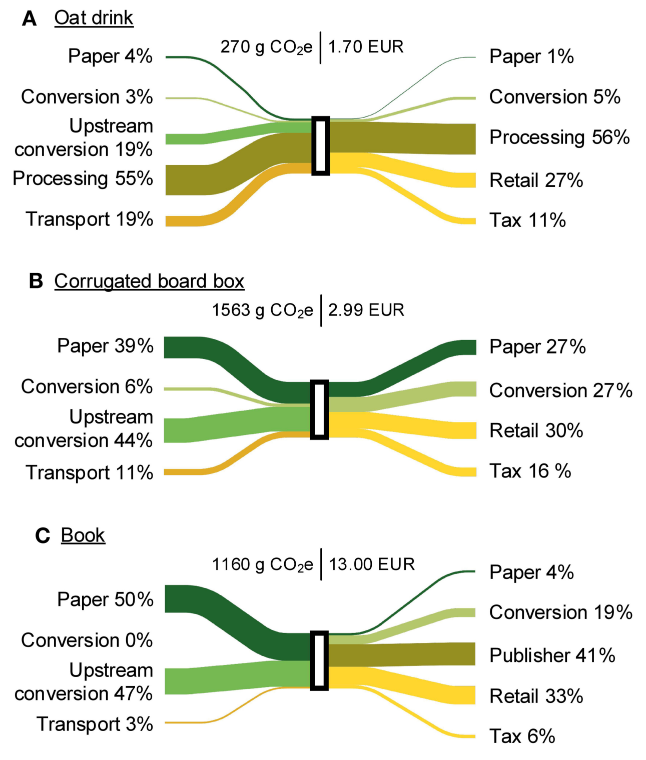

FIGURE 1 | Current composition of the carbon footprint (left) and cost distribution (right) for the three case study products. "Paper" refers to the paper production, "Conversion" refers to the conversion of the paper to packaging or a book, "Upstream conversion" refers to emissions related to the conversion process, i.e., electricity generation or the production of chemicals/ glue, "Transport" refers to the transport-related emissions, and "Content" refers to content production.

RESULTS

Impacts on Carbon Footprint and Cost at the Product Level

Figure 1 shows the current carbon footprint (left side) for each of the three case study products and the different cost components share of the retail price (right side). The comparison shows that for the corrugated board boxes and the hardback book, the production of paper accounts for a relatively high share of the carbon footprint, while the economic value is relatively low. In the case of the oat drink, the shares of paper in the carbon footprint and cost are relatively low. Here, the major contributors to both the carbon footprint and cost are content production and upstream processes related to the production of input materials and electricity.

Figure 2 shows the estimated cost and carbon footprint impact of BECCS implementation in the PPI for each of the three case study products. The carbon footprints decrease by 14–60%, while the costs increase by up to 0.7%. The oat drinks packaging uses 21.6 g of paper, which results in a cost increase of 0.003 EUR (+0.15%) while the carbon footprint decreases by 37 g (−14%). The corrugated board boxes use 177 g of virgin Kraftliner, which results in a cost increase of 0.021 EUR (+0.7%), while the carbon footprint decreases by 300 g (−19%). The hardback book uses 409 g of sulphate paper (softwood and hardwood), which results in a cost increase of 0.048 EUR (+0.37%), while the carbon footprint decreases by 696 g (−60%). Both changes need to be considered against the background that we assumed an average capture rate of 70% (see **Supplementary Table 2**) and that an average of the BECCS costs estimates is used, rather than the cheapest options.

The results show that, in the case of the oat drink and the hardback book, BECCS can offset more emissions than those originating from paper production. In both cases, we assumed that all the pulp was produced with BECCS. For the corrugated board, only the virgin sulphate paper could be produced with BECCS. The highest relative cost increase linked to BECCS implementation is for the set of moving boxes, which consist entirely of paper. If the same corrugated board was not purchased as a moving box, but instead as packaging for products such as electrical appliances or furniture, the cost increase of 0.02 EUR for the two packaging boxes would be negligible.

The central assumptions made in this study relate to the amount of captured and stored biogenic CO_2 per tonne of paper produced (E_{BECCS}) and the cost of captured and storage ($Cost_{BECCS}$). **Figure 3** shows the effect of varying both, E_{BECCS} and $Cost_{BECCS}$. The factor used for the captured emissions of 1.7 tCO_2/ADt paper is altered ±0.5 (to 1.2 and 2.2 tCO_2/ADt paper), and the cost increase of 117 EUR/ ADt paper is altered ±50% (to 58.50 and 175.50 EUR/ADt paper). The results illustrate their linear dependence on the factors and the unchanged magnitude difference of the results. While the carbon footprints decrease by 10%−80%, the costs increase only by up to 1%.

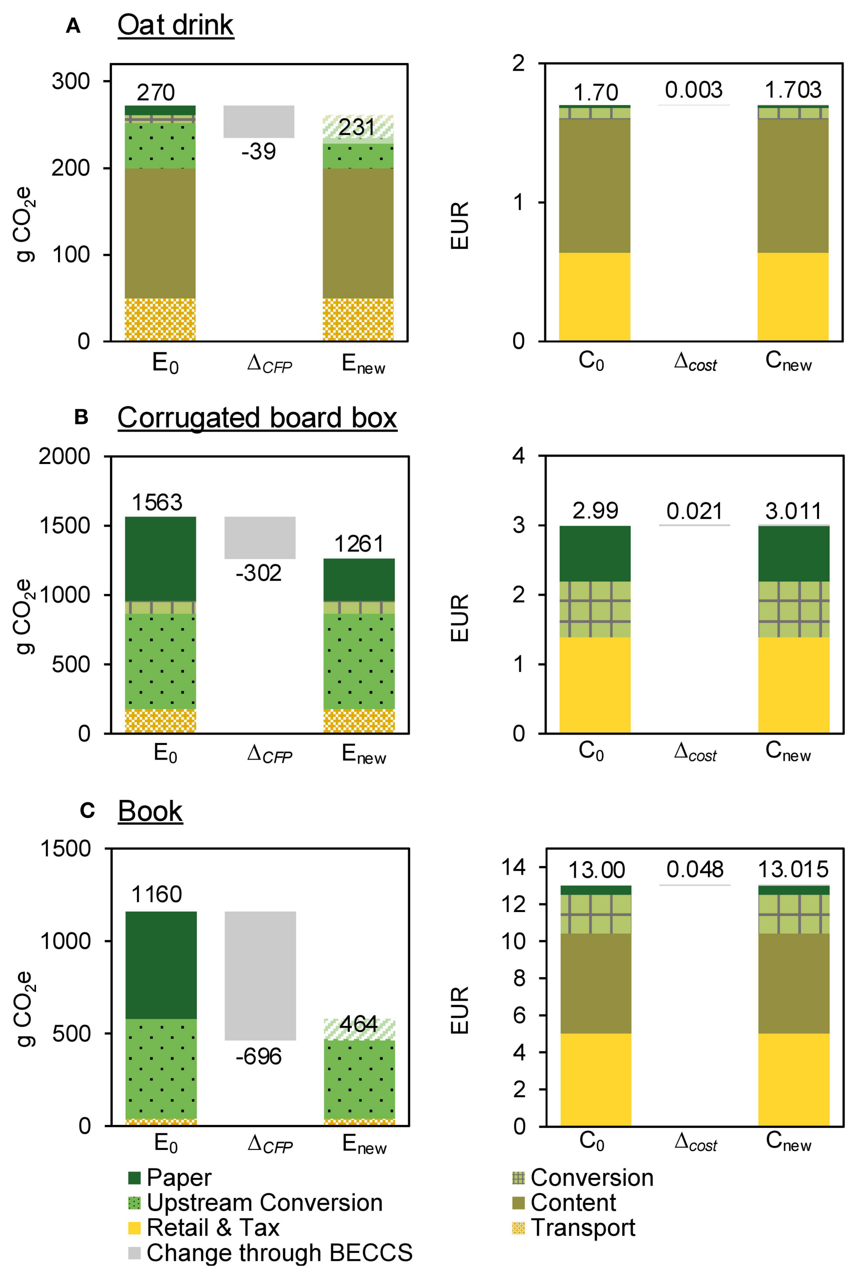

FIGURE 2 | Current carbon footprint E_0 and cost C_0 compositions of the three case study products, with the potential carbon footprint reduction Δ_{CFP} (left) achieved through applying BECCS at a pulp mill, and the corresponding cost increases Δ_{cost} (right). E_{new} and C_{new}. represent the compositions of the carbon footprint and costs after BECCS application.

Revenue Streams and Profits

Figure 4 shows how a price premium of 0.01 and 0.04 EUR per package of liquid packaging board increases the revenue and shortens the payback period of the BECCS investment. The results show that the higher premium of 0.04 EUR per package allows the pulp producer to break even within the first year of operation. The low premium of 0.01 EUR per package would allow the operator to break even within the first 3 years of operation. This is a large reduction, compared to the assumed operational life-times of 15 years (Onarheim et al., 2017a,b) and 22 years (Skagestad et al., 2018) of the reference BECCS studies (see **Supplementary Table 1**).

The short payback period becomes feasible due to the large market on which the revenue could be generated and the increased economic value of the paper. While the initial cost of liquid packaging board is 0.02 EUR and the cost of BECCS for the oat drink is 0.003 EUR, the investigated price premiums significantly increase the cash flow of the pulp producer.

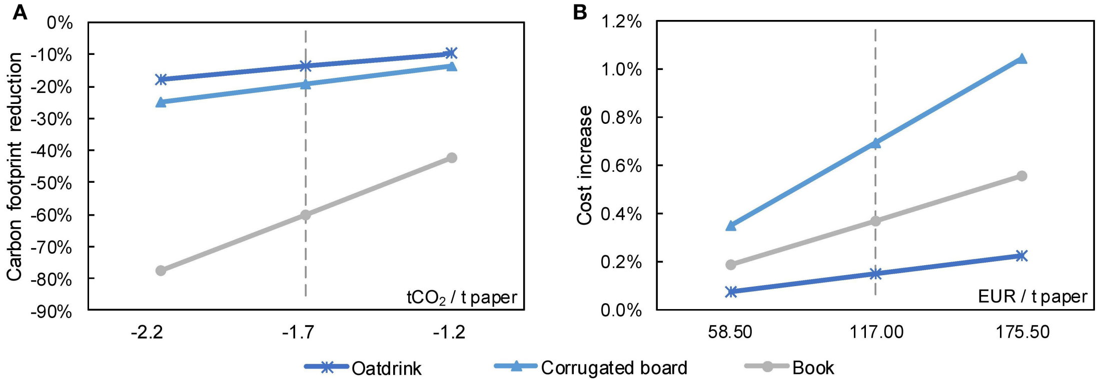

FIGURE 3 | Sensitivity analysis showing: **(A)** how changes in the amount of captured CO_2 per tonne of paper produced (E_{BECCS}) influence the carbon footprint reduction; and **(B)** how changes in the cost of capture ($Cost_{BECCS}$) influence the estimated cost increase.

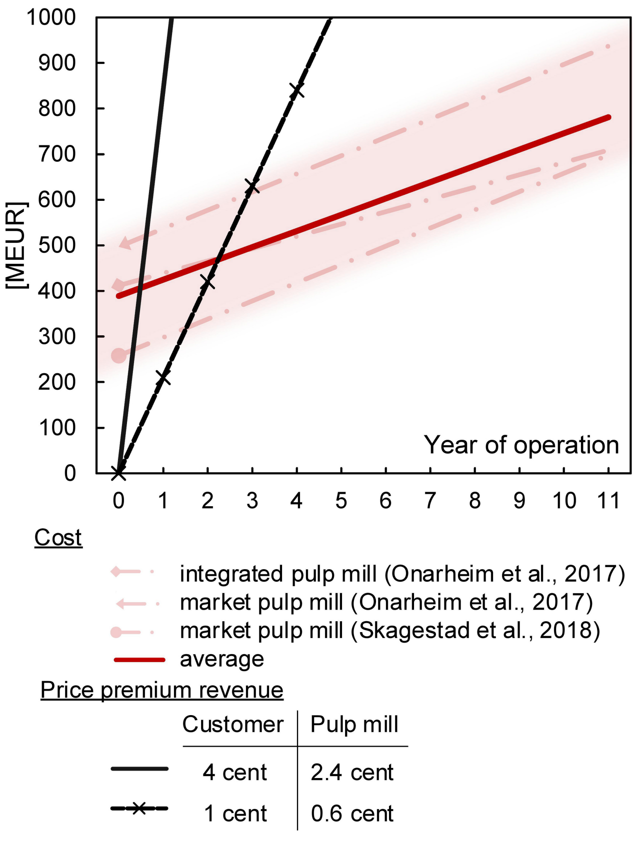

FIGURE 4 | Break-even analysis for a BECCS plant with revenues of a 1 cent and 4 cents price premium on products that use CDR pulp, exemplified by the oat drink case study.

DISCUSSION

Setting BECCS deployment into the context of carbon lean production shifts BECCS from a mitigation option at the industrial stacks to being part of a production system of low-carbon products. This incorporates BECCS in the existing field of basic material decarbonisation (Wesseling et al., 2017), Corporate Governance and responsible innovation (von Schomberg, 2012; Scherer and Voegtlin, 2020), sustainable finance (Friede et al., 2015) and corporate and technology forecast (Gordon et al., 2020). This allows to draw comparisons and benefit from a wider field of research and experience, instead of only treating BECCS as a new and unique governance challenge.

Value of Products with BECCS

We suggest that the consumer willingness-to-pay for low-carbon products exceeds the cost of decarbonising pulp production. We investigated this proposition by assuming that the usage of CDR pulp increases the intangible value of consumer products by decreasing the products' climate footprint and by contributing to the development of BECCS as such. However, even though the cost increase for the consumer products may be considered as marginal, the price premium must be borne by the customer. A lack of willingness-to-pay is often presented as a barrier for private led decarbonisation (Wesseling et al., 2017). Examining the extensive field of sustainable-consumption consumer decision-making the willingness-to-pay barrier should be analysed context specifically (Bangsa and Schlegelmilch, 2020). For example, Breustedt (2014) found a substantial willingness-to-pay to offset the carbon footprints of milk and juice products. In line with these arguments, the results of a recent survey of the Swedish population indicate that 70% of Swedes would pay up to 5% more for a company's product if they knew that the company was working on its emissions performance (The Swedish EPA, 2018).

To communicate the reduced carbon footprint to the consumer, the products could be labelled with their carbon footprint or a label stating that the production of the product involved negative emissions. Research around carbon labelling is extensive and can be used to increase the effectiveness, applicability, and practicality of labelling (Liu et al., 2016). If applied in a BECCS financing context, the label would then be used to justify the price premium to the customer and encourage other supply chains to also adopt BECCS in pulp production. Further, while labels will not directly lead to "climate friendly consumption", a beneficial usage could increase the customers "climate literacy" (Soneryd and Uggla, 2015; Boström and Klintman, 2019). The design of an impactful labelling and communication scheme for the supply chain driven BECCS implementation and its products climate benefit, also including the communication to investors, implies an interaction between Private Actors, Civil Society, and Governments (*cf.* Lambin and Thorlakson, 2018).

In fact, a carbon-neutral office paper is already being offered by the pulp and paper producer Stora Enso, and the diary company Arla Foods offers all its ecological milk in Sweden with a net-zero-carbon footprint (Arla, 2019; Stora Enso, 2019), indicating that there is a market for such products. In these cases, however, "carbon neutrality" is achieved through the purchase of carbon emissions reduction certificates from voluntary carbon offsetting programs, which are being criticised for the difficulties associated with their verifiability (Lovell and Liverman, 2010; Schneider et al., 2020), for lacking legitimacy, and for being used as a smokescreen by rich countries and companies that are trying to stall their own efforts to reduce emissions (Blum and Lövbrand, 2019). In this context, CCS with standardised mechanisms for storage monitoring should have a much higher degree of verifiability (Allen et al., 2020), yet also faces challenges of public acceptance (Bui et al., 2018; Bellamy et al., 2019). Additionally, the notion of climate neutral biomass is controversial. The net effect of biomass use depends on the assumptions and needs to be analysed context specifically, incorporating for example related land-use change emissions (*cf.* Creutzig et al., 2015; Cintas et al., 2016).

Political Corporate Social Responsibility as BECCS Incentive

Companies of different sectors increasingly commit to carbon neutral targets, so far more than 1,500 companies with an aggregated revenue exceeding US$ 11.4 trillion adopted these targets (Data-Driven EnviroLab, and NewClimate Institute, 2020). Even though different definitions and strategies can be translated into different relations to carbon dioxide removal (Allen et al., 2020; Data-Driven EnviroLab, and NewClimate Institute, 2020; Science Based Targets Initiative, 2020), this indicates a shifting of corporate governance towards more focus on climate impact—even detached from the product level as discussed here. This includes also Swedish and Finnish PPI companies. Rodriguez et al. (2020) find a willingness of these companies to contribute to BECCS development, yet they do not feel the responsibility to financial commitment. Defining BECCS within the supply chain has therefore the potential to include a wider range of companies into its commercialisation, i.e., in its innovation ecosystem (Adner, 2017; Walrave et al., 2018).

Existing decarbonisation activities in the energy intensive industry already name Corporate Social Responsibility as an important driver (Knoop et al., 2019; Tönjes et al., 2020).

Required Market Size

The "buyers' coalition" consortium as presented here needs to ensure a market for CDR pulp before committing to an investment in BECCS. Using the case study products and assuming respective realistic pulp mill capacity, we estimated the amount of resulting low carbon products. Comparing these estimations with the current market situation reveals that, depending on the sector, single companies would be able to purchase all the CDR pulp from a pulp producer. However, several similar companies should be involved in the consortium in case the required market size exceeds the paper demand of single companies, or their access to the market segment that accepts low carbon products. Please refer to the **Appendix D** for more details.

Another option to ensure a market for CDR pulp is to reduce the required market size by allocating the climate benefit and cost impact only to a share x% of the produced pulp. The climate benefit and cost of the remaining CDR pulp would then increase inversely by x^{-1} %. Assuming as an example an allocation to 50% of the pulp, the carbon footprint would decrease by 27%, 39% and 121% for the Oatdrink, Moving box and Hardcover book, respectively. The cost increase would simultaneously double to +0.30%, +1.39%, and +0.74%. In the light of Life Cycle Assessment (LCA) standards, Prado et al. (2020) discussed a similar system of cost and emissions allocation to business units to incentivise investments in environmental improvement in the chemical industry, particularly emphasising the importance of clearly communicating that method. To mitigate the risk of transferring the entire existing production volume into a new market, Pinkse and Kolk (2010) suggested this "hybridisation" approach of offering conventional and improved products in parallel. Furthermore, instead of taking allocation as a means to reduce the market risk, it could also be seen as a possibility to achieve higher offsets or even a negative carbon footprint.

The Investment in BECCS

Besides technological and regulatory challenges previous work often raise economic uncertainties as major barrier to the demonstration and commercialisation of low-carbon technologies (Polzin, 2017). Levihn et al. (2019), for example, have described how economic uncertainties are regarded as the largest barrier to BECCS application at a combined heat and power plant in Stockholm. The investments into pulp mills similarly poses a considerable financial and entrepreneurial risk with investment costs in the range of 43–500 MEUR for a 700,000 tonne/year pulp mill. Therefore, a solid risk management and ownership structure is needed to form a viable business model [see Durusut and Mattos (2018) for the different business model elements, risk forms and the business models of existing industrial CCS installations].

By introducing a small price premium on the consumer products, our analysis confirms the possibility to break-even in the first few years of operation. Building the business model around low carbon products as revenue model and funding source, as suggested here, carries the risk whether a market for low carbon products can be created. To reduce this risk a consortium of actors in the supply chain could be formed (Tönjes et al., 2020). This buyers' coalition consortium, as suggested here, would agree on a purchase agreement for the more-expensive CDR pulp. Similar corporate purchase agreements are exemplified by Apple in the ELYSIS consortium for carbon free aluminium production (Bataille, 2019), the development of a hydrogen and e-fuel production facility backed by several commercial customers (Ørsted, 2020), and is already common within renewable energy development (Miller et al., 2018).

Moreover, political support, i.e., the recognition of and involvement in climate mitigation opportunities that emerge "bottom up" in companies, are of key importance for their success (Pinkse and Kolk, 2010; Bellamy and Geden, 2019; Söderholm et al., 2019; Tönjes et al., 2020). Thus, we do not envision a process without governmental involvement and support, but such should collaboratively support the value proposition of CDR pulp and not only be limited to compensate carbon dioxide removal "at the stack." Kolster (2019) has highlighted the role of public policies in insuring the financial risk of the investment and ensuring the infrastructure (e.g., for the transportation and long-term storage of CO_2), so as to reduce the associated costs of CCS. In fact, the risk management of most current CCS projects is characterised by considerable political involvement, including the public underwriting of risks or loan guarantees (Durusut and Mattos, 2018). However, while the costs are considerable, they should also be interpreted in the context of the already capital-intensive PPI. In the period 2016–2018, single Swedish investments in new facilities and machines were in the range of 400–800 MEUR, comparable to the cost of a full-sized CCS plant. In total, the investments in the Swedish PPI during that period amounted to 4.2 Billion EUR (Skogsindustrierna, 2019).

The investment cost estimates from Onarheim et al. (2017b) and Skagestad et al. (2018), which have been used as the basis for our analysis, are in line with estimates of investment costs for CCS applications in other industries (Garðarsdóttir, 2017). Post-combustion CO_2 capture, as applied in this analysis, can be considered to be a mature technology and can also be applied to the PPI (Onarheim et al., 2017b; Bui et al., 2018). However, the presented investment costs are taken from studies that assumed the installation of a N^{th}-of-a-kind plant. As there is currently no CCS plant operating in a pulp mill, the cost for a first large-scale project is likely to be higher (van der Spek et al., 2019). This includes the development of pilot and demonstration plants, which would likely require public funding to offer important learnings (Mossberg et al., 2020).

CONCLUSIONS

This work investigates the potential for "climate-friendly" consumer products to act as enablers of BECCS in the pulp and paper industry. This involves estimating how passing on the costs and negative emissions associated with BECCS would influence the carbon footprints and costs of a selection of consumer products. We show how cooperation between stakeholders in the supply chain could enable the production of products with a substantially reduced carbon footprint (by 14–60%), while increasing the final costs of the products only marginally ($<$0.7%). We therefore suggest that the consumer willingness-to-pay for low-carbon products could exceed the cost of decarbonising pulp production.

Furthermore, assuming that the value of the products increases more than their cost increases, we investigate the effects of introducing a price premium, which would create a revenue stream that could shorten the pay-back period and generate a profit from BECCS. The results of the break-even analysis show that the BECCS plant can be profitable within the first few years of operation, depending on the premium applied. This means that a minimal charge for single consumer products could enable the implementation of BECCS in pulp production, assuming that the market for such products is sufficiently large.

Even though the possibility to realise the suggested type of buyers' coalition under real market conditions remains uncertain, we believe that the conceptual framework will shed new light on (1) how new forms of proactive corporate governance can lead to collaborations that contribute towards unlocking investments in BECCS and (2) how governments could support "bottom up" emerging BECCS deployment, led by companies.

The set-ups for buyers' coalitions (*cf.* Bataille, 2019), as suggested here or through transformation funds (Rootzén and Johnsson, 2017), are examples of cross-industry collaboration for low-carbon innovation in energy intensive industries (*cf.* Tönjes et al., 2020). This new concept allows actors along the supply chains for basic materials, such as pulp and paper, steel and cement, to contribute collectively to securing financing and de-risking investments in low-, zero-, or negative-emission technologies, especially in the scale-up and roll-out phases of new technologies. We conclude that the elaboration and evaluation of such collaboration and financing concepts, which could complement existing climate policy measures and contribute to speeding up the technical transformation of the basic material industry also towards NET deployment, deserves more attention and provides fruitful avenues for future research.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

JK and JR together laid out the methodology. JK conducted the analysis and drafted the manuscript under the supervision of JR, FN, and FJ. All authors contributed to manuscript revision and conceptualized the work.

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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.2021.615578/full#supplementary-material

REFERENCES

Adner, R. (2017). Ecosystem as structure. *J. Manage.* 43, 39–58. doi: 10.1177/0149206316678451

Allen, M., Axelsson, K., Caldecott, B., Hale, T., Hepburn, C., Hickey, C., et al. (2020). *The Oxford Principles for Net Zero Aligned Carbon Offsetting 2020*, (Oxford: Smith School of Enterprise and the Environment, University of Oxford).

Arla (2019). *Nu har alla våra Arla Ko® EKO-produkter netto noll klimatavtryck*. Available online at: https://www.arla.se/om-arla/vart-ansvar/ekologiskt/netto-noll-klimatavtryck/ (accessed November 12, 2019).

Bangsa, A. B., and Schlegelmilch, B. B. (2020). Linking sustainable product attributes and consumer decision-making: insights from a systematic review. *J. Clean. Prod.* 245:118902. doi: 10.1016/j.jclepro.2019.118902

Bataille, C. (2019). "Low and zero emissions in the steel and cement industries: Barriers, technologies and policies," in *Issue Paper Conference version* (Paris).

Bednar, J., Obersteiner, M., and Wagner, F. (2019). On the financial viability of negative emissions. *Nat. Commun.* 10:1783. doi: 10.1038/s41467-019-09782-x

Bellamy, R., Fridahl, M., Lezaun, J., Palmer, J., Rodriguez, E., Lefvert, A., et al. (2021). Incentivising bioenergy with carbon capture and storage (BECCS) responsibly: Comparing stakeholder policy preferences in the United Kingdom and Sweden. *Environ. Sci. Policy* 116, 47–55. doi: 10.1016/j.envsci.2020.09.022

Bellamy, R., and Geden, O. (2019). Govern CO_2 removal from the ground up. *Nat. Geosci.* 12, 874–876. doi: 10.1038/s41561-019-0475-7

Bellamy, R., Lezaun, J., and Palmer, J. (2019). Perceptions of bioenergy with carbon capture and storage in different policy scenarios. *Nat. Commun.* 10:743. doi: 10.1038/s41467-019-08592-5

Blum, M., and Lövbrand, E. (2019). The return of carbon offsetting? The discursive legitimation of new market arrangements in the Paris climate regime. *Earth System Governance* 2:100028. doi: 10.1016/j.esg.2019.100028

Börsenverein des Deutschen Buchhandels (2015). *Buchkäufer und -leser 2015: Profile, Motive, Einstellungen*. Available online at: https://www.boersenverein.de/markt-daten/marktforschung/studien-umfragen/buchkaeufer-und-buchleser-studie-2015/ (accessed November 18, 2019).

Boström, M., and Klintman, M. (2019). Can we rely on 'climate-friendly' consumption? *J. Consumer Cult.* 19, 359–378. doi: 10.1177/1469540517717782

Breustedt, G. (2014). *Demand for Carbon-Neutral Food—Evidence From a Discrete Choice Experiment for Milk and Apple Juice*, Kiel. doi: 10.22004/ag.econ.169748

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., et al. (2018). Carbon capture and storage (CCS): the way forward. *Energy Environ. Sci.* 11, 1062–1176. doi: 10.1039/C7EE02342A

CarbonCloud, A. B. (2019). *Report: The Climate Footprint of enriched Oat Drink Ambient: Oat drink Sweden: Oatly, 1.5%*. Available online at: https://www.oatly.com/uploads/attachments/ck16jh9jt04k9bggixfg6ssrn-report-the-climate-footprint-of-enriched-oat-drink-ambient-carboncloud-20190917.pdf

CEPI (2017). *Key Statistics 2017: European Pulp & Paper industry*. Available online at: http://www.cepi.org/keystatistics2017 (accessed January 30, 2019).

Cintas, O., Berndes, G., Cowie, A. L., Egnell, G., Holmström, H., and Ågren, G. I. (2016). The climate effect of increased forest bioenergy use in Sweden: evaluation at different spatial and temporal scales. *WIREs Energy Environ.* 5, 351–369. doi: 10.1002/wene.178

Cox, E., and Edwards, N. R. (2019). Beyond carbon pricing: policy levers for negative emissions technologies. *Climate Policy* 19, 1144–1156. doi: 10.1080/14693062.2019.1634509

Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., et al. (2015). Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy* 7, 916–944. doi: 10.1111/gcbb.12205

Data-Driven EnviroLab, and NewClimate Institute. (2020). *Accelerating Net Zero: Exploring Cities, Regions, and Companies' Pledges to Decarbonise*.

Durusut, E., and Mattos, A. (2018). *Industrial carbon Capture Business Models: Report for Department for Business, Energy and Industrial Strategy*, Cambridge.

FEFCO (2018). *European Database for Corrugated Board Life Cycle Studies*, Brussels.

FEFCO (2019). *Ecodesign*. Available online at: http://www.fefco.org/circular-by-nature/ecodesign

Florén, B., Nilsson, K., and Wallman, M. (2013). *LCA på färsk och aseptisk havredryck*, (Gothenburg).

Fridahl, M., and Lehtveer, M. (2018). Bioenergy with carbon capture and storage (BECCS): global potential, investment preferences, and deployment barriers. *Energy Res. Soc. Sci.* 42, 155–165. doi: 10.1016/j.erss.2018.03.019

Fridahl, M., and Bellamy, R. (2018). "Multilevel Policy Incentives for BECCS in Sweden," in *Bioenergy With Carbon Capture and Storage: From Global Potentials to Domestic Realities*, ed. M. Fridahl (Stockholm: European Liberal Forum), 57–67.

Friede, G., Busch, T., and Bassen, A. (2015). ESG and financial performance: aggregated evidence from more than 2000 empirical studies. *J. Sust. Finance Invest.* 5, 210–233. doi: 10.1080/20430795.2015.1118917

Fuss, S., Canadell, J. G., Ciais, P., Jackson, R. B., Jones, C. D., Lyngfelt, A., et al. (2020). Moving toward net-zero emissions requires new alliances for carbon dioxide removal. *One Earth* 3, 145–149. doi: 10.1016/j.oneear.2020.08.002

Fuss, S., Jones, C. D., Kraxner, F., Peters, G., Smith, P., Tavoni, M., et al. (2016). Research priorities for negative emissions. *Environ. Res. Lett.* 11:115007. doi: 10.1088/1748-9326/11/11/115007

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., et al. (2018). Negative emissions—Part 2: costs, potentials and side effects. *Environ. Res. Lett.* 13, 63002. doi: 10.1088/1748-9326/aabf9f

Garðarsdóttir, S. Ó. (2017). *Technical and economic conditions for efficient implementation of CO_2 capture: Process design and operational strategies for power generation and process industries* (Thesis for the Degree of Doctor of Philosophy). Chalmers University of Technology, Department of Space, Earth and Environment, Göteborg, Sweden.

Garðarsdóttir, S. Ó., Normann, F., Andersson, K., and Johnsson, F. (2014). Process evaluation of CO2 capture in three industrial case studies. *Energy Procedia* 63, 6565–6575. doi: 10.1016/j.egypro.2014.11.693

Garðarsdóttir, S. Ó., Normann, F., Skagestad, R., and Johnsson, F. (2018). Investment costs and CO2 reduction potential of carbon capture from industrial plants—A Swedish case study. *Int. J. Greenhouse Gas Control* 76, 111–124. doi: 10.1016/j.ijggc.2018.06.022

Geden, O., Peters, G., and Scott, V. (2019). Targeting carbon dioxide removal in the European Union. *Climate Policy* 19, 487–494. doi: 10.1080/14693062.2018.1536600

Geden, O., and Schenuit, F. (2020). *Unconventional Mitigation: Carbon Dioxide Removal as a New Approach in EU Climate Policy*. Berlin: German Institute for International and Security Affairs.

Gordon, A. V., Ramic, M., Rohrbeck, R., and Spaniol, M. J. (2020). 50 Years of corporate and organizational foresight: looking back and going forward. *Technol. Forecast. Soc. Change* 154:119966. doi: 10.1016/j.techfore.2020.119966

Hansson, J., Hackl, R., Taljegard, M., Brynolf, S., and Grahn, M. (2017). The potential for electrofuels production in sweden utilizing fossil and biogenic CO2 point sources. *Front. Energy Res.* 5:133. doi: 10.3389/fenrg.2017.00004

Hedström, J. (2014). *Simulation and Assessment of Carbon Capture Processes Applied to a Pulp Mill* (Master of Science Thesis). Chalmers University of Technology, Department of Energy and Environment Division of Energy Technology, Göteborg, Sweden.

Heffron, R. J., Downes, L., Bysveen, M., Brakstad, E. V., Mikunda, T., Neele, F., et al. (2018). Three layers of energy law for examining CO2 transport for carbon-capture and storage. *J. World Energy Law Business* 11, 93–115. doi: 10.1093/jwelb/jwx035

Hektor, E. (2008). *Post-combustion CO2 Capture In Kraft Pulp and Paper Mills: Technical, Economic and System Aspects*. Doktorsavhandlingar. Göteborg: Chalmers University of Technology, Department of Heat & Power Technology.

Hektor, E., and Berntsson, T. (2007). Future CO2 removal from pulp mills—Process integration consequences. *Energy Conver. Manag.* 48, 3025–3033. doi: 10.1016/j.enconman.2007.06.043

Hektor, E., and Berntsson, T. (2009). Reduction of greenhouse gases in integrated pulp and paper mills: possibilities for CO2 capture and storage. *Clean Techn. Environ. Policy* 11, 59–65. doi: 10.1007/s10098-008-0166-3

Honegger, M., and Reiner, D. (2018). The political economy of negative emissions technologies: consequences for international policy design. *Climate Policy* 18, 306–321. doi: 10.1080/14693062.2017.1413322

IEA (2019). *CCUS in Industry and Transformation: CCUS in Industry and Transformation*. Available online at: https://www.iea.org/tcep/industry/ccus/ (accessed September 24, 2019).

IEA (2020). *ETP Clean Energy Technology Guide*. IEA. Available online at: https://www.iea.org/articles/etp-clean-energy-technology-guide (accessed September 17, 2019).

IPCC (2018). "Summary for Policymakers," in *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, eds. V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, et al. (Geneva: Intergovernmental Panel on Climate Change), 93–174.

Jönsson, J., and Berntsson, T. (2012). Analysing the potential for implementation of CCS within the European pulp and paper industry. *Energy* 44, 641–648. doi: 10.1016/j.energy.2012.05.028

Jönsson, J., Pettersson, K., Berntsson, T., and Harvey, S. (2013). Comparison of options for utilization of a potential steam surplus at kraft pulp mills-Economic performance and CO 2 emissions. *Int. J. Energy Res.* 37, 1017–1035. doi: 10.1002/er.2905

Kaya, Y., Yamaguchi, M., and Geden, O. (2019). Towards net zero CO2 emissions without relying on massive carbon dioxide removal. *Sustain. Sci.* 354, 182. doi: 10.1007/s11625-019-00680-1

Klimatpolitiska vägvalsutredningen, M. (2020). *Vägen till en Klimatpositiv Framtid: The pathway to a Climate Positive Future—Strategy and Action Plan for Achieving Negative Greenhouse Gas Emissions After,* 2045.

Knoop, K., Lechtenböhmer, T., Mölter, H., Tönjes, A., and Witte, K. (2019). *Drivers of Low-Carbon Innovation: Deliverable 3.6.*, (Wuppertal: REINVENT).

Kolster, C. (2019). *Economic, process and reservoir modelling for evaluating large-scale deployment of carbon capture and storage* (Ph.D. Thesis). Imperial College London, Faculty of Natural Sciences, London, United Kingdom.

Kuparinen, K., Vakkilainen, E., and Tynjäl,ä, T. (2019). Biomass-based carbon capture and utilization in kraft pulp mills. *Mitig. Adapt Strateg. Glob. Change* 10:2491. doi: 10.1007/s11027-018-9833-9

Lacoste, S. (2016). Sustainable value co-creation in business networks. *Industrial Market. Manag.* 52, 151–162. doi: 10.1016/j.indmarman.2015.05.018

Lambin, E. F., and Thorlakson, T. (2018). Sustainability standards: interactions between private actors, civil society, and governments. *Annu. Rev. Environ. Resour*. 43, 369–393. doi: 10.1146/annurev-environ-102017-025931

Levihn, F., Linde, L., Gustafsson, K., and Dahlen, E. (2019). Introducing BECCS through HPC to the research agenda: the case of combined heat and power in Stockholm. *Energy Rep.* 5, 1381–1389. doi: 10.1016/j.egyr.2019.09.018

Liu, T., Wang, Q., and Su, B. (2016). A review of carbon labeling: standards, implementation, and impact. *Renew. Sust. Energy Rev.* 53, 68–79. doi: 10.1016/j.rser.2015.08.050

Lovell, H., and Liverman, D. (2010). Understanding carbon offset technologies. *New Political Eco.* 15, 255–273. doi: 10.1080/13563460903548699

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O. Y., Pietzcker, R. C., Rogelj, J., et al. (2018). Residual fossil CO2 emissions in 1.5–2 °C pathways. *Nat. Clim. Chang*. 8, 626–633. doi: 10.1038/s41558-018-0198-6

Markwardt, S., Wellenreuther, F., Drescher, A., Harth, J., and Busch, M. (2017). *Comparative Life Cycle Assessment of Tetra Pak® Carton Packages and Alternative Packaging Systems for Liquid Food on the Nordic Market: Final Report. Commissioned.* Heidelberg: Tetra Pak International SA.

McGrail, B. P., Freeman, C. J., Brown, C. F., Sullivan, E. C., White, S. K., Reddy, S., et al. (2012). Overcoming business model uncertainty in a carbon dioxide capture and sequestration project: case study at the boise white paper mill. *Int. J. Greenhouse Gas Control* 9, 91–102. doi: 10.1016/j.ijggc.2012.03.009

Miller, L., Carriveau, R., and Harper, S. (2018). Innovative financing for renewable energy project development—recent case studies in North America. *Int. J. Environ. Studies* 75, 121–134. doi: 10.1080/00207233.2017.1403758

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions—Part 1: research landscape and synthesis. *Environ. Res. Lett.* 13:63001. doi: 10.1088/1748-9326/aabf9b

Möllersten, K. (2002). *Opportunities for CO2 Reductions and CO2-Lean Energy Systems in Pulp and Paper Mills* (Doctoral Thesis). Royal Institute of Technology, Dept. Of Chemical Engineering and Technology/Energy Processes, Stockholm, Sweden.

Mossberg, J., Frishammar, J., Söderholm, P., and Hellsmark, H. (2020). Managerial and organizational challenges encountered in the development of sustainable technology: Analysis of Swedish biorefinery pilot and demonstration plants. *J. Clean. Prod*, 124150. doi: 10.1016/j.jclepro.2020.124150

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., et al. (2018). Negative emissions—Part 3: innovation and upscaling. *Environ. Res. Lett.* 13:63003. doi: 10.1088/1748-9326/aabff4

Nwaoha, C., and Tontiwachwuthikul, P. (2019). Carbon dioxide capture from pulp mill using 2-amino-2-methyl-1-propanol and monoethanolamine blend: techno-economic assessment of advanced process configuration. *Appl. Energy* 250, 1202–1216. doi: 10.1016/j.apenergy.2019.05.097

Onarheim, K., Santos, S., Kangas, P., and Hankalin, V. (2017a). Performance and costs of CCS in the pulp and paper industry part 1: performance of amine-based post-combustion CO 2 capture. *Int. J. Greenhouse Gas Control* 59, 58–73. doi: 10.1016/j.ijggc.2017.02.008

Onarheim, K., Santos, S., Kangas, P., and Hankalin, V. (2017b). Performance and cost of CCS in the pulp and paper industry part 2: economic feasibility of amine-based post-combustion CO 2 capture. *Int. J. Greenhouse Gas Control* 66, 60–75. doi: 10.1016/j.ijggc.2017.09.010

Ørsted (2020). Danish companies plan 1.3 GW electrolyser using offshore wind. *Fuel Cells Bull.* 2020, 8–9. doi: 10.1016/S1464-2859(20)30244-3

O'Sullivan, O. S., Hopkinson, L., Crockatt, M. E., Laird, P., and Bebber, D. P. (2016). Stable forest carbon stocks support current assumption of biogenic carbon neutrality in the case of European-manufactured beverage cartons. *Int. J. Life Cycle Assess* 21, 118–128. doi: 10.1007/s11367-015-0989-1

Peters, G., and Geden, O. (2017). Catalysing a political shift from low to negative carbon. *Nat. Clim Change* 7, 619–621. doi: 10.1038/nclimate3369

Pihkola, H., Nors, M., Kujanp,ää, M., Helin, T., Kariniemi, M., Pajula, T., et al. (2010). *Carbon Footprint and Environmental Impacts of Print Products From Cradle to Grave: Results from the LEADER project (Part 1)*. Helsinki; Espoo: VTT Technical Research Centre of Finland.

Pinkse, J., and Kolk, A. (2010). Challenges and trade-offs in corporate innovation for climate change. *Bus. Strat. Env*. 28, n/a-n/a. doi: 10.1002/bse.677

Platt, D., Workman, M., and Hall, S. (2018). A novel approach to assessing the commercial opportunities for greenhouse gas removal technology value chains: developing the case for a negative emissions credit in the UK. *J. Clean. Prod.* 203, 1003–1018. doi: 10.1016/j.jclepro.2018.08.291

Polzin, F. (2017). Mobilizing private finance for low-carbon innovation—A systematic review of barriers and solutions. *Renew. Sust. Energy Rev.* 77, 525–535. doi: 10.1016/j.rser.2017.04.007

Prado, V., Glaspie, R., Waymire, R., and Laurin, L. (2020). Energy apportionment approach to incentivize environmental improvement investments in the chemical industry. *J. Clean. Prod.* 257:120550. doi: 10.1016/j.jclepro.2020.120550

Rickels, W., Merk, C., Reith, F., Keller, D. P., and Oschlies, A. (2019). (Mis)conceptions about modeling of negative emissions technologies. *Environ. Res. Lett.* 14:104004. doi: 10.1088/1748-9326/ab3ab4

Rickels, W., Proel,ß, A., Geden, O., Burhenne, J., and Fridahl, M. (2020). *The Future of (negative) Emissions Trading in the European Union*. Kiel Working Paper, No. 2164. Kiel: Institute for the World Economy (IfW).

Rintamäki, T., and Kirves, K. (2017). From perceptions to propositions: profiling customer value across retail contexts. *J. Retail. Consumer Serv.* 37, 159–167. doi: 10.1016/j.jretconser.2016.07.016

Rodriguez, E., Lefvert, A., Fridahl, M., Grönkvist, S., Haikola, S., and Hansson, A. (2020). Tensions in the energy transition: Swedish and Finnish company perspectives on bioenergy with carbon capture and storage. *J. Clean. Prod*. 124527. doi: 10.1016/j.jclepro.2020.124527

Rogelj, J., D., Shindell, K., Jiang, S., Fifita, P., Forster, V., et al. (2018). "Mitigation pathways compatible with 1.5°c in the context of sustainable development," in *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to* eradicate poverty, eds. V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, et al. (Geneva: Intergovernmental Panel on Climate Change), 3–24.

Rootzén, J., and Johnsson, F. (2017). "Technologies and policies for GHG emission reductions along the supply chains for the Swedish construction industry," in *Consumption, Efficiency & Limits*, ed. T. Lindström (Stockholm: Eceee Secretariat), 1401–1407.

Rootzén, J., Kjärstad, J., Johnsson, F., and Karlsson, H. (2018). *"Deployment of BECCS in Basic Industry: A Swedish Case Study*.

Scherer, A. G., and Voegtlin, C. (2020). Corporate governance for responsible innovation: approaches to corporate governance and their implications for sustainable development. *AMP* 34, 182–208. doi: 10.5465/amp.2017.0175

Schneider, L., Healy, S., Fallasch, F., León, F., de, Rambharos, M., Schallert, B., et al. (2020). *What Makes a High-Quality Carbon Credit?* (World Wildlife Fund (WWF-US), Environmental Defense Fund (EDF) and Oeko-Institut).

Science Based Targets Initiative (2020). *Foundations for Science-Based Net-Zero Target Setting in the Corporate Sector*.

Skagestad, R., Garðarsdóttir, S., Normann, F., Anheden, M., and Wolf, J. (2018). A case study of partial capture of CO2 from a pulp mill - the effect on CO2 capture cost. *14th Greenhouse Gas Control Technologies Conference Melbourne*, (GHGT-14) 21–26. doi: 10.2139/ssrn.3366243

Skogsindustrierna (2019). *Marknadsrapport: Så går det för skogsindustrin Februari 2019* (Stockholm: Skogsindustrierna).

Söderholm, P., Hellsmark, H., Frishammar, J., Hansson, J., Mossberg, J., and Sandström, A. (2019). Technological development for sustainability: the role of network management in the innovation policy mix. *Technol. Forecast. Soc. Change* 138, 309–323. doi: 10.1016/j.techfore.2018.10.010

Soneryd, L., and Uggla, Y. (2015). Green governmentality and responsibilization: new forms of governance and responses to 'consumer responsibility'. *Env. Polit* 24, 913–931. doi: 10.1080/09644016.2015.1055885

Stora Enso (2019). *Multicopy Zero*. Avilable online at: https://www.storaenso.com/en/products/paper/office-papers/multicopy-zero (accessed May 27, 2019).

Suhr, M., Klein, G., Kourti, I., Gonzalo, M. R., Santonja, G. G., Roudier, S., et al. (2015). *Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)*. Luxembourg: Publications Office of the European Union.

The Royal Society (2018). *Greenhouse Gas Removal*. London: The Royal Society; Royal Academy of Engineering.

The Swedish EPA (2018). *Allmänheten om klimatet 2018: En kvantitativ undersökning om den svenska allmänhetens syn på lösningar för klimatet.* Available online at: https://www.naturvardsverket.se/attityd-klimat-2018 (accessed February 26, 2019)

Tönjes, A., Lechtenböhmer, T., Witte, K., Knoop, K., and Mölter, H. (2020). "Dynamics of cross-industry low-carbon innovation in energy-intensive industries," in *ECEEE Industrial Summer Study proceedings: Industrial Efficiency 2020: Decarbonise industry!* (Wuppertal), 467–476.

Torvanger, A. (2019). Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement. *Climate Policy* 19, 329–341. doi: 10.1080/14693062.2018.1509044

van der Spek, M., Roussanaly, S., and Rubin, E. S. (2019). Best practices and recent advances in CCS cost engineering and economic analysis. *Int. J. Greenhouse Gas Control* 83, 91–104. doi: 10.1016/j.ijggc.2019.02.006

van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., van den Berg, M., Bijl, D. L., Boer, H. S., et al. (2018). Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat. Clim Change* 8, 391–397. doi: 10.1038/s41558-018-0119-8

Voeth, M., and Herbst, U. (2006). Supply-chain pricing—A new perspective on pricing in industrial markets. *Indust. Mark. Manag.* 35, 83–90. doi: 10.1016/j.indmarman.2005.08.010

von Schomberg, R. (2012). "Prospects for technology assessment in a framework of responsible research and innovation," in *Technikfolgen abschätzen lehren: Bildungspotenziale transdisziplinärer Methoden*, eds. M. Dusseldorp, and R. Beecroft (Wiesbaden: Springer VS), 39–61.

Walrave, B., Talmar, M., Podoynitsyna, K. S., Romme, A. G. L., and Verbong, G. P. J. (2018). A multi-level perspective on innovation ecosystems for path-breaking innovation. *Technol. Forecast. Soc. Change* 136, 103–113. doi: 10.1016/j.techfore.2017.04.011

Wesseling, J. H., Lechtenböhmer, S., Åhman, M., Nilsson, L. J., Worrell, E., and Coenen, L. (2017). The transition of energy intensive processing industries towards deep decarbonization: characteristics and implications for future research. *Renew. Sust. Energy Rev.* 79, 1303–1313. doi: 10.1016/j.rser.2017.05.156

Wiedmann, T., and Minx, J. C. (2008). "A Definition of 'Carbon Footprint'," in *Ecological Economics Research Trends*, ed. C. C. Pertsova (Hauppauge, NY: Nova Science Publishers Incorporated), 1–11.

Wikberg, E. (2018). *Boken 2018:—marknaden, trender och analyser*. Available online at:https://www.forlaggare.se/vara-rapporter (accessed November 18, 2019).

Zakkour, P., Kemper, J., and Dixon, T. (2014). Incentivising and accounting for negative emission technologies. *Energy Procedia* 63, 6824–6833. doi: 10.1016/j.egypro.2014.11.716

Zetterberg, L., Källmark, L., and Möllersten, K. (2019). *Incitament och finansiering av Bio-CCS i Sverige*, Stockholm.

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POLICY AND PRACTICE REVIEWS
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Carbon Dioxide Removal Policy in the Making: Assessing Developments in 9 OECD Cases

Felix Schenuit[1,2]*, Rebecca Colvin[3], Mathias Fridahl[4], Barry McMullin[5], Andy Reisinger[6], Daniel L. Sanchez[7], Stephen M. Smith[8], Asbjørn Torvanger[9], Anita Wreford[10] and Oliver Geden[2]

[1] Center for Sustainable Society Research, University of Hamburg, Hamburg, Germany, [2] German Institute for International and Security Affairs (SWP), Berlin, Germany, [3] Crawford School of Public Policy, Australian National University, Canberra, ACT, Australia, [4] Department of Thematic Studies, Environmental Change, Centre for Climate Science and Policy Research, Linköping University, Linköping, Sweden, [5] Dublin City University, Dublin, Ireland, [6] Ministry for the Environment, Wellington, New Zealand, [7] Department of Environmental Science, Policy, and Management (ESPM), University of California, Berkeley, Berkeley, CA, United States, [8] Smith School of Enterprise and the Environment, Oxford University, Oxford, United Kingdom, [9] Center for International Climate Research (CICERO), Oslo, Norway, [10] Agribusiness and Economics Research Unit (AERU), Lincoln University, Christchurch, New Zealand

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Heriot-Watt University,
United Kingdom

***Correspondence:**
Felix Schenuit
felix.schenuit@uni-hamburg.de

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Since the adoption of the Paris Agreement in 2015, spurred by the 2018 IPCC Special Report on Global Warming of 1.5°C, net zero emission targets have emerged as a new organizing principle of climate policy. In this context, climate policymakers and stakeholders have been shifting their attention to carbon dioxide removal (CDR) as an inevitable component of net zero targets. The importance of CDR would increase further if countries and other entities set net-negative emissions targets. The scientific literature on CDR governance and policy is still rather scarce, with empirical case studies and comparisons largely missing. Based on an analytical framework that draws on the multi-level perspective of sociotechnical transitions as well as existing work on CDR governance, we gathered and assessed empirical material until early 2021 from 9 Organization for Economic Co-operation and Development (OECD) cases: the European Union and three of its Member States (Ireland, Germany, and Sweden), Norway, the United Kingdom, Australia, New Zealand, and the United States. Based on a synthesis of differences and commonalities, we propose a tripartite conceptual typology of the varieties of CDR policymaking: (1) incremental modification of existing national policy mixes, (2) early integration of CDR policy that treats emission reductions and removals as fungible, and (3) proactive CDR policy entrepreneurship with support for niche development. Although these types do not necessarily cover all dimensions relevant for CDR policy and are based on a limited set of cases, the conceptual typology might spur future comparative work as well as more fine-grained case-studies on established and emerging CDR policies.

Keywords: carbon dioxide removal, net zero, climate policy, case studies, typology, socio-technical transitions, OECD

INTRODUCTION

Since the adoption of the Paris Agreement and the publication of the IPCC's Special Report on Global Warming of 1.5°C (SR1.5), numerous political actors have agreed on net zero emissions targets. This type of long-term target—usually, but not always, defined as a balance of greenhouse gas (GHG) emissions and removals—is emerging as a new organizing principle of climate policy at almost all political levels. Attempts to operationalize net zero targets have been accompanied by increasing attention on the need for anthropogenic carbon dioxide removal[1] (CDR) to achieve these targets (Geden, 2016a; Fuss et al., 2020). The importance of CDR would increase further if pathways involving net-negative emissions are pursued in order to recover carbon budgets consistent with temperature goals after they are exceeded (IPCC, 2018).

The scarce but growing academic literature on the governance of CDR has shown that the configuration and design of CDR policies, as well as their interactions with other climate policies, have important implications for the role of CDR in the transition toward net zero emissions societies (Bellamy et al., 2019; McLaren et al., 2019; Geden and Schenuit, 2020). Based on a comparison of nine case studies, this article attempts to track the extent to which CDR policies are already part of domestic climate policy regimes and how the integration of CDR is evolving. While the transition of international climate governance toward a bottom-up, polycentric, and performative climate governance unfolds (Aykut et al., 2020), analyzing the facts on the ground of transformations toward deep decarbonization becomes even more important (Victor et al., 2019).

In the process of case selection, we followed four key criteria: (1) We limit our cases to members of the Organization for Economic Co-operation and Development (OECD). Countries with high income and high historical emissions are generally expected to be responsible for a greater quantity of CDR deployment if distributional equity is taken into account (Fyson et al., 2020; Pozo et al., 2020). This reflects the expectations institutionalized in the international climate negotiations under the United Nations Framework Convention on Climte Change (UNFCCC). Although the Paris Agreement does not officially maintain the dichotomy of Annex 1 and non-Annex 1 countries and has introduced a less rigid distinction between developed and developing countries as well as other subtle differentiations (Pauw et al., 2019), aggregate expectations for high-income countries with historically high emissions to lead on climate change mitigation continue to shape the negotiations. At the same time, these countries are expected to have rather high shares of mid-century residual emissions in hard-to-abate sectors (Davis et al., 2018; Luderer et al., 2018; Bataille, 2020); challenges to and high costs of achieving their net zero targets will shift increasing attention toward CDR. This is not to argue that developments in other countries with different socio-economic structures, land resources, and climate policy priorities would be less relevant; an assessment of those countries is already planned in future research projects.

In addition to this first criterion, we limit this study to countries: (2) that have already integrated CDR in their existing policy mix; (3) in which the adoption of net zero targets has spurred a debate about the integration of CDR policies in the climate policy regime, or; (4) in which developments in niches, e.g., geochemical-based CDR, begin to put pressure on the existing regime. We therefore have an intentional bias toward countries that already deal with CDR and exclude those without CDR policies or emerging debates about it.

Based on these criteria, we identified the following set of case studies: the European Union (EU)[2] (and three of its Member States: Ireland, Germany, and Sweden), Norway, the United Kingdom (UK), New Zealand, and the United States (US)[3]. Drawing on the case studies, provided by authors from each country and updated as of January 2021, we attempt to explore the varieties of CDR integration into climate policy regimes and propose an analytical typology to distinguish between different ways of approaching CDR politically.

Analytical Framework

To provide a systematic overview of recent developments in CDR policy across the cases, we developed an analytical framework consisting of five key dimensions and a template of questions. The framework is based on the multi-level perspective (MLP) heuristic of socio-technical transitions and integrates key findings of academic literature on CDR policy and governance. The following sections summarize key elements of the MLP and the CDR governance literature. Subsequently, we provide a brief overview of how these perspectives are being applied in this exploratory study to systematically track and assess CDR-related developments across the nine cases.

Applying the Multi-Level Perspective (MLP) to CDR Policies

Research on sustainability transitions has increased rapidly in the past 10 years (Köhler et al., 2019). The MLP on socio-technical transitions is one of the most prominent strands of transition studies. It provides a "middle range theory that conceptualizes overall dynamic patterns in socio-technical transitions" (Geels, 2011, p. 26)[4]. While it provides a straightforward heuristic for exploring transition processes, it should not be misunderstood as being capable of predicting future trajectories.

We do not attempt to provide a full MLP analysis of all nine case studies here. Rather, we apply the MLP heuristic to

[1] See definition by the IPCC, SR1.5: "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, 2018).

[2] The EU as a supranational organization is not a full member of the OECD, but the European Commission takes part in its daily work.

[3] Throughout the initial process of case selection, experts from several other OECD countries were contacted (among them Japan and Canada) to decide whether these countries would fit into this set.

[4] For a discussion of middle range theory approaches, see Geels (2007).

structure our effort to track and compare transitions toward integrating CDR policy. The advantage of the MLP perspective is its "relatively straightforward way of ordering and simplifying the analysis of complex, large-scale structural transformations" (Smith et al., 2010, p. 441) while still taking into account macro-political developments and developments in small niches. This makes the MLP our preferred choice over other more fine-grained theories[5], concepts and heuristics in the—to our knowledge—first attempt to compare CDR policy development across countries.

The MLP sees transitions as non-linear processes resulting from interactions between developments at three different levels: First, the *socio-technical regimes* "represent the institutional structuring of existing systems leading to path dependence and incremental change" (Köhler et al., 2019, p. 4). Second, the *exogenous socio-technical landscape*, which consists of broader political, economic or demographic "contextual developments that influence the socio-technical regime and over which regime actors have little or no influence" (Geels et al., 2017, p. 465). And third, *niche innovations,* a level that describes "protected spaces and the locus for radical innovations" (Köhler et al., 2019, p. 4) which differ substantially from the currently dominant system and can put pressure on the existing regime (Geels et al., 2017). In addition, MLP adds a temporal dimension and distinguishes between the three phases of emergence, diffusion and reconfiguration (Geels et al., 2019).

Key strengths of heuristics such as the MLP are their capacity to identify path-dependencies, lock-in incentives and power distributions within a current system, as well as in emerging and diffusing innovation dynamics (Geels et al., 2017)—aspects that most integrated assessment models hardly address in their pathways (van Sluisveld et al., 2020). The strong focus on innovation in MLP should, however, not lead to an overly optimistic innovation bias; questions of possible "unanticipated consequences" (Merton, 1936, p. 894) and "intended but unrealized effects" (Hirschman, 1977, p. 131) should therefore always be part of analyzing transition processes.

Key Insights From the CDR Policy Governance Literature

The literature on scientific and technical aspects of CDR is growing rapidly (Minx et al., 2017) and, since the adoption of the Paris Agreement, literature on CDR governance and policy-making has also started to gain traction. Key issues addressed by scholars are the risk of mitigation obstruction (Morrow, 2014; Minx et al., 2018; McLaren et al., 2019), and the importance of policy and target design to address this risk, e.g., through prioritizing conventional mitigation and separate targets for emission reductions and removals (McLaren et al., 2019; Geden and Schenuit, 2020).

Other important strands of the debate touch on the patterns of emerging societal debates and their possible polarization (Colvin et al., 2020) as well as the public perception (Cox et al., 2020), socio-political prioritization (Fridahl, 2017; Rodriguez et al., 2020), innovation dynamics (Nemet et al., 2018), incentive structures for research and deployment (Lomax et al., 2015; Cox and Edwards, 2019; Fajardy et al., 2019; Torvanger, 2019; Fridahl et al., 2020; Bellamy et al., 2021) and framings of different CDR methods (Bellamy and Osaka, 2020; Waller et al., 2020; Woroniecki et al., 2020). Furthermore, the literature highlights the role of CDR in integrated assessment modeling and possible implications for climate policy (Geden, 2016b; Beck and Mahony, 2018; Haikola et al., 2019; Workman et al., 2020), negative implications of deploying large-scale CDR for sustainability and biodiversity (Buck, 2016; Smith et al., 2019; Dooley et al., 2020; Honegger et al., 2020), and justice and equity considerations (Anderson and Peters, 2016; Peters and Geden, 2017; Shue, 2018; Fyson et al., 2020; Morrow et al., 2020; Pozo et al., 2020).

Especially in political debates, CDR methods are often separated with the rather ambiguous differentiation of "natural" and "technological" approaches. As framings of certain CDR methods have considerable political implications, in particular the terminology of "natural" or "nature-based" (Bellamy and Osaka, 2020; Waller et al., 2020; Woroniecki et al., 2020), we use the analytical and intended to be value-neutral distinction between *ecosystem-based* and *geochemical-based* approaches[6].

Five Dimensions for Observing CDR Policy

The following five dimensions represent an attempt to apply and bridge the conceptual work of the MLP on socio-technical transitions with existing research on CDR policy and governance to provide an analytical framework that allows systematic exploration of different case studies in a comparable way (see **Table 1**).

While the dimensions (1) institutional setting, actors, and coalitions, (3) policy instruments and (4) expert bodies and science attempt to explore key aspects of the MLP-levels *socio-technical regimes* and *exogenous socio-technical landscape*, dimension (5) particularly focuses on observing *niche innovations*. Dimension (2) CDR accounting and methods covers important aspects on definition, accounting and framings raised by the emerging academic CDR governance literature.

Limiting the comparison to these five dimensions means that neither all dimensions of MLP can be covered, nor can all aspects of CDR literature be fully represented. But this rather narrow and straightforward analytical framework enabled the systematic collection and comparison of facts on the ground in nine cases in this study. Analyses based on this material, however, must consider its limitations.

[5]Future research would gain from integrating insights from other strands of the sustainable transition literature, as well as other concepts developed in political science such as public policy paradigms Carson et al. (2010) and policy innovation Jordan and Huitema (2014).

[6]While ecosystem-based methods refer to deliberately exploiting and enhancing sink functions of ecosystems, geochemical-based CDR describes CO_2 capture from the atmosphere through technical devices and geological storage. Some CDR methods, such as BECCS, are hybrid forms, see e.g., United Nations Environmental Program (2017). Note that ecosystem-based methods are not necessarily positive for wider ecosystem services and biodiversity, as this depends on their mode and scale of implementation.

TABLE 1 | Dimensions of observation.

(1) Institutional setting, actors, and coalitions	• Overall institutional and political setting in domestic climate policy (incumbent regime) • Macro-political developments that influence CDR debate [e.g., Paris Agreement, Sustainable Development Goals (SDGs), …] • Actors and coalitions in CDR-related climate policy making but also in broader societal debate [business/industry, environmental non-governmental organizations (ENGOs), …]
(2) CDR accounting and methods	• Accounting practices of CDR toward domestic climate targets and its relation to gross emission reductions • Methods addressed and differences in accounting • Groupings/separation and framings of different methods (e.g., "technological"/vs. "natural" CDR) • Socio-political prioritization of different methods
(3) Policy instruments	• Policy approach • Timing and broader political circumstances • Political struggles in public policy processes (main critique vs. justification patterns) • Relation to other climate, environmental and sustainability policy instruments and targets (discursively, politically, legally)
(4) Expert bodies and science	• Role for expert bodies and science more generally in societal CDR debate as well as in public policy processes • Role of IPCC reports (esp. 5th Assessment Report, SR1.5 and Special Report on Climate Change and Land (SRCCL) and domestic modeling or technology development
(5) Developments in CDR niches	• Developments with regard to CDR methods in "protective spaces" that shield, nurture, empower (Smith and Raven, 2012) • Emerging business cases • New actors that demand change in incumbent climate policy regimes to integrate CDR

CASE STUDIES

The case studies presented in this section were conducted by experts from each country and followed the analytical framework presented above (see **Table 1**). In addition to the dimensions for observation, a template of guiding questions for each dimension was provided to the case study author teams to ensure comparable findings across cases. The five dimensions also structure the presentation of the highly condensed results in the following sections.

European Union

Institutional Setting, Actors, and Coalitions

The European Union (EU) is regarded as a key frontrunner in international climate policy and was a driving force behind the Paris Agreement. Among its Member States and between EU institutions, however, the appropriate level of ambition is contested (Rayner and Jordan, 2016). The EU's climate policies are separated into three regulatory pillars: the EU Emissions Trading System (EU ETS), the Effort Sharing Regulation (ESR), and the land use, land-use change and forestry (LULUCF) Regulation (Kulovesi and Oberthür, 2020). While the EU ETS covers emissions from power stations, energy-intensive industries and intra-European aviation, ESR sets national targets for emissions reductions in the transport, buildings, and agriculture sectors.

Since the adoption of the Paris Agreement and the IPCC SR1.5, the EU's executive arm, the European Commission, has started to address the issue of CDR proactively (European Commission, 2018). Recent policy initiatives are directly linked to the new 2050 target of net zero GHG emissions. The European Parliament and Member State governments in the Council of the EU—the co-legislators in EU policymaking—are still negotiating, but it is already apparent that the EU Member States differ considerably in how they approach CDR politically (see the case studies on Germany, Ireland, and Sweden). The shared competence between the EU and its Member States on the environment and therefore climate policy, combined with path-dependencies, deep-rooted conflict lines (Szulecki et al., 2016), and new distributional issues will shape the upcoming decisions (Geden and Schenuit, 2020). ENGOs are likely to play a vocal role in this process. Although ENGOs increasingly acknowledge the need for CDR to achieve the net zero target, their positions are often critical, especially with regard to what some call large-scale "artificial negative emissions technologies" (Climate Action Network, 2018, p. 3). Other advocacy groups have started to call for integrating CDR into EU climate policy (e.g., Bellona). Furthermore, governmental and industry representatives of the Northern Lights project (see the case study on Norway) turned to the EU to promote cooperation on carbon capture and storage (CCS), including bioenergy with CCS (BECCS).

CDR Accounting and Methods

The Commission regards CDR as key to achieving net zero GHG emissions by 2050. Its modeling shows that net zero pathways require ecosystem- (LULUCF) and geochemical-based direct air capture and CCS (DACCS) CDR, as well as BECCS as a hybrid form. At present, the EU does not fully account for LULUCF removals toward its economy-wide mitigation targets of −40% by 2030 compared to 1990 levels. In the context of revising the target (−55%) and its new Nationally Determined Contribution (NDC) submitted in December 2020, the Commission and the Member States, however, modified the accounting toward a full consideration of the LULUCF sink. It is likely that the rather unspecific differentiation between "natural" and "technological" CDR will become a controversial issue. ENGOs have invested substantial political capital in this differentiation, and the Member States have different socio-political CDR prioritizations (Geden and Schenuit, 2020).

Policy Instruments

The current 2030 Climate and Energy Framework established in 2018 includes no distinct CDR policy. However, given the new 2030 target, this will change by 2022. The current LULUCF Regulation contains a "no-debit rule" meaning that countries are obliged to balance any emissions with removals in the LULUCF sector. To a very limited extent, LULUCF credits can be counted toward mitigation targets in the ESR sector (Ø 1% of 2005 ESR emissions). This flexibility, however, was not explicitly framed as CDR policy, i.e., intentionally incentivizing removal capacities to achieve an economy-wide mitigation target, but rather as acknowledging the hard-to-abate emissions in the politically influential agricultural sector (Böttcher et al., 2019; Matthews, 2019). For now, explicit CDR policies are only under preparation by the Commission. Gradually, however, they are being taken up by the Council and the Parliament. These initiatives focus mostly on ecosystem-based methods: In its Circular Economy Action Plan, the Commission announced a regulatory framework for the certification of CDR by 2023. In its Farm to Fork Strategy, the Commission proposed to use money from the Common Agriculture Policy to reward farmers and foresters who sequester carbon. Apart from that, most existing initiatives are linked to research and innovation funding. The EU's Horizon 2020 program funds large CDR research projects and the EU ETS Innovation Fund (€10 billion) is open for applications from CDR and CCS pilot and demonstration plants. Furthermore, the Commission supports new geological storage projects such as Porthos in Rotterdam and Northern Lights politically and financially (see the case study on Norway). Almost all climate legislation is up for re-negotiation in 2021 and 2022 in the context of upgrading the 2030 target. CDR will likely be addressed in these revisions, maybe even in the EU ETS (Rickels et al., 2020).

Expert Bodies and Science

The Commission refers to the IPCC SR1.5 and in-house modeling efforts to justify CDR (European Commission, 2018). This justification is in line with a paradigm in EU climate policy that attaches great importance to evidence-based target setting and policy design (Geden et al., 2018). Concurrently, the EU plays a key role in funding the production and mobilization of climate science, in particular, it played a decisive role in the financing of the integrated assessment modeling community (Lövbrand, 2011; Cointe et al., 2019)—one of the key gateways for the diffusion of the CDR issue on the political agenda (Low and Schäfer, 2020). Although the EU's long-term strategy models net negative CO_2 in the second half of the century (European Commission, 2018) and legislation includes language on the need for it, actual target-setting and other policy initiatives do not address the issue so far; it is almost exclusively addressed by climate scientists.

Developments in CDR Niches

With regard to CDR niches, the involvement of the Commission in CCS projects in the Netherlands and Norway and the funding opportunities for researching and demonstrating CDR under the EU ETS Innovation Fund are the most important developments. In November 2020, three EU Member States (Netherlands, Denmark, and Sweden) together with Norway published a "Non-paper on Carbon Capture and Storage" in which they stress the importance of CCS as well as CO_2 removals to achieve the EU's goal of climate neutrality (Klima- Energi-og Forsyningsudvalget Denmark, 2020). Other niche developments can be best observed at the Member State level (see the case studies on Germany, Ireland, and Sweden).

Germany

Institutional Setting, Actors, and Coalitions

Germany is often perceived as a frontrunner in crafting mitigation policies. Since the late 1990, German policymakers have promoted the "Energiewende" (energy transition) and its main purpose of supporting the expansion of renewable energy sources to reduce CO_2 emissions. At the same time, its climate policy is deeply interwoven with EU policy making (see EU case), occasionally creating tensions between the largest EU Member State and the EU level (Jänicke, 2017). Although German climate policy explicitly refers to the net zero GHG target stemming from Art. 4 of the legally-binding Paris Agreement (German Government, 2016), the issue of CDR to balance residual emissions is not explicitly addressed. This holds also true for the Climate Law adopted in 2019. Neither the balancing of residual emissions nor net-negative emissions beyond 2050 are addressed in the law (Bundesgesetzblatt, 2019).

After the German government decided to follow the EU Commission's proposal to set a net zero GHG emissions target in 2019, the fact that achieving net zero target requires removals, both ecosystem-based and geochemical-based got increasing attention in German climate policy (Prognos, Öko-Institut, Wuppertal-Institut, 2020). In general, however, the issue of CDR is approached with restraint. The Free Democratic Party is the only party in the German parliament calling for a proactive approach to CDR. The political reluctance is linked to the strong political path-dependencies created by the energy transition and the low level of public acceptance of CCS (Dütschke et al., 2016). However, the acknowledgment that residual emissions must be balanced to achieve net zero GHG emissions in 2050 is likely to lead to an intensified CDR debate and incremental modifications of existing climate policy. ENGOs increasingly acknowledge the fact that some carbon removal will be needed, and support for enhancing "natural" sinks is being expressed (Deutscher Naturschutz Ring, 2020). Their position toward integrating geochemical-based CDR remains very skeptical. Their main arguments against the integration are concerns about mitigation obstruction as well as strong rejection of CCS. The German industry has so far not been openly calling for the integration of CDR in future climate policy.

CDR Accounting and Methods

CDR is not yet accounted for in national mitigation targets, neither natural (e.g., enhanced LULUCF sink) nor geochemical-based methods (except for limited flexibilities, see EU case). However, EU Member States including the German government and the EU Commission now support a proposal of changing the accounting methods for climate targets at EU level, incl. the 2030 target, toward a "net" emissions logic. Such a reform would then likely also be implemented in the German climate law.

Policy Instruments

The emerging CDR debate in Germany is shaped by the differentiation between "natural" and "technological" methods. Options linked to CCS in particular are quite contested. In the years before the incremental acknowledgment of the need for CDR to neutralize residual emissions in the context of net zero targets, deliberate CDR was not discussed by political actors but only by climate scientists and usually dismissed as a form of climate engineering. At the national level, no CDR-related policy instruments exist yet. The developments at EU level, however, will shape German climate policy substantially.

Not only because of EU competencies in climate and energy policy, but also because it is easier for German policymakers to elevate a rather controversial issue to Brussels. As the German LULUCF sink is projected to decrease and turn into a source of emissions (Umweltbundesamt, 2020) and the existing EU legislation already requires to adhere to the "no-debit rule" (see EU case), the development of policies that aim for enhancing LULUCF removals are to be expected.

Expert Bodies and Science

In the National Energy and Climate Plan 2030, submitted to the EU in 2020, the German government addresses both "natural" CDR ("plant growth") and "technological" CDR ("direct air capture"). It is being noted that research will be stepped up (Bundesministerium für Wirtschaft und Energie, 2020, p. 61). A research initiative is also announced with regard to the enhancement of the sink function of soils and forests (Bundesministerium für Wirtschaft und Energie, 2020, p. 119). The integration of controversial topics into the political debate through formalized expert bodies and research funding is a common approach in Germany (Jasanoff, 2005). For 2021, the Federal Ministry for Education and Research announced two large research funding lines (Bundesministerium für Bildung und Forschung, 2020a,b).

The debate on CDR entered the policy debate only after the IPCC's SR1.5 in 2018. Policymakers in parliament and public officials in the relevant ministries, however, are still reluctant. Since the adoption of the net zero target, the debate is incrementally shifting and a discussion about funding for researching and developing CDR emerges. So far, CDR measures were almost absent from domestic modeling efforts (Hahn et al., 2020). However, first studies on achieving net zero GHG emissions indicate the need for large-scale geochemical-based CDR (5% of 1990 emissions) (Prognos, Öko-Institut, Wuppertal-Institut, 2020). The issue of net-negative emissions in the second half of the century, however, is only addressed by climate scientists so far.

Developments in CDR Niches

Due to the aforementioned strong path dependencies in German climate policy, the support for CDR niches is rather limited. The new funding lines indicate emerging support for research and development but not for deployment of geochemical-based CDR. An increasing amount of German companies are cooperating with internationally emerging CDR businesses in order to explore possible ways to achieve voluntary climate targets, e.g., Audi/Volkswagen with ClimeWorks in Iceland (VW, 2020). The decreasing LULUCF sink and existing regulatory obligations might put pressure on German climate policy regime and could accelerate the support for niches.

Ireland

Institutional Setting, Actors, and Coalitions

Ireland expresses consistent aspirational support for effective climate policies, but following the financial crisis of 2008 it generally prioritized economic recovery. Within the EU's multi-level processes Ireland has played a generally constructive role but resisting high ambition, and maximizing so-called "flexibilities." The role of GHG sinks, and specifically forestry-based sinks, has been part of Irish policy since the adoption of the Kyoto protocol. Ireland's compliance with its (relatively modest) obligations under the first commitment period of the protocol relied on including accounting for forestry sinks. However, the overall Irish LULUCF sector continues to be a net GHG source rather than sink. The government that took office in 2020 tabled a draft for new national climate action legislation, including a statutory net zero objective for 2050, explicitly defined as a balance between GHG emissions and removals (Irish Government, 2020).

Since 2016, after IPCC's AR5 and the adoption of the Paris Agreement, there is active discussion of net removals among a small number of scientific experts, agencies, and relevant government departments but not apparently extending to senior ministerial level. Among these, views are very preliminary, but there is some rough consensus on the need for strengthening national policy capacity and understanding. To date, geochemical-based CDR has played virtually no role in public discourse. Among NGO actors, CDR is largely viewed with suspicion and assumed to be a device for mitigation obstruction. There is active consideration by industry actors in the agriculture and forestry sectors, focused on potential "credits" (financial or otherwise) to be gained by accounting of gross removals. The influential Irish agri-food sector strongly promotes the potential role of land use removals.

CDR Accounting and Methods

Current national policy ring-fences any removals attributable to forestry as implicitly contributing to a 2050 approach to GHG neutrality *within* the agriculture, forestry, and other land use (AFOLU) sector, separate from all other sectors. The new legislation would, if enacted, supersede this by establishing an integrated *economy-wide* GHG neutral by 2050 target. Afforestation is incentivised, but Ireland is characterized by low existing forest cover and afforestation rates have consistently fallen short of targets. Relatively maximal flexibility for LULUCF removals was also sought under the EU Effort Sharing Regulation (ESR) for 2021–2030 (see EU case). There is a separation between discussion of forestry and soil carbon sequestration as against geochemical-based approaches, partly due to relative familiarity and deployment maturity, and because the agriculture sector views the former as tacitly balancing N_2O and CH_4 under the EU ESR. Bioenergy policy should cut across this: but current bioenergy development is still assessed in terms of *unabated use* in direct fossil fuel substitution, rather than potential combination with CCS for CDR (BECCS). There is some ongoing exploration of CCS deployment for fossil fuel emissions abatement, but not CDR.

Policy Instruments

So far, no explicit CDR policy exists, except for incentivising private forestry development. But this policy is generally perceived as primarily about promoting forestry as an economic sector rather than climate mitigation. The proposed climate bill refers to a need for policy flexibility "to take advantage of opportunities … to accelerate the removal of greenhouse gases" (Irish Government, 2020, p. 9). It also proposes the adoption of a rolling programme of 5-year cumulative GHG budgets, though the draft is equivocal as to whether these would be net, or separated into gross emission and removal components. Perhaps more significantly, it makes provision for potential allocation of funding for "projects that seek to increase the removal of greenhouse gas, *particularly nature based solutions that enhance biodiversity*" (emphasis added, Irish Government, 2020, p. 51).

Expert Bodies and Science

In light of AR5 and the Paris Agreement, the Irish Environmental Protection Agency sponsored a research project to provide a preliminary assessment of the overall potential for negative emissions technologies in Ireland (McMullin et al., 2020). From 2017 onwards, reports of the national Climate Change Advisory Council (CCAC) have started arguing more clearly and explicitly for enhancement of forestry specifically as mitigation. The most recent CCAC annual report (Climate Change Advisory Council, 2020) contained, for the first time, a full section introducing and reviewing the potential role of CDR in Irish climate action. IPCC's SR1.5 has contributed to the expert discussion. Especially to the most recent documents and reports from the Irish Climate Change Advisory Council. Since then, net zero by 2050 has acquired a sort of totemic usage. Domestic academic analysis is starting to incorporate the finite cumulative GHG budget framing, including downscaling to the national level (based on explicit interpretations of prudence and equity) and this in turn is strengthening consideration of CDR (Glynn et al., 2018; McMullin et al., 2019; McMullin and Price, 2020). The fact that IPCC scenarios assume large scale global net-negative emissions (post 2050) has so far received only marginal political attention. A CCAC communication to Government on the subject of setting national carbon budgets noted that any overshoot or exceedance "will have to be recovered with negative emissions" (Climate Change Advisory Council, 2019, p. 2). It is unclear if this message is yet seriously percolating into national policy thinking, and is not an aspect of wider public discourse. But local NGOs are beginning to raise the issue, particularly in the context of global and intergenerational climate justice.

Developments in CDR Niches

In general, a perception of Ireland as a technology taker rather than innovator in heavy industry sectors prevails in Irish climate policy. From a general industry point of view, interest will remain very limited unless there are plausibly profitably CDR business models. The governmental support for developing or deploying niche CDR methods is therefore rather limited. The new climate bill, however, might change this perspective.

Sweden

Institutional Setting, Actors, and Coalitions

Sweden has pioneered climate policy development since the 1980s. Around the mid-1980s, it adopted several policies targeting energy efficiency and, by the early 1990s, became one of the first countries to instigate a carbon tax. Today, Swedish climate policy is highly interwoven with EU policies and Sweden is traditionally one of the EU Member States with the highest climate ambitions. Although the Swedish political debate on CDR is old and tied to forestry, it intensified after the adoption of the Paris Agreement and following a broad Parliamentary approval of the Swedish climate law in 2017 (Government of Sweden, 2017). The climate law was preceded by intense debate among researchers, NGOs, and politicians on the appropriateness of planning for BECCS to contribute to long-term climate targets. While the Swedish BECCS potential is high, planning for BECCS, it was argued, could lead to near-term mitigation obstruction followed by inability to meet the long-term target if BECCS did not deliver. Policymakers agreed on a compromise, with separate targets for emission reductions and so-called supplementary measures.

CDR Accounting and Methods

The separated target structure established by the Swedish climate law distinguishes between emissions reductions (at least −85% compared to 1990 levels) and supplementary measures (maximum 15%), i.e., CDR through targeting additional enhancement of LULUCF sinks and BECCS (Government of Sweden, 2016) as well as international offsetting. Supplementary measures have mostly been justified as a means to provide flexibility to the milestone targets and to balance hard-to-mitigate residual emissions in 2045. While all Swedish climate policy is anchored in the climate law and framework, CDR-related policies are largely done separately.

Policy Instruments

In 2020, a government committee proposed a strategy to realize the supplementary measures (Government of Sweden, 2020). Although international offsetting was forwarded as one alternative, the committee suggested to minimizing offsetting and to instead focus on BECCS and enhanced LULUCF. The over 50 actions proposed by the strategy include state-led reverse auctions for BECCS, improved coordination, increased funding to afforestation, agroforestry, rewetting of drained peatlands, and to push for an EU-wide BECCS policy and improved monitoring and reporting rules. The proposed strategy has received substantial backing by Swedish industry and civil society. Some politicians have indicated resistance to subsidized BECCS, including representatives of the Green Party, while others have largely reacted with silence. In January 2021, the Swedish Government tasked the Swedish Energy Agency to design a support scheme for BECCS to be implemented in 2022 either as a reverse auction or as a flat subsidy (Government of Sweden, 2021). Forest and energy companies are requesting policy-induced economic incentives to deploy BECCS and are also generally of the opinion that biomass may contribute to decarbonization and negative emissions in many other ways (Rodriguez et al., 2020). Several NGOs have criticized the strategy for not capitalizing fully on the potential of enhanced "natural" carbon sinks.

While forest-based CDR has long been discussed, LULUCF sinks are not foreseen as the main CDR method; LULUCF sources and sinks are reported but unaccounted toward the climate targets. Taking the LULUCF sink into full account would enable net zero emissions soon after the mid-2020s, provided that fossil emissions continue to decline. The proposal is to only account for additional LULUCF removals that are a direct effect of new supplementary measures policy and that are not necessary to meet the no-debit target in the EU LULUCF Regulation (Government of Sweden, 2016, 2020). In addition to initiatives in the context of the climate law, policy measures for LULUCF sinks exist, a few existing policy measures also target BECCS and biochar. These instruments include the Industrial Leap Scheme Industriklivet, an investment fund with a specific appropriation for BECCS RDD&D, and the Climate Leap Program Klimatklivet and the Rural Development Programme that supports biochar market introduction. Regulatory clarity on CO_2 transport and storage is also in force, in response to EU regulation (Government of Sweden, 2014).

Expert Bodies and Science

When the debate on fossil CCS intensified in the late 1990s, Swedish researchers started exploring BECCS as a source of negative emissions (Obersteiner et al., 2001; Möllersten, 2002) and to expand the technology portfolios of integrated assessment models (Azar et al., 2001). At the time of the approval of SR1.5, the Swedish climate law had already been passed in Parliament. By then, the Swedish debate had matured to take note of the high uncertainties related to BECCS but also to distinguish between the large trade-offs associated with the widespread BECCS deployment assumed in many global scenarios and the more limited but less problem-struck domestic potential for BECCS (Fridahl, 2018). In the process of designing the separated targets, domestic modeling played an important role. It was used both to arrive at the total target quantity for supplementary measures in 2045, and to argue for bringing the target forward from 2050 to 2045. The Swedish potential for net-negative emissions in the second half of the century is also discussed in expert circles and established as a climate objective yet in unspecified qualitative terms (to achieve net-negative emissions after 2045).

Developments in CDR Niches

Due to strong governmental support for research, development, and deployment, BECCS is developing quite fast. Most prominently, Stockholm Exergi, an energy utility, pledges to become "climate positive" (i.e., net-negative) by 2025, relying on its own production of biochar and BECCS deployment to deliver on its pledge. About 10 other companies are also planning to implement BECCS between 2025 and 2030.

Norway

Institutional Setting, Actors, and Coalitions

Norway's climate target is to reduce GHG emissions by 50–55% by 2030 compared to 1990 but does not have a specific net zero target. By 2050 the ambition is to reduce GHG emissions by 90–95%. The industry and energy sectors are fully integrated in the EU ETS, whereas other policy instruments are directed at the transportation, agriculture, buildings, and waste sectors. According to the EU's LULUCF regulation, which Norway is associated with, the no-debit rule applies to LULUCF by 2030 (see EU case). The CDR story in Norway is short, and there is not much public debate about CDR. However, the CCS story is longer—stretching back to the 80s in terms of research and mid-90 in terms of the first industrial application. CCS is not a CDR approach on its own but needed for BECCS and DACCS. CCS entered the public debate in the early 1990s, and gained traction from 1996 onwards after CO_2 was separated from natural gas at the Sleipner platform to make the gas commercial and geologically stored. The subsequent debate on CCS in Norway was associated with power production from natural gas. CCS became a compromise between industrial development based on natural gas and climate policy. Full-chain CDR operations, foremost biomass use combined with CO_2 capture in industry and biochar, have only been on the debate agenda for the last decade, catalyzed by IPCC's SR1.5 from 2018.

The interest in industry-based CCS has picked up in the last years, foremost in some energy-intensive industries, to capture fossil- and process-related CO_2 emissions, or to produce hydrogen from natural gas combined with CCS. These industries also have plans to replace some of the fossil inputs with biogenic materials, which would establish a CDR chain. One example is the planned carbon capture operation at the waste incineration plant of Fortum Oslo Varme AS. However, so far little attention has been given to specialized BECCS. The agricultural sector has taken some interest in biochar and established a network (Norsk Biokullnettverk, 2020). Technology focused environmental NGOs accept geochemical-based CDR, whereas the nature conservation focused NGOs favor ecosystem-based CDR. Industry groupings and agriculture see themselves as stakeholders in CDR, but still expect significant public facilitation in terms of public funding and an improved policy framework.

CDR Accounting and Methods

Norway has had a net CO_2 sink through forest growth for decades but has been cautious to include this in the national GHG accounting, with a view to the country's position on sinks in international climate policy negotiations. In the case of BECCS, waste incineration, and biogenic inputs for industry with CCS, removals can be accounted for if these can be subtracted from emissions of CO_2 and other GHG. There is a challenge with CDR in industry due to the EU ETS, however, since biomass is included in the baseline (i.e., assumed to be CO_2-neutral) and biomass-based entities are excluded from the trading system.

Policy Instruments

Explicit CDR policies are currently almost absent from Norwegian climate regulation. So far government financial support for R&D has been the major policy instrument for CCS and CDR development. Since Norway is fully linked to the EU ETS, CDR-related funding from the EU's Innovation fund (see EU case) will also provide some CDR incentives in Norway. As part of a broader debate, one proposal is to establish a specific fund to catalyze CCS and CDR deployment in industries. Regarding forestry, in 2016 a scheme for enhanced carbon fixation in forests was introduced, with economic support for forest fertilization, denser tree planting, and development of improved tree species. Aside from managing the net CO_2 sink of forests, there will not be much development on other CDR methods.

The Northern Lights project, a CCS project to transport and sequester CO_2 from Norway and other countries, is a key initiative. This project is part of emerging international full-CDR chains and potentially a component of future CDR business cases in Norway and beyond.

Expert Bodies and Science

The first actors to push both CCS and CDR into the policy debate were scientific experts and some NGOs. Aside from an earlier start in the scientific community, the public attention and debate first picked up after recent IPCC reports. In Norway, this awakening has merged with the longer-term understanding of the need and potential for CCS to reduce GHG emissions, and Norway being in a promising position to facilitate the required technology development, not the least regarding storage of CO_2.

Developments in CDR Niches

In Norway, several CDR-related CCS projects are emerging, financed by the government as well as possibly by the EU's Innovation Fund. In September 2020, the government launched the project Langskip, announcing that a full-scale CCS facility at Norcem Heidelberg Cement, Brevik, will receive close to full government funding. Furthermore, a full-scale CCS facility at the Fortum Oslo Varme AS waste incineration plant will receive almost 50% government funding, contingent on remaining funding from own and other sources. Parts of these processes can be regarded as CDR. The Northern Lights initiative is the third component, in which an infrastructure for transportation and storage of CO_2 under the North Sea seabed is developed, supported by Equinor, Shell, Total, and the Norwegian government. Companies from other European countries are invited to join. So far, companies from Norway, the UK, the US, Ireland, Sweden, Belgium, France, and Germany, have expressed an interest. More generally, there is wide-spread industrial interest in Norway to reduce industry-related CO_2 emissions through installing CCS facilities and using biogenic resources.

United Kingdom

Institutional Setting, Actors, and Coalitions

Before submitting its first NDC in 2020, the UK had made its commitments under the UNFCCC as part of the EU. The UK has had comprehensive emission targets set by domestic legislation since 2008, however, and withdrawal from the EU does not appear to have changed its overall positioning as an international leader. The legislation of the 2050 target for a UK GHG reduction of at least 100% (i.e., net zero) (UK Government, 2019) has raised the profile of the debate around CDR, in the UK often referred to as Greenhouse Gas Removal (GGR) to keep open the possibility of non-CO_2 approaches. CDR entered the national political debate with the publication of the 2016 report "UK Climate Action following the Paris Agreement" by the Committee on Climate Change (CCC) (Committee on Climate Change, 2016). Before that, CDR was not explicitly addressed as a topic but several initiatives indicated implicit CDR policy. Reforestation was a policy topic in the UK early on after a history of heavy deforestation. The UK had integrated carbon storage as a goal of forestry by 1994 and committed to create more woodland in the context of climate targets in 2009 (Raum and Potter, 2015). Increased tree planting became a high-profile campaign issue during the 2019 election, with the environment, and carbon in particular, highlighted as a key motivation.

Recently, some businesses and industries have promoted geochemical-based CDR. Perhaps the most notable (in terms of potential scale) is Drax, the UK's largest thermal power station, which is trialing carbon capture on its biomass-fired units with the aim of becoming a BECCS facility. Other, smaller-scale CDR start-ups are also emerging. Conclusions from the UK Citizens' Assembly on Climate Change suggest a majority of the public prefers ecosystem-based approaches to geochemical approaches. There is however some support for research into "engineered" CDR. Common concerns include CO_2 leaks from storage and that CDR fails to address the root cause of the problem (Climate Assembly UK, 2020). Other UK surveys confirm this, and suggest publics may not accept removal unless accompanied by ambitious near-term emission reductions (Cox et al., 2020). The position of UK ENGOs on CDR is rather mixed. Mitigation deterrence is a concern, although at least some consider a need for geochemical CDR alongside widespread emissions cuts (Friends of the Earth, 2018).

CDR Accounting and Methods

In UK mitigation targets, emissions and removals are treated equally in accounting and LULUCF sources and sinks are included (UK Government, 2019). The legislation only mentions the LULUCF sector in reference to removals which can be accounted for in targets. This implies that any CDR reported outside the LULUCF sector (e.g., BECCS, DACCS) would not be included, however, an adjustment to the legislation would at least in principle be simple.

Policy Instruments

The most developed area of policy relating to CDR in the UK is for forestry. A framework for monitoring, reporting, and verification (MRV) of voluntary actions to increase carbon in forests has been developed as the Woodland Carbon Code. Incentives exist in the form of grants and, more recently, the Woodland Carbon Guarantee which provides long-term prices for carbon credits. Several policies are in place to reduce the wider negative impacts of these policies (UK Government, 2018).

Despite previous failed attempts to initiate CCS in the UK, the government intends to deploy CCS at scale by the mid-2020s. It has announced a CCS Infrastructure Fund of £1 billion to build four clusters by 2030 (UK Government, 2020b). Support has been given to several innovation projects, FEED studies and strategy documents, and a consultation carried out on business models to support different CCS applications, including BECCS. The government has also announced it will invest £640 million in tree planting and peatland restoration (i.e., enhanced soil carbon) in England (UK Government, 2020a), is studying policy options to incentivise a range of CDR methods (Vivid Economics, 2019) and has noted its openness to considering future inclusion in carbon pricing mechanisms. Up to £100 m support for innovation in CDR has been announced (UK Government, 2020a).

Expert Bodies and Science

The UK's approach is guided substantially by the CCC. Its advice emphasizes independent expertise and scenario building, with the overall timing and scope of domestic action guided by global pathways necessary to meet the Paris Agreement, taken primarily from the IPCC's SR1.5 (Committee on Climate Change, 2019). The CCC is now analyzing CDR as a sector alongside other more traditional sectors such as power and transport, and has offered a package of policy recommendations (Committee on Climate Change, 2020). The wider academic climate research community has also been a key player in the debate. The UK research councils have already funded one programme of CDR research and are commissioning a new programme of demonstration. A report on CDR was published by the Royal Society and Royal Academy of Engineering in 2018 (Royal Society Royal Academy of Engineering, 2018).

Developments in CDR Niches

In the UK, CDR niches are supported proactively by the government. The substantial amounts of funding for research, demonstrating, and deployments indicate that the UK intends to develop into a frontrunner and a technology-provider in the context of CDR. The government has stated "we want the UK's entrepreneurs, universities and engineering industries to be well-placed to exploit the advantages of global demand for these new technologies" (UK Government, 2017, p. 57). Companies, including established businesses and start-ups, are exploring CDR.

Australia

Institutional Setting, Actors, and Coalitions

Climate policy in Australia is a contested policy field, shaped by high vulnerabilities to the impacts of climate change on the one hand and politically influential fossil fuel interests on the other. Australia has a weak pledge for emissions reduction to the Paris climate agreement (Den Elzen et al., 2019), with a commitment to 26–28% reduction on 2005 levels by 2030, though eschewing any formal commitment to a net zero target. The federal-level reticence around climate targets is contrasted sharply by all Australian states and territories, which have adopted net zero by 2050 (or sooner) targets (Climate Council, 2020). The issue of CDR has been implicitly present in Australia's climate policy for some time. After the publication of the King Review, the Australian Government released its first Statement on the Technology Investment Roadmap (Department of Industry, Science, Energy and Resources, Australia, 2020c) in which CDR was acknowledged. The statement outlines prioritized technologies, notably including carbon capture and storage (CCS) (plus compression, transport, etc.) explicitly justified by the pursuit of negative emissions. The Statement also includes prioritization of soil carbon, a watching brief on direct air capture (DAC), and carbon capture and use (CCU) as an emerging technology. NGOs and private sector actors have not engaged substantively with CDR in public discourse (outside of the high-profile debates about CCS). The changes in 2020 sit atop a legacy of deeply contested climate policy in Australia (Crowley, 2017); a legacy which offers important context for CDR (Colvin et al., 2020) and highlights the implicit governance of some CDR approaches in Australia.

CDR Accounting and Methods

In the National Greenhouse Gas Inventory, emissions and removals by sector including LULUCF, are aggregated to provide a net-total for the country. Ecosystem-based CDR methods are already an implicit part of the policy mix in Australia and regarded as fungible with conventional mitigation. In recent years, LULUCF contributed net-removals to Australia's total emissions (Department of Industry, Science, Energy and Resources, Australia, 2020b). The centrality of technical methods, particularly CCS, to the 2020 Statement further complicates how CDR has entered Australia's climate policy discourse. CCS in Australia has been a critical technology underpinning "clean coal" rhetoric, which was first advanced in the 1990s and considered a delaying tactic for meaningful emissions reduction (Marshall, 2016). Therefore, the promotion of CCS in 2020 initiative raises the potential that CDR will be perceived or used as the latest iteration of emissions reduction delay.

Policy Instruments

The Climate Solutions/Emissions Reduction Fund (ERF) is Australia's primary climate policy instrument. This economy wide abatement subsidy scheme was introduced in 2014, and uses reverse auctions to "purchase carbon abatement at the lowest per-unit cost" (Evans, 2018, p. 39). Under the ERF, CDR has arguably been enacted in Australia via ecosystem-based approaches such as soil carbon sequestration, tree planting, and improved grazing practices (Department of Industry, Science, Energy and Resources, Australia, 2020a). In Australia's climate policy discourse, many consider the ERF to be a suboptimal policy option (Burke, 2016). It was part of the "Direct Action" approach, implemented following repeal of Australia's short-lived carbon price. This "implementation and reversal" period of climate policy (Chan, 2018, p. 302) was marked by negative and divisive politics and well-financed and influential fossil fuel industry campaigning (McKnight and Hobbs, 2018). The consequence is that the divisive politics, the contested Direct Action approach, and the forgone carbon price have fostered an *industry-first, climate-later* view of the political intent of the ERF.

The government response to the King Review noted that efforts to develop methods for including CCS & CCUS under the ERF are in development (Australian Government, 2020). Due to the fact that the ERF already includes carbon removal practices, the regulatory effort to include geochemical-based CDR would be comparatively low. Approaches under the ERF that may be considered CDR have been positioned in the context of emissions reductions (and now, climate solutions), rather than explicitly as CDR.

Expert Bodies and Science

The scientific community is increasingly engaging with the issue of CDR (Australian Academy of Science, 2018; Dunne, 2018) and an expert panel appointed by the government provided the King Review (Carbon Abatement Panel, 2020), which noted the IPCC and IEA regard negative emissions technologies as significant for the Paris Agreement goals.

Developments in CDR Niches

Australia has an established sector focused on ecosystem-based CDR ("carbon farming") that has been engaging with the ERF and voluntary markets (Evans, 2018). With regard to geochemical-based CDR there are few early movers. Notably, Mineral Carbonation International is an emerging Australian company, and the key entity of CO_2 Value Australia, a peak body representing the nascent carbon utilization sector. The decision to expand the scope for investment beyond renewable energy to include low, zero, and negative emissions technologies of the government agencies Climate Change Authority, Australian Renewable Energy Agency and the Clean Energy Finance Corporation may provide support for niche development. Cooperation by research, industry, and the government may guide the future development of CDR via the ERF and Technology Investment Roadmap toward a productive policy environment in which CDR is not in effect nor perception a 2020+ iteration of "clean coal" emissions reduction delay. CDR as a climate-industry win-win may promote repair of destructive climate politics and inadequate climate policy, and governance via the existing ERF mechanism may accelerate implementation.

New Zealand

Institutional Setting, Actors, and Coalitions

Climate policy in New Zealand to date has been shaped by a strong focus on a price-based, least cost approach to mitigation, combined with the significant economic role of the primary (land-use) sector with high emissions from agriculture and removals from afforestation. CDR from afforestation has been integral to New Zealand's conceptualization of climate change targets and policy from the early 1990s, recognizing that gross CO_2 emissions were projected to increase, but an increasing forest sink would partly compensate for this growth. New Zealand strongly argued for inclusion of carbon sinks in the design of the Kyoto Protocol and the formulation of gross-net emission targets. The domestic debate remained during the late 1990s and early 2000s about the most appropriate incentives for enhancing forest sinks.

Afforestation remains a significant element of New Zealand's approach to meeting its NDC and 2050 emission targets as it provides a comparatively cheap and significant carbon sink[7]. Despite initial concerns in the 1990s, the forestry industry is broadly supportive of plantation forests receiving units that can be traded in the emissions trading scheme (ETS). However, different groups in NZ are increasingly expressing concern. Rural community groups are concerned about the potential loss of employment, population and associated effects on the community and services if widespread afforestation occurs at the expense of sheep and extensive beef farms (Harrison and Bruce, 2019). Some rural advocates regard the significant reliance on afforestation as evidence of a rural/urban split, i.e., urban elites evading the need to reduce their own (gross) emissions by relying on carbon sequestration occurring on the backs of rural communities. Environmental NGOs are primarily concerned that excessive reliance on CDR may lead to mitigation obstruction, along with risks to the permanence of forest sinks. Other concerns relate to the dominance of an introduced tree species (*Pinus radiata*) and only limited support for biodiversity goals that could be derived from slower growing native forests.

CDR Accounting and Methods

CO_2 removals are treated as fully equivalent to CO_2 abatement, not only in how they are defined and used to account for emission targets but also in terms of policy settings. It is therefore seen as a perfectly valid and fungible integrated component of the country's overall mitigation strategy. Other types of CDR are not being seriously discussed. There is growing interest in the farming sector to recognize carbon sequestration in soils, but insufficient science to support adoption of this method. There is a notable absence of serious discussion of BECCS, given the potentially suitable land, coupled with very limited biofuel policies compared to EU countries (Wreford et al., 2019). After several abandoned attempts to introduce price based policies, New Zealand introduced an emissions trading scheme in 2008. In this ETS, CO_2 emissions and removals from forestry are treated as fully equivalent to emissions or avoided emissions from gross emitters, to our knowledge the only ETS at national scale to do so. This use of afforestation CDR is consistent with a dominant least-cost principle to climate policy in New Zealand.

Policy Instruments

This primary price-based policy is complemented by a number of additional government programmes, most recently the One Billion Trees programme that seeks to accelerate forest planting for both climate and non-climate benefits such as erosion control and biodiversity through cash grants and technical support. The Billion Trees programme calls for "the right tree in the right place," reflecting concerns regarding widespread tree monocultures creeping across extensive but productive farmland (Ministry for Primary Industries, New Zealand, 2020). Suggestions are also being made to limit the rate of carbon-price driven afforestation by allowing local government to control plantations using existing environmental (non-climate) legislation. A further point of concern, raised mainly by stakeholders from the agriculture sector, is that New Zealand chose relatively restrictive parameters for what land qualifies as forest and hence can be recognized for afforestation, including a minimum area of 1 hectare and a minimum width of 30 m. Work programmes have been initiated to consider options to recognize the carbon being sequestered in smaller-scale plantings on farmland, especially if agricultural non-CO_2 emissions (which

[7]The net zero target covers all gases other than biogenic methane (for NZ, essentially CO_2 and N_2O). For biogenic methane, the government has set a separate reduction target range of −24 to −47% reduction by 2050 based on IPCC SR1.5.

are currently excluded from climate policy) become exposed to emission prices as currently planned by 2025.

Expert Bodies and Science

The integration of CDR into the policy mix has been driven primarily by government officials with support from scientists, in what may be called a technocratic approach to policy development initially (Rimmer, 2016). Policymakers and experts followed the view that "net emissions is what the atmosphere sees." This first-principles lens readily leads to treating carbon removals as fungible with gross emissions. Subsequent scientific criticism of the consequences of this approach (e.g., Parliamentary Comissioner for the Environment, New Zealand, 2019), covering the range of concerns noted above, has not been sufficient to change the overall framework. Impermanence was seen as an insufficient argument against the use of forest sinks, it only indicated the need for policies that provide accountability for subsequent emissions if and when they occurred. The IPCC SR1.5 strongly facilitated the adoption of the net zero target for long-lived gases in New Zealand but did not fundamentally change the CDR policy debate, apart from an increasing recognition of the scale of afforestation and potential for negative side-effects if emissions and removals are priced consistent with that target (Productivity Commission, New Zealand, 2018; Ministry for the Environment, New Zealand, 2019; Parliamentary Comissioner for the Environment, New Zealand, 2019).

Developments in CDR Niches

As afforestation has a well-established and low-cost role in the policy mix, activity in CDR niches is rather low. Industry interest in CCS exists but is strongly linked with enhanced oil recovery and not seen as industry opening up a more general option to pursue geochemical CDR at scale. Claims and interests in CDR via soil carbon are generally seen as speculative for the near and even medium term, but are the focus of increased government funding for research. This is, however, in part a preparation and insurance for future accounting requirements, not necessarily a goal of developing a new CDR option. While there has been some interest, biofuels policy is limited compared to EU countries (Wreford et al., 2019), and BECCS attracts no significant attention in the national debate.

USA

Institutional Setting, Actors, and Coalitions

CDR remains a nascent, yet relatively bipartisan, political issue in the US. National electoral politics in the US, expressed most recently in the 2020 Presidential election, typically focus on the validity of climate change science and modifying the climate policy tools implemented by former-President Barack Obama. Legislatively, most national Democrats (one of two major political parties in the US) are focused on the Trump administration's weakening of environmental regulations, and formation of post-2020 climate policy under a Democratic Biden administration. Early decisions and announcements indicate that CDR will continue to move up the US climate agenda over the coming years. So far, CDR has been discussed in US national politics in two forums: ENGOs, and the Congress.

The US currently has no economy wide emissions target. The new Biden-Harris administration, however, has re-joined the Paris Agreement and will therefore have to provide a new NDC. With regard to a long-term target, the Biden-Harris administration raised expectations toward the adoption of a net zero emissions target in one of the early executive orders (The White House, 2021). The US' first NDC was an economy-wide reduction of GHG emissions by 26–28% below 2005 levels in 2025. CDR played a relatively small role in this NDC, primarily through inclusion of a robust sink of CO_2 in the LULUCF sector. Most US ENGOs, think tanks, trade groups, and philanthropy have been largely supportive of research, development, and deployment of CDR. ENGOs supporting carbon removal have tended to be relatively technology-agnostic, supporting both ecosystem-and geochemical-based methods. A small minority of US ENGOs oppose CDR, primarily "technological" forms of removal such as DACCS. Much of this opposition stems from opposition to CCS as mitigation option for fossil fuel technology. A core area of disagreement between these groups and other ENGOs is whether geochemical-based carbon removal can be a just and progressive form of climate action (Buck, 2019).

CDR Accounting and Methods

In its first NDC, the US intended to include all categories of emissions by sources and removals by sinks, to account for the LULUCF sector using a net-net approach, and to use a "production approach" to account for harvested wood products consistent with IPCC guidance. Arguments for carbon removal in the US tend to embrace the essential role of carbon removal in achieving climate change goals, technology innovation, sustainable agriculture, and job creation (Energy Futures Initiative, 2019; Friedmann, 2019). These innovation-centric framings span both ecosystem- and geochemical-based CDR methods (Larsen et al., 2019). Relatively few actors promoting CDR have adapted framings around equity and justice, despite its prominence in current US climate policy debates.

Policy Instruments

CDR has featured prominently in modest climate policy passed between 2016 and 2020. One prominent example of bipartisan legislation is the Agriculture Improvement Act, known commonly as the 2018 Farm Bill. This omnibus bill provides roughly half a trillion dollars in funding for various USDA functions over a period of 5 years through crop insurance, conservation payments, and loan support (Congressional Research Service, 2018). In a departure from historical precedent, the 2018 Farm Bill establishes a variety of new research programs, funding opportunities, and task forces to aid the development and deployment of a wide range of CDR methods. CDR provisions fall into four main titles: (1) Conservation, (2) Research, Extension, and Related Matters, (3) Forestry, and (4) Energy. Within these new provisions, the 2018 Farm Bill supports and incentivizes research on ecosystem-based (soils, forestry, and grazing management), hybrid (bioenergy and biogas/renewable natural gas), and geochemical-based (carbon utilization) CDR methods (Jacobson and Sanchez, 2019).

Not explicitly introduced as CDR policy, but relevant for geochemical-based or hybrid methods is the 45Q tax credit for sequestration of qualified carbon oxides, adopted in 2009. The tax credit is available for 12 years to projects. Several dozen US CCS projects have been announced in part because of the enhanced 45Q tax credit (Clean Air Task Force, 2020), and CDR projects are expected to calculate with the tax credited.

Finally, the Energy Act of 2020, a bipartisan renewable energy bill passed at the end of 2020, contains several provisions to promote CDR. These include establishment of an interagency CDR research program, a prize competition for direct air capture, and allocation of funds for carbon removal, carbon utilization, and carbon sequestration projects. The bill was adopted by bipartisan majorities in both houses of Congress.

Policy instruments to promote CDR have emerged in recent Congressional legislation. These instruments are primarily allocations and appropriations for research and development, and demonstration. Others make small modifications to existing regulations to promote CDR. Such proposals often enjoy bipartisan support in the US, particularly in the Senate. CDR proposals were also included in the platforms of numerous Democrats vying for their party's Presidential nomination in 2020. The platforms prominently emphasized ecosystem-based CDR approaches such as regenerative agriculture. The new administration is expected to follow-up on these and develop new CDR initiatives.

Expert Bodies and Science

Due to the negative view of the past administration of multilateral fora and scientific expertise on climate change, the IPCC SR1.5 did not play an important role in US climate policy. But the scientific community as well as experts from think tanks and ENGOs are increasingly engaged in CDR debates. As discussed above, most ENGOs in the US have been largely supportive of research, development, and deployment of CDR and contribute to the CDR debate. Prominent themes emphasized include the necessity of CDR in climate action, economic opportunity, and innovation.

Developments in CDR Niches

Specific deployment opportunities for CDR in the US are still emerging. Nevertheless, deployment prospects are strong due to the US' particular strength in science and engineering, as well as suitable geography for demonstration and early deployment (Sanchez et al., 2018). State level technology and policy opportunities are beginning to materialize at the State and regional scale. Furthermore, start-ups are emerging and prominent technology companies, such as Microsoft and Apple, have made commitments to support and invest in CDR; developments that are likely to be accelerated by the more prominent role for CDR in the new administration.

SYNTHESIS

The case studies show the multiplicity and varieties of ways CDR is beginning to be, or already is, part of existing climate policy mixes. Even in these countries—which were selected because they already address the CDR in some form—considerable differences in the pace and forms of acknowledging and governing CDR are observed. While CDR policy has already been adopted in some cases for quite some time, in others it is currently being shaped by political positioning of different actors. In order to identify differences and patterns of CDR policy making, we organize the synthesis along the five dimensions of the analytical framework presented in **Table 1**. Based on these findings, we develop a conceptual typology of the observed varieties and patterns. It is our intention that the contribution of a first attempt of organizing current developments into a conceptual frame will spur work on more fine-grained comparisons and prospects for CDR policy.

Institutional Setting, Actors, and Coalitions

In all nine case studies, climate policy is a well-institutionalized policy domain with clearly-defined actors, political positions and path-dependencies. The countries differ, however, in the ambition and design of emissions reduction targets. They also choose different policy instruments and measures to achieve their commitments. It can be observed that net zero targets—which began to diffuse into domestic climate politics after the macro-political changes of the adoption of the Paris Agreement and the IPCC SR1.5—facilitated or gave new importance to CDR debates. Australia and the US are the only countries in this selection that do not currently (January 2021) have a formally adopted net zero emissions target of some kind at national level.

The existing net zero targets differ substantially in their scope and timing. Whereas most countries address all GHG emissions, New Zealand for example, excludes biogenic methane from its net zero ambition. Questions of target design have a significant impact on the amount of residual emissions that need to be balanced by CDR to achieve net zero (McLaren et al., 2019; Fridahl et al., 2020), and are therefore an important overarching dimension of CDR policies.

Between Highlighting and Kicking off CDR Policies After the Paris Agreement

The developments in Australia, the UK, and New Zealand show that domestic climate policies aiming at deliberately balancing emissions with removals to achieve mitigation targets is not only a post-Paris development. Although pre-Paris CDR policies were not directly framed as a tool to compensate for residual gross emissions, they aimed at incentivising different actors to enhance the LULUCF sink to help achieve mitigation targets at lower costs. In these countries, the Paris Agreement brought new attention to an already existing strand of climate policy. In the other cases, the emergence of CDR policies is closely connected with the macro-political change represented by the Paris Agreement. Here, CDR in the pre-Paris era was, if at all, regulated implicitly. Public policy on explicitly regulating and incentivising additional removals and accounting them toward domestic mitigation targets only kicked off in connection with or in the aftermath of adopting net zero targets.

Business and Industry

The positioning and engagement of business and industry actors reflects the variety of current status and prospects of CDR in each country. In cases where the LULUCF sinks are already routinely counted toward mitigation targets, the forestry and to some extent agriculture sector generally supports the use of ecosystem-based CDR (i.e., New Zealand, the UK, and Australia), as well as existing or new initiatives to reward CDR. In the UK and the US, geochemical-based CDR methods are getting increasing attention by business actors. Also in Sweden and Ireland, the business sector is generally in support of the recent domestic CDR initiatives; some actors are directly involved in exploring business cases and actual deployment. Whereas businesses in Ireland are focused on ecosystem-based methods, Swedish companies are involved in a wider range of CDR approaches. In Norway, the fossil and energy-intensive industries are, supported by the government, engaged in deploying and promoting a CCS infrastructure relevant for durably storing domestic and imported CO_2 that could support a future expansion of geochemical-based CDR. In Germany, the industry is rather reluctant with regard to CDR; early collaborations between industry and CDR companies, however, signal a potential change.

Environmental Non-Governmental Organizations

How ENGOs approach CDR policy also differs significantly and can be conceptualized as a continuum between suspicion and agnosticism. In the EU and its Member States, their position is primarily driven by suspicion that integrating CDR in the climate regime obstructs necessary changes to reduce gross emissions. Although the need for CDR is increasingly accepted and addressed by ENGOs, geochemical-based methods are a particular source of concern. In the US, ENGOs are mostly technology-agnostic, some support geochemical-based CDR proactively. In New Zealand, Norway, and the UK, the picture is rather mixed; whereas some ENGOs are skeptical especially of geochemical-based CDR or approaches that threaten biodiversity, others do acknowledge the need for CDR. In New Zealand, civil society also highlights a rural/urban conflict; rural communities are critical of the idea that they should live with the socio-economic consequences of land-use change to balance on-going emissions caused in cities. In Australia, ENGOs have not engaged substantially nor explicitly on CDR.

CDR Accounting and Methods

The accounting of CDR varies between full equivalence and reluctance to aggregate emissions and removals. In Australia, New Zealand, and the UK, LULUCF removals are regarded as fungible[8] with gross emissions to achieve climate targets. There is currently no cap on the amount of removals that can be used to achieve the domestic targets. This is in contrast to the EU and Norway, where policymakers have so far been rather reluctant to account for large shares of LULUCF sinks toward their mitigation targets. Recent policy initiatives, however, are inducing change. At the Member State level, Sweden has adopted a net zero target with two components: a minimum amount of emissions reductions and maximum amount of CDR in combination with international offsets, so-called supplementary measures. In Ireland, land use sinks were tacitly used to balance emissions from ruminant agriculture, but emerging climate legislation gives new and more explicit importance to removals. Germany has not pursued efforts to integrate removals in their mitigation target, but a net target at EU-level would affect German accounting practices as well.

Differentiating CDR Methods

Different CDR methods attract varying degrees of attention in the analyzed set of countries. While specific definitions and attribution of methods to categories of "natural" and "technological" methods are contingent and in flux, the general distinction shapes the public policy processes and societal debates in all cases. In the UK, Sweden, and Norway geochemical-based methods are proactively addressed, as in Australia and the US though to a more limited extent. In Germany, all methods that include CCS are highly contested in the societal debate. At the EU level, a need for geochemical-based CDR is acknowledged by the European Commission, but the policy initiatives announced so far focus on ecosystem-based CDR. All eight case studies have policy debates or pursue initiatives linked to ecosystem-based CDR in one way or the other, especially afforestation.

The Changing Political Status of Forestry

The comparison across the cases indicates that the role of forestry in climate policy is changing, a change facilitated by integrating CDR into climate policy. The countries differ in the degree to which forestry is accounted toward climate targets. Especially in those countries that aggregate emissions and removals and account for the forest sink in mitigation targets, forestry and its capacity to remove CO_2 is a key component of climate policy. Other countries, like the EU and its Member States, for example, just launched political initiatives for considering the full LULUCF sink in the context of their mitigation targets and thereby give new importance to forestry in climate policy making. In line with recent findings on the history of carbon removal (Carton et al., 2020) and a review of policy tools (vonHedemann et al., 2020) we find that the political status of the LULUCF sink, and forestry in particular, has changed with the emergence of CDR policies, legitimizing the use of LULUCF in some countries while raising questions about the scale and practices of afforestation in others. Future work on CDR policy should therefore analyze the political drivers and implications of these shifts.

Policy Instruments: Between Trading, Rewarding, and R&D

The comparison of CDR-related policy instruments reveals three key groups. The first consists of different policy approaches for mitigation instruments that fully integrate removals. Examples of this are the Australian reverse auction scheme under the

[8]We use the term "fungible" to express that CDR and emissions reduction are interchangeable and mutual substitutes in accounting practices of mitigation targets.

Emissions Reduction Fund, or the emission trading scheme in New Zealand, that treat emissions and removals as fully equivalent. With its separate net zero target, Sweden is a special case: its policies to incentivize and instigate deployment of geochemical-based and ecosystem-based CDR are structurally linked to the overall climate target, but are largely independent from conventional mitigation policies.

A second group of instruments is composed of rewarding schemes to incentivize CDR, which are not directly linked to or integrated with climate policy instruments targeting conventional mitigation. Examples are the Woodland Carbon Guarantee in the UK, or the US 45Q Tax Credit. Incentive structures aiming to enhance the LULUCF sink through afforestation or rewetting of drained peatlands outside emissions pricing policies are also established in New Zealand, Norway, Ireland, and Sweden. In Norway and the UK, the efforts to establish a CCS infrastructure by industry and political actors are increasingly framed as CDR-relevant, although questions of their actual accounting are not yet decided. In general, it can be observed that already existing non-integrated instruments targeting CDR received substantially more attention after the adoption of the Paris Agreement than before. In addition, many new initiatives and policy instruments were proposed and adopted since then.

A third group of policy instruments contains R&D funding initiatives that mostly target geochemical-based CDR approaches. However, as mentioned above, definitions of CDR are in flux—especially in the context of researching new approaches. One major difference across the cases is the degree to which the research funding targets deployment of geochemical-based CDR. In the UK, Sweden, and Australia, research funding targets a wide range of CDR approaches, including funds for demonstration and deployment of the geochemical-based methods. The EU Innovation Fund and Norway's support for CDR-related R&D in the context of CCS infrastructure are pointing in a similar direction. CDR research is also part of a large Farming Bill adopted in 2018 in the US. The US supports and incentivizes research on a broad portfolio of CDR methods. R&D as well as demonstration and deployment funding is expected to increase substantially in the coming years. Similarly, in Germany, the government decided to create two large CDR research funding lines from 2021 onwards—deployment, however, is not a specific objective here.

The Role of Experts and Science

In all case studies, scientific expertise is important for initiating and developing CDR policies. CDR entered the public policy decision making processes through a rather technocratic approach. Scientific experts and specialized policymakers in the administrations have been key actors in pursuing CDR integration. The public debate is—compared to other climate policy related issues—almost non-existent except where it is linked with wider land management practices. The IPCC's SR1.5 and follow-up publications by national science advisory bodies in particular, however, elevated the issue of CDR on the agenda of think tanks, policymakers, NGOs etc.

National modeling studies increasingly address possible compositions of mid-century residual emissions and the amounts and types of CDR required to balance them. The need for at least some countries to achieve domestic net-negative GHG emissions, however—a necessary part of Paris Agreement's global long-term temperature target of well below 2°C while pursuing 1.5°C—is still only addressed by small groups of scientific experts and narrow policy circles. Despite the fact that OECD countries can be argued to have a particular responsibility for achieving net-negative emissions (Robiou Du Pont et al., 2017; Fyson et al., 2020; Pozo et al., 2020), the issue is only rarely and briefly addressed in emerging policy initiatives and could be argued to be actively disabled by a focus on net zero emission targets.

Developments in CDR Niches

Developments in the niches range from very small start-up initiatives with low support to proactive support for large CDR initiatives by industrial actors. Across the case study countries, we observe very different actors engaged in the protective spaces of CDR development. Among them: energy sector companies in the UK and Sweden, fossil fuel, and energy-intensive industries in Norway, and start-ups in Australia, the US and the UK. The niches are protected in various ways and to different degrees: Most prominently, the UK support for innovation exemplifies how a government tries to strategically position itself as a frontrunner and technology-provider. In Norway, the government also proactively supports innovations in CDR-related initiatives, both in terms of developing, but also politically in the form of advocating the EU to support export of CO_2 to Norway. Together with Sweden, where especially innovations in and deployment of BECCS are supported by the government, this group of countries engage in "nurturing" and "empowering" (Smith and Raven, 2012) CDR development and deployment. In the other countries, niche developments are not supported in such a proactive way but are generally limited to incentives or research funding. However, in New Zealand for example, path-dependent reliance on incumbent CDR regimes can actively reduce incentives to invest in the proactive development of additional CDR approaches.

VARIETIES OF INTEGRATING CDR INTO CLIMATE POLICY: TOWARD A TYPOLOGY

The synthesis provided an overview of the varieties of CDR policymaking in the countries. While the peculiarities of individual cases became particularly clear, in a second step we are attempting to identify broader patterns of CDR policy making and develop an analytical typology. In doing so, we follow the MLP of socio-technical transitions, where identifying typologies of transitions is a common tool to conceptualize commonalities and differences across case studies (Smith et al., 2005; Geels and Schot, 2007; Geels et al., 2016). This work is an important reminder of the fact that transitions are not "teleological or deterministic, but continuously enacted by and contested between a variety of actors" (Geels et al., 2016, p. 900). Shifts between different types are of course possible (Geels et al., 2016), for example, if societal power structures and political alliances change (Hess, 2014).

In a first step of conceptualizing our findings, we propose five key dimensions to aggregate varieties of CDR policymaking. Each dimension represents a continuum of manifestations that we identified across the cases (see **Table 2**). It is important to note that these continua are drawn from the synthesis of case studies, and we do not intend for them to represent a definitive nor exhaustive coverage of all possible CDR policy making dynamics. However, we believe these are a useful representation as a first step to carve out differences and commonalities between political approaches toward CDR and therefore a useful step to develop a typology of CDR policymaking that may enable future comparative analysis of other countries and across policy domains and support analysis of change in CDR policy making dynamics over time.

In a second step, we use the five dimensions and continua to build a three-tiered typology on how CDR is currently being addressed and integrated in climate policy regimes. The types are *idealized*; differences are deliberately overstated in order to support analytical clarity[9]. Their main utility is to illustrate divergent possible policy approaches toward CDR that we observed in the case studies. Based on the continua observed in the case studies, we attempt to identify the conceptually most distinctive types of how CDR is approached. In reality, countries might lean to one or the other type, but do not necessarily match all typical characteristics or may represent hybrids. In actual CDR policymaking, boundaries are blurry and overlaps exist. Furthermore, shifts between the different types and developing new types is possible over time; discussions about which direction to follow in CDR policymaking is expected to be politically contested. Identifying these conceptual types is, however, a way of further synthesizing the knowledge gathered through empirical case studies. It may inform future comparative work on CDR policy as well as spur a debate about possible and plausible developments in future CDR policy. These types are not formulated as a finite result. Future work, e.g., on a different set of countries might identify important amendments and additions to this typology.

Table 3 and **Figure 1** provide an overview of the three conceptual types of CDR policymaking; the following sections describe the three types in more detail and give an overview of typical cases and hybrid forms of CDR policy approaches among the cases.

[9]Identifying typologies has a long tradition in social science more generally. For a discussion of methodological merits and criticisms in political science, see e.g., Steinberger (1980), Smith (2002), Elman (2005), Collier et al. (2012).

Incremental Modification: Limited Integration of CDR

The type of incremental modification is shaped by a restrained approach toward integrating CDR into existing climate policy instruments to address the need to balance residual emissions. These incremental steps to integrate CDR are shaped by rather strict separations between emission reductions and removals in the accounting toward mitigation targets. CDR policies and policy instruments linked to conventional mitigation are also strictly separated. Over time, the incremental opening could lead to an advancing integration of removal and reduction instruments.

Incumbent actors do not ignore the need for CDR completely; in particular, macro-political developments toward the new importance of sinks puts pressure on the climate policy regime. In this context, their incremental approach leads to a step by step integration of ecosystem-based CDR approaches. With regard to policy instruments, a cautious opening toward CDR is characteristic for this type, allowing for accounting of a limited amount of ecosystem-based CDR. Regarding geochemical-based CDR, the focus is on RD&D. Support for new CDR methods in small niches and their deployment, however, is limited; research funding is the only support for them.

Early Integration and Fungibility of Emission Reductions and Removals

In this type, CDR is already part of the climate policy regime. Even before macro-political developments such as the Paris Agreement and the diffusion of long-term net zero targets, fungibility of emissions and removals was established. Established policies reflect the assumption that "net emissions is what the atmosphere sees." Since the Paris Agreement, incumbent actors give more attention toward CDR; policymakers and other actors are now exploring options to foster and expand CDR's role in achieving long-term goals.

This type is characterized by the fact that ecosystem-based removals are fully integrated in policy instruments such as emission trading schemes or reverse auctions. Geochemical-based CDR would—from a sheer regulatory point of view—be comparatively easy to integrate, especially because the share of CDR that can be used to achieve climate targets is not limited in this type. Because CDR approaches are already part of a stable

TABLE 2 | Five dimensions of CDR policy making and continua of observed manifestations.

Dimensions	Continua	
CDR in mitigation targets	Fungible	Strictly separated
View of CDR among actors of the incumbent regime	Proactive integration	Restrained integration
CDR methods addressed	Only ecosystem-based	Wide range of methods
Relation of CDR policy instruments to broader climate policy mix	Incremental opening	Full integration
Government support for developing CDR niches	Limited support	Nurturing and empowering

TABLE 3 | Three types of integrating CDR into climate policy.

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

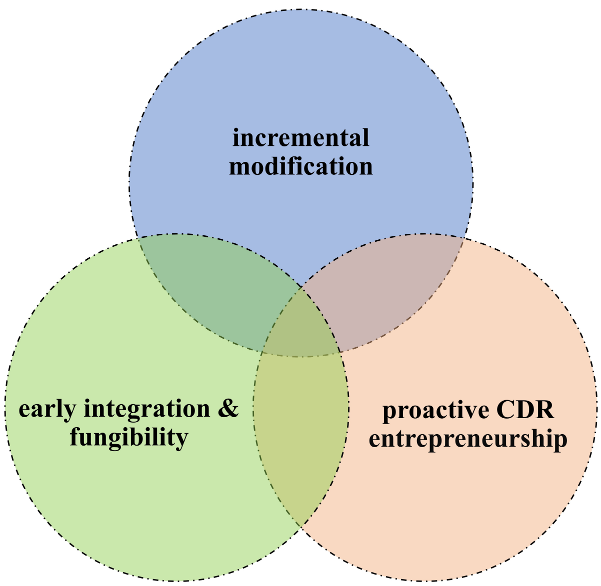

FIGURE 1 | Three types of integrating CDR into climate policy.

climate policy regime and macro-political changes did not put pressure on the regime in countries of this type, developments in niches and their support is not very pronounced.

Proactive CDR Entrepreneurship

The political envisioning of a net zero emissions society is directly linked to the deployment of CDR in the type of proactive CDR policy entrepreneurship[10]. The incumbent actors address the need to integrate and deploy CDR and pursue the reorientation and opening-up of current conventional mitigation climate policies proactively. In comparison to other types, niches of radical geochemical-based CDR innovations are deliberately nurtured and empowered. In general, CDR policy is open to a wide range of CDR methods.

In contrast to the early integration type, CDR-specific policy instruments are being developed (e.g., reverse auction or financial rewarding schemes) which are not fully integrated into conventional mitigation policy instruments. This is not only because of path-dependencies created by existing policy instruments, but also because incumbent actors follow the objective of supporting the CDR development and deployment specifically. Being perceived as a frontrunner in changing macro-political contexts as well as a technology provider through developing and deploying CDR technologies and exploring business cases is one of the political objectives of the incumbent actors in this third idealized type of CDR policymaking.

Typical Cases and Hybrids

If we try to locate our case studies on this spectrum of varieties of CDR policy making, they can be differentiated between typical cases and hybrids. The UK can be described as a typical case for the type of proactive CDR policy entrepreneurship. None of the other countries studied have such explicit policy support for the development and deployment of various CDR measures. To a limited extent, policy entrepreneurship can also be identified in the European Union. However, the initiatives come mainly from within the European Commission; only the coming years will show how the Member States position themselves. Within the EU, Sweden is the country with the most specific and advanced CDR policy and shows policy entrepreneurship. Its regulative approach of separating reductions and removals as well as long-lasting debates on LULUCF removals, however, indicate overlaps to the types of incremental modification as well as early integration and fungibility. In Norway, we observe policy entrepreneurship with regard to CCS, a key component of several geochemical CDR approaches. Initiatives for specific CDR policies, however, are so far limited and emerging only incrementally. The new US administration is expected to establish and develop specific CDR policies in the coming years. With respect to geochemical-based CDR in particular, the US is signaling that it is striving to be perceived and act as a frontrunner.

Australia and New Zealand are typical cases for the early integration and fungibility type. Both integrated CDR into their domestic policy before the recently rising attention toward these measures. In addition, both policy-designs are shaped by fungibility of emissions and removals. Some aspects of this type are also to be found in the case study of Ireland. At the same time, however, we also observe aspects of incremental modification in Ireland. Germany is a typical case for this third type of incremental modification. Although actual integration of CDR into the climate policy mix is almost absent so far, the societal and political debate is increasingly opening toward CDR.

It is important to highlight that this assessment can only be a snapshot. How CDR is approached politically is currently

[10]The term "policy entrepreneur" describes "their willingness to invest their resources—time, energy, reputation, and sometimes money—in the hope of a future return" in public policy making Kingdon (1995, p. 122).

contested and will be subject to political struggles in the future. Future work on comparing CDR policy approaches should therefore not only extend the list of countries but also assess how the countries initially studied for this project are developing. The cases identified as hybrids are of particular interest—an in-depth analysis of the dynamics currently taking place, including the opportunity to reveal emerging new political approaches to CDR, would be an important contribution to the emerging literature on CDR.

CONCLUSIONS

In our analysis of nine empirical case studies we analyzed the varieties of CDR policymaking and provide a snapshot of a rapidly developing policy field. Based on the analytical framework that tries to bridge insights from the multi-level perspective on socio-technical transitions and the emerging literature on CDR policy and governance, we tracked the developments across these cases. The synthesis of this rich empirical material reveals substantial differences as well as commonalities across the cases. In an attempt to conceptualize different patterns of CDR policymaking, we identified five dimensions of CDR policymaking and proposed three idealized types of CDR policy making: (1) incremental modification, (2) early integration and fungibility, and (3) proactive CDR policy entrepreneurship.

It is important to note that boundaries of these idealized types are blurry; in the real-world, specific cases do not necessarily match all characteristics of one type and hybrids exist. In addition, countries can shift between different types over time and new types might emerge. Such an evolution is expected not only because policies and approaches are expected to evolve, but also because CDR policies are contested as political actors struggle for different prospects of governing CDR. These drivers are capable of re-directing current developments in CDR policymaking toward different or entirely new types of CDR policy and governance.

The proposed conceptualization helps to synthesize the knowledge collected through the case studies and illustrates divergent possible approaches. As a conceptual typology, however, it is reductionist and does not cover all dimensions relevant to regulating CDR. Despite these limitations, this initial work on comparing CDR policymaking and conceptualizing different analytical types might spur future, more fine-grained work, including comparing different sets of countries, investigating in-depth single case studies and tracking changes in CDR policymaking over time.

AUTHOR CONTRIBUTIONS

FS conceptualized the research with contributions from OG. FS drafted the manuscript for sections Introduction, Synthesis, Varieties of integrating CDR into climate policy: Toward a typology, and Conclusions. FS, OG, BM, MF, AT, SS, BC, AR, AW, and DS provided the case studies. All authors revised and improved the manuscript.

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REFERENCES

Anderson, K., and Peters, G. P. (2016). The trouble with negative emissions. *Science* 354, 182–183. doi: 10.1126/science.aah4567

Australian Academy of Science (2018). *2018 Negative Emissions Conference: The Big Picture of Negative Emissions*. Available online at: https://www.science.org.au/news-and-events/events/2018-negative-emissions-conference-big-picture-negative-emissions (accessed January 24, 2021).

Australian Government (2020). *Australian Government Response to the Final Report of the Expert Panel Examining Additional Sources of Low-Cost Abatement ('the King Review')*. Available online at: https://www.industry.gov.au/data-and-publications/government-response-to-the-expert-panel-report-examining-additional-sources-of-low-cost-abatement (accessed January 24, 2021).

Aykut, S. C., d'Amico, E., Klenke, J., and Schenuit, F. (2020). *The Accountant, the Animator, and the Admonisher: Global Climate Governance in Transition. Report From the COP25 Climate Summit in Madrid*. CSS Working Paper Series No 1. Hamburg: Center for Sustainable Society Research. doi: 10.25592/css-wp-001

Azar, C., Lindgren, K., and Persson, T. (2001). *Carbon Sequestration From Fossil Fuels and Biomass - Long-Term Potentials. Second Nordic Mini Symposium on Carbon Dioxide Capture and Storage, Gothenburg*. Available online at: http://www.entek.chalmers.se/$\sim$anly/symp/01azar.pdf (accessed January 24, 2021).

Bataille, C. G. F. (2020). Physical and policy pathways to net-zero emissions industry. *WIREs Clim. Change* 11:e633. doi: 10.1002/wcc.633

Beck, S., and Mahony, M. (2018). The politics of anticipation: the IPCC and the negative emissions technologies experience. *Glob. Sustain*. 1:e8. doi: 10.1017/sus.2018.7

Bellamy, R., Fridahl, M., Lezaun, J., Palmer, J., Rodriguez, E., Lefvert, A., et al. (2021). Incentivising bioenergy with carbon capture and storage (BECCS) responsibly: comparing stakeholder policy preferences in the United Kingdom and Sweden. *Environ. Sci. Policy*. 116, 47–55. doi: 10.1016/j.envsci.2020.09.022

Bellamy, R., Lezaun, J., and Palmer, J. (2019). Perceptions of bioenergy with carbon capture and storage in different policy scenarios. *Nat. Com*. 10:743. doi: 10.1038/s41467-019-08592-5

Bellamy, R., and Osaka, S. (2020). Unnatural climate solutions? *Nat. Clim. Chang*. 10, 98–99. doi: 10.1038/s41558-019-0661-z

Böttcher, H., Zell-Ziegler, C., Herold, A., and Siemons, A. (2019). *EU LULUCF Regulation Explained: Summary of Core Provisions and Expected Effects*. Berlin: Öko-Institut. Available online at: https://www.oeko.de/fileadmin/oekodoc/Analysis-of-LULUCF-Regulation.pdf (accessed January 24, 2021).

Buck, H. J. (2016). Rapid scale-up of negative emissions technologies: social barriers and social implications. *Clim. Change* 139, 155–167. doi: 10.1007/s10584-016-1770-6

Buck, H. J. (2019). *After Geoengineering: Climate Tragedy, Repair, and Restoration*. London, Brooklyn, NY: Verso.

Bundesgesetzblatt (2019). *Gesetz zur Einführung eines Bundes-Klimaschutzgesetzes*. Part I Nr. 48, 2513–2521. Available online at: http://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl&jumpTo=bgbl119s2513.pdf (accessed January 24, 2021).

Bundesministerium für Bildung und Forschung (2020a). *Richtlinie zur Förderung von Forschungs- und Entwicklungsvorhaben im Rahmen des Forschungsprogramms der Bundesregierung MARE:N - Küsten-, Meeres- und Polarforschung: Forschungsmission "Marine Kohlenstoffspeicher als Weg zur Dekarbonisierung" der Deutschen Allianz Meeresforschung*. Available online at: https://www.bmbf.de/foerderungen/bekanntmachung-3017.html (accessed January 24, 2021).

Bundesministerium für Bildung und Forschung (2020b). *Richtlinie zur Förderung von Projekten zum Thema "Methoden zur Entnahme von atmosphärischem Kohlendioxid (Carbon Dioxide Removal)"*. Available online at: https://www.bmbf.de/foerderungen/bekanntmachung-3047.html (accessed January 24, 2021).

Bundesministerium für Wirtschaft und Energie (2020). *German Integrated National Energy and Climate Plan.* Available online at: https://ec.europa.eu/energy/sites/ener/files/documents/de_final_necp_main_en.pdf (accessed January 24, 2021).

Burke, P. J. (2016). Undermined by adverse selection: Australia's direct action abatement subsidies. *Econ. Pap*. 35, 216–229. doi: 10.1111/1759-3441.12138

Carbon Abatement Panel (2020). *Report of the Expert Panel Examining Additional Sources of Low Cost Abatement*. Available online at: https://apo.org.au/sites/default/files/resource-files/2020-05/apo-nid305063.pdf (accessed January 24, 2021).

Carson, M., Burns, T., and Calvo, D. (eds.) (2010). *Paradigms in Public Policy: Theory and Practice of Paradigm Shifts in the EU.* Frankfurt a.M.: Peter Lang. doi: 10.3726/978-3-653-01189-0

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *WIREs Clim. Change* 11:e671. doi: 10.1002/wcc.671

Chan, G. (2018). *Rusted Off: Why Country Australia is Fed Up*. Sydney, NSW: Vintage Australia.

Clean Air Task Force (2020). *Potential Carbon Capture Projects Database*. Available online at: https://docs.google.com/spreadsheets/d/115hsADg3ymy3lKBy4PBQRXz_MBknptqlRtlfuv79XV8/edit#gid=1540463113 (accessed January 24, 2021).

Climate Action Network (2018). *Position Paper on Forest and Land Restoration - Natural Ways of Limiting Temperature Rise to Below 1.5°C.* Available online at: http://www.climatenetwork.org/sites/default/files/can_land_and_forest_position_final.pdf (accessed January 24, 2021).

Climate Assembly UK (2020). *The Path to Net Zero*. Available online at: https://www.climateassembly.uk/report/read/final-report.pdf (accessed January 24, 2021).

Climate Change Advisory Council (2019). *Advice on a Suitable Approach for Preparation of Multi-Annual Carbon Budgets to Inform Preparation of Drafting of Legislation*. Available online at: https://www.climatecouncil.ie/media/climatechangeadvisorycouncil/contentassets/publications/Carbon%20Budget%20Background%20paper.pdf (accessed January 24, 2021).

Climate Change Advisory Council (2020). *Annual Review 2020.* Available online at: https://www.climatecouncil.ie/media/climatechangeadvisorycouncil/contentassets/publications/CCAC_AnnualReview2020FINAL.pdf (accessed January 24, 2021).

Climate Council (2020). *What Does Net Zero Emissions Mean*? Available online at: https://www.climatecouncil.org.au/resources/what-does-net-zero-emissions-mean/ (accessed December 6, 2020).

Cointe, B., Cassen, C., and Nadai, A. (2019). Organising policy-relevant knowledge for climate action: integrated assessment modelling, the IPCC, and the emergence of a collective expertise on socioeconomic emission scenarios. *Sci. Technol. Stud*. 32, 36–57. doi: 10.23987/sts.65031

Collier, D., LaPorte, J., and Seawright, J. (2012). Putting typologies to work. *Political. R. Q.* 65, 217–232. doi: 10.1177/1065912912437162

Colvin, R. M., Kemp, L., Talberg, A., De Castella, C., Downie, C., Friel, S., et al. (2020). Learning from the climate change debate to avoid polarisation on negative emissions. *Environ. Commun*. 14, 23–35. doi: 10.1080/17524032.2019.1630463

Committee on Climate Change (2016). *UK Climate Action following the Paris Agreement*. Available online at: https://www.theccc.org.uk/wp-content/uploads/2016/10/UK-climate-action-following-the-Paris-Agreement-Committee-on-Climate-Change-October-2016.pdf (accessed January 24, 2021).

Committee on Climate Change (2019). *Net Zero: The UKs Contribution to Stopping Global Warming*. Available online at: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/ (accessed January 24, 2021).

Committee on Climate Change (2020). *Sixth Carbon Budget Report*. Available online at: https://www.theccc.org.uk/publication/sixth-carbon-budget/ (accessed January 24, 2021).

Congressional Research Service (2018). *Agriculture and Related Agencies: FY2018 Appropriations*. CRS Report, R45128. Available online at: https://fas.org/sgp/crs/misc/R45406.pdf (accessed January 24, 2021).

Cox, E., and Edwards, N. R. (2019). Beyond carbon pricing: policy levers for negative emissions technologies. *Clim. Policy* 19, 1144–1156. doi: 10.1080/14693062.2019.1634509

Cox, E., Spence, E., and Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nat. Clim. Chang.* 10, 744–749. doi: 10.1038/s41558-020-0823-z

Crowley, K. (2017). Up and down with climate politics 2013-2016: the repeal of carbon pricing in Australia. *WIREs Clim. Change* 8:e458. doi: 10.1002/wcc.458

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., et al. (2018). Net-zero emissions energy systems. *Science* 360:eaas9793. doi: 10.1126/science.aas9793

Den Elzen, M., den, Kuramochi, T., Höhne, N., Cantzler, J., Esmeijer, K., Fekete, H., et al. (2019). Are the G20 economies making enough progress to meet their NDC targets? *Energy Policy* 126, 238–250. doi: 10.1016/j.enpol.2018.11.027

Department of Industry, Science, Energy and Resources, Australia (2020a). *Methods for the Emissions Reduction Fund*. Available online at: https://www.industry.gov.au/regulations-and-standards/methods-for-the-emissions-reduction-fund (accessed January 24, 2021).

Department of Industry, Science, Energy and Resources, Australia (2020b). *Quarterly Update of Australia's National Greenhouse Gas Inventory: March 2020*. Available online at: https://www.industry.gov.au/data-and-publications/national-greenhouse-gas-inventory-march-2020 (accessed January 24, 2021).

Department of Industry, Science, Energy and Resources, Australia (2020c). *Technology Investment Roadmap: First Low Emissions Technology Statement*. Available online at: https://www.industry.gov.au/sites/default/files/September%202020/document/first-low-emissions-technology-statement-2020.pdf (accessed January 24, 2021).

Deutscher Naturschutz Ring (2020). *Von Worten zu Taten: Für ein Paris-kompatibles EU-Klimaschutzgesetz*. Available online at: https://www.dnr.de/fileadmin/Positionen/2020-05-05-EU-Klimaschutzgesetz-Verbaendeposition.pdf (accessed January 24, 2021).

Dooley, K., Harrould-Kolieb, E., and Talberg, A. (2020). Carbon-dioxide removal and biodiversity: a threat identification framework. *Glob. Policy*. 1–11. doi: 10.1111/1758-5899.12828

Dunne, D. (2018). *Negative Emissions Scientists Meet in Australia to Discuss Removing CO2 From the Air*. Carbon Brief, 1 Nov. Available online at: https://www.carbonbrief.org/negative-emissions-scientists-meet-in-australia-to-discuss-removing-co2-from-air (accessed January 24, 2021).

Dütschke, E., Wohlfarth, K., Höller, S., Viebahn, P., Schumann, D., and Pietzner, K. (2016). Differences in the public perception of CCS in Germany depending on CO 2 source, transport option and storage location. *Int. J. Greenh. Gas Control* 53, 149–159. doi: 10.1016/j.ijggc.2016.07.043

Elman, C. (2005). Explanatory typologies in qualitative studies of international politics. *Int. Org.* 59, 293–326. doi: 10.1017/S0020818305050101

Energy Futures Initiative (2019). *Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies. Report*. Available online at: https://www.ourenergypolicy.org/resources/clearing-the-air-a-federal-rdd-initiative/ (accessed January 24, 2021).

European Commission (2018). *In-Depth Analysis in Support of the Commission Communication COM(2018) 773. A Clean Planet for all - A European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*. Available online at: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf (accessed January 24, 2021).

Evans, M. C. (2018). Effective incentives for reforestation: lessons from Australia's carbon farming policies. *Curr. Opin. Environ. Sustain*. 32, 38–45. doi: 10.1016/j.cosust.2018.04.002

Fajardy, M., Patrizio, P., Daggash, H. A., and Mac Dowell, N. (2019). Negative emissions: priorities for research and policy design. *Front. Clim*. 1:6. doi: 10.3389/fclim.2019.00006

Fridahl, M. (2017). Socio-political prioritization of bioenergy with carbon capture and storage. *Energy Policy* 104, 89–99. doi: 10.1016/j.enpol.2017.01.050

Fridahl, M. (2018). (ed.). *Bioenergy With Carbon Capture and Storage: From Global Potentials to Domestic Realities*. Brussels: European Liberal Forum.

Fridahl, M., Hansson, A., and Haikola, S. (2020). Towards indicators for a negative emissions climate stabilisation index: problems and prospects. *Climate* 8:75. doi: 10.3390/cli8060075

Friedmann, S. J. (2019). Engineered CO2 removal, climate restoration, and humility. *Front. Clim*. 1:3. doi: 10.3389/fclim.2019.00003

Friends of the Earth (2018). *A Pathway to 'net zero' Greenhouse Gas Emissions*. Briefing. Available online at: https://cdn.friendsoftheearth.uk/sites/default/files/downloads/Pathway-net-zero-greenhouse-gas-emissions-UK.pdf (accessed January 24, 2021).

Fuss, S., Canadell, J. G., Ciais, P., Jackson, R. B., Jones, C. D., Lyngfelt, A., et al. (2020). Moving toward Net-Zero emissions requires new alliances for carbon dioxide removal. *One Earth* 3, 145–149. doi: 10.1016/j.oneear.2020.08.002

Fyson, C. L., Baur, S., Gidden, M., and Schleussner, C. F. (2020). Fair-share carbon dioxide removal increases major emitter responsibility. *Nat. Clim. Chang*. 10, 836–841. doi: 10.1038/s41558-020-0857-2

Geden, O. (2016a). An actionable climate target. *Nat. Geosci*. 9, 340–342. doi: 10.1038/ngeo2699

Geden, O. (2016b). The Paris agreement and the inherent inconsistency of climate policymaking. *WIREs Clim. Change* 7, 790–797. doi: 10.1002/wcc.427

Geden, O., and Schenuit, F. (2020). *Unconventional Mitigation: Carbon Dioxide Removal as a New Approach in EU Climate Policy*. SWP Research Paper 8/2020. Berlin: German Institute for International and Security Affairs.

Geden, O., Scott, V., and Palmer, J. (2018). Integrating carbon dioxide removal into EU climate policy: prospects for a paradigm shift. *WIREs Clim. Change* 9:e521. doi: 10.1002/wcc.521

Geels, F. G., Kern, F., Fuchs, G., Hinderer, N., Kungl, G., Mylan, J., et al. (2016). The enactment of socio-technical transition pathways: a reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990-2014). *Res. Policy* 45, 896–913. doi: 10.1016/j.respol.2016.01.015

Geels, F. G., Turnheim, B., Asquith, M., Kern, F., and Kivimaa, P. (2019). *Sustainability Transitions: Policy and Practice*. Brussels: European Environmental Agency. Available online: https://www.eea.europa.eu/publications/sustainability-transitions-policy-and-practice (accessed January 24, 2021).

Geels, F. W. (2007). Feelings of discontent and the promise of middle range theory for STS. *Sci. Technol. Hum. Values* 32, 627–651. doi: 10.1177/0162243907303597

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: responses to seven criticisms. *Environ. Innov. Soc. Transit*. 1, 24–40. doi: 10.1016/j.eist.2011.02.002

Geels, F. W., and Schot, J. (2007). Typology of sociotechnical transition pathways. *Res. Policy* 36, 399–417. doi: 10.1016/j.respol.2007.01.003

Geels, F. W., Sovacool, B. K., Schwanen, T., and Sorrell, S. (2017). The socio-technical dynamics of low-carbon transitions. *Joule* 1, 463–479. doi: 10.1016/j.joule.2017.09.018

German Government (2016). *Climate Action Plan 2050: Principles and Goals of the German Government's Climate Policy*. Available online at: https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/klimaschutzplan_2050_en_bf.pdf (accessed January 24, 2021).

Glynn, J., Gargiulo, M., Chiodi, A., Deane, P., Rogan, F., and, Ó Gallachóir, B. (2018). Zero carbon energy system pathways for Ireland consistent with the Paris agreement. *Clim. Policy* 19, 30–42. doi: 10.1080/14693062.2018.1464893

Government of Sweden (2014). *Förordning (2014:21) om geologisk lagring av koldioxid [Decree on geological storage of carbon dioxide, including amendments until 2016:1190*]. Stockholm.

Government of Sweden (2016). *En klimat- och luftvårdsstrategi för Sverige, del 1, SOU 2016:47 [A climate and clean air strategy for Sweden, part 1, SOU 2016:47]*. Stockholm.

Government of Sweden (2017). *Klimatlagen, svensk författningssamling 2017:720 [The climate law, swedish statues 2017:720]*. Stockholm.

Government of Sweden (2020). *Vägen till en klimatpositiv framtid, SOU 2020:4 [The pathway to a climate-positive future, SOU 2020:4]*. Stockholm.

Government of Sweden (2021). *Regleringsbrev för budgetåret 2021 avseende Statens energimyndighet, Regeringsbeslut II 18 [Public service agreement for the 2021 budget appropriation concerning the Energy Agency, Government decision II 18]*. Stockholm.

Hahn, A., Szarka, N., and Thrän, D. (2020). German energy and decarbonization scenarios: "Blind Spots" with respect to biomass-based carbon removal options. *Front. Energy Res*. 8, 1–15. doi: 10.3389/fenrg.2020.00130

Haikola, S., Hansson, A., and Fridahl, M. (2019). Map-makers and navigators of politicised terrain: expert understandings of epistemological uncertainty in integrated assessment modelling of bioenergy with carbon capture and storage. *Futures* 114:102472. doi: 10.1016/j.futures.2019.102472

Harrison, E., and Bruce, H. (2019). *Socio-Economic Impacts of Large-Scale Afforestation on Rural Communities in the Wairoa District*. Waingawa: Beef + Lamb NZ. Available online at: https://beeflambnz.com/sites/default/files/Wairoa%20Afforestation_FINAL.pdf (accessed January 24, 2021).

Hess, D. J. (2014). Sustainability transitions: a political coalition perspective. *Res. Policy* 43, 278–283. doi: 10.1016/j.respol.2013.10.008

Hirschman, A. O. (1977). *Passions and the Interests - Political Arguments for Capitalism Before Its: Political Arguments for Capitalism Before Its Triumph*. Princeton, NJ: Princeton University Press. doi: 10.1515/9781400848515

Honegger, M., Michaelowa, A., and Roy, J. (2020). Potential implications of carbon dioxide removal for the sustainable development goals. *Clim. Policy*. 1–21. doi: 10.1080/14693062.2020.1843388. [Epub ahead of print].

IPCC (2018). *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Geneva: IPCC.

Irish Government (2020). *Climate Action and Low Carbon Development (Amendment) Bill 2020*. Available online at: https://assets.gov.ie/90167/93bd2ab8-fde8-40ae-b896-38b1f0854321.pdf (accessed January 24, 2021).

Jacobson, R., and Sanchez, D. L. (2019). Opportunities for carbon dioxide removal within the United States Department of Agriculture. *Front. Clim*. 1:2. doi: 10.3389/fclim.2019.00002

Jänicke, M. (2017). "Germany: innovation and climate leadership," in *The European Union in International Climate Change Politics. Still Taking a Lead?*, eds R. Wurzel, J. Connelly, and D. Liefferink (London; New York, NY: Routledge), 114–129.

Jasanoff, S. (2005). *Designs on Nature: Science and Democracy in Europe and the United States*. Princeton, NJ: Princeton University Press. doi: 10.1515/9781400837311

Jordan, A., and Huitema, D. (2014). Innovations in climate policy: the politics of invention, diffusion, and evaluation. *Env. Polit*. 23, 715–734. doi: 10.1080/09644016.2014.923614

Kingdon, J. W. (1995). *Agendas, Alternatives, and Public Policies*. 2. ed. New York, NY: Longman.

Klima- Energi-og Forsyningsudvalget Denmark (2020). *Non-paper on Carbon Capture and Storage (CCS). By the Netherlands, Norway, Denmark and Sweden*. Available online at: https://www.ft.dk/samling/20201/almdel/KEF/bilag/87/2288136.pdf (accessed January 24, 2020).

Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., et al. (2019). An agenda for sustainability transitions research: state of the art and future directions. *Environ. Innov. Soc. Transit*. 31, 1–32. doi: 10.1016/j.eist.2019.01.004

Kulovesi, K., and Oberthür, S. (2020). Assessing the EU's 2030 climate and energy policy framework: incremental change toward radical transformation? *RECIEL* 29, 151–166. doi: 10.1111/reel.12358

Larsen, J., Herndon, W., Grant, M., and Marsters, P. (2019). *Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology*. New York, NY: Rhodium Group. Available online at: https://rhg.com/wp-content/uploads/2019/05/Rhodium_CapturingLeadership_May2019-1.pdf (accessed December 6, 2020).

Lomax, G., Lenton, T. M., Adeosun, A., and Workman, M. (2015). Investing in negative emissions. *Nat. Clim. Chang*. 5, 498–500. doi: 10.1038/nclimate2627

Lövbrand, E. (2011). Co-producing European climate science and policy: a cautionary note on the making of useful knowledge. *Sci. Pub. Pol*. 38, 225–236. doi: 10.3152/030234211X12924093660516

Low, S., and Schäfer, S. (2020). Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling. *Energy Res. Soc. Sci*. 60:101326. doi: 10.1016/j.erss.2019.101326

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O. Y., Pietzcker, R. C., Rogelj, J., et al. (2018). Residual fossil CO2 emissions in 1.5-2 °C pathways. *Nat. Clim. Chang* 8, 626–633. doi: 10.1038/s41558-018-0198-6

Marshall, J. P. (2016). Disordering fantasies of coal and technology: carbon capture and storage in Australia. *Energy Policy* 99, 288–298. doi: 10.1016/j.enpol.2016.05.044

Matthews, A. (2019). *Accounting for the LULUCF Sector in the EU's 2030 Climate Targets*. CAP Reform Blog. Available online at: http://capreform.eu/accounting-for-the-lulucf-sector-in-the-eus-2030-climate-targets/ (accessed January 24, 2021).

McKnight, D., and Hobbs, M. (2018). "Fighting for coal: public relations and the campaigns against lower carbon pollution policies in Australia," in *Carbon Capitalism and Communication. Confronting Climate Crisis*, eds B. Brevini and G. Murdock (London: Palgrave Macmillan), 115–29. doi: 10.1007/978-3-319-57876-7_10

McLaren, D. P., Tyfield, D. P., Willis, R., Szersynksi, B., and Markusson, N. O. (2019). Beyond "Net-Zero": a case for separate targets for emissions reduction and negative emissions. *Front. Clim*. 1:4. doi: 10.3389/fclim.2019.00004

McMullin, B., Jones, M. B., Price, P. R., McGeever, A., and Rice, P. (2020). *Investigating the Potential for Negative Emissions Technologies (NETs) in Ireland*. Report 354. Wexford: Environmental Protection Agency Ireland. Available online at: https://www.epa.ie/pubs/reports/research/climate/Research_Report_354.pdf (accessed January 24, 2021).

McMullin, B., Price, P., Jones, M. B., and McGeever, A. H. (2019). Assessing negative carbon dioxide emissions from the perspective of a national "fair share" of the remaining global carbon budget. *Mitigat. Adapt. Strat. Global Change* 25, 579–602. doi: 10.1007/s11027-019-09881-6

McMullin, B., and Price, P. R. (2020). *Synthesis of Literature and Preliminary Modelling Relevant to Society-wide Scenarios for Effective Climate Change Mitigation in Ireland*. Report 352. Wexford: Environmental Protection Agency Ireland. Available online at: http://www.epa.ie/pubs/reports/research/climate/Research_Report_352.pdf (accessed January 24, 2021).

Merton, R. (1936). The unanticipated consequences of purposive social action. *Am. Sociol. Rev*. 1, 894–904. doi: 10.2307/2084615

Ministry for Primary Industries, New Zealand (2020). *About the One Billion Trees Programme*. Available online at: https://www.mpi.govt.nz/forestry/funding-tree-planting-research/one-billion-trees-programme/about-the-one-billion-trees-programme/ (accessed January 24, 2021).

Ministry for the Environment, New Zealand (2019). *Zero Carbon Bill Economic Analysis: A Synthesis of Economic Impacts*. Available online at: https://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/Zero-Carbon-Bill-Economic-Analysis-Report-FINAL.pdf (accessed January 24, 2021).

Minx, J. C., Lamb, W. F., Callaghan, M. W., Bornmann, L., and Fuss, S. (2017). Fast growing research on negative emissions. *Environ. Res. Lett*. 12:35007. doi: 10.1088/1748-9326/aa5ee5

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions-Part 1: Research landscape and synthesis. *Environ. Res. Lett*. 13:63001. doi: 10.1088/1748-9326/aabf9b

Möllersten, K. (2002). *Opportunities for CO2 Reductions and CO2-LeanEnergy Systems in Pulp and Paper Mills*. Doctoral thesis. KTH Royal Institute of Technology, Stockholm.

Morrow, D. R. (2014). Ethical aspects of the mitigation obstruction argument against climate engineering research. *Phil. Trans. R. Soc. A* 372:20140062. doi: 10.1098/rsta.2014.0062

Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., et al. (2020). Principles for thinking about carbon dioxide removal in just climate policy. *One Earth* 3, 150–153. doi: 10.1016/j.oneear.2020.07.015

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., et al. (2018). Negative emissions-Part 3: Innovation and upscaling. *Environ. Res. Lett*. 13:63003. doi: 10.1088/1748-9326/aabff4

Norsk Biokullnettverk (2020). *Mandat for Norsk Biokullnettverk*. Available online at: https://www.biokull.info/mandat (accessed January 24, 2021).

Obersteiner, M., Azar, C., Kauppi, P., Möllersten, K., Moreira, J., Nilsson, S., et al. (2001). Managing climate risk. *Science* 294, 786–787. doi: 10.1126/science.294.5543.786b

Parliamentary Comissioner for the Environment, New Zealand (2019). *Farms, Forests and Fossil Fuels: The Next Great Landscape Transformation?* Available online at: https://www.pce.parliament.nz/media/196523/report-farms-forests-and-fossil-fuels.pdf (accessed January 24, 2021).

Pauw, P., Mbeva, K., and van Asselt, H. (2019). Subtle differentiation of countries' responsibilities under the Paris agreement. *Palgrave Commun*. 5:86. doi: 10.1057/s41599-019-0298-6

Peters, G. P., and Geden, O. (2017). Catalysing a political shift from low to negative carbon. *Nat. Clim. Chang*. 7, 619–621. doi: 10.1038/nclimate3369

Pozo, C., Galán-Martín, Á., Reiner, D. M., Mac Dowell, N., and Guillén-Gosálbez, G. (2020). Equity in allocating carbon dioxide removal quotas. *Nat. Clim. Chang*. 10, 640–646. doi: 10.1038/s41558-020-0802-4

Productivity Commission, New Zealand (2018). *Low-Emissions Economy: Final Report*. Available online at: https://www.productivity.govt.nz/assets/Documents/4e01d69a83/Productivity-Commission_Low-emissions-economy_Final-Report.pdf (accessed January 24, 2021).

Prognos, Öko-Institut, Wuppertal-Institut (2020). *Towards a Climate-Neutral Germany: Three Steps for Achieving Climate Neutrality by 2050 and an Intermediate Target of—65% in 2030 as Part of the EU Green Deal: Executive Summary Conducted for Agora Energiewende, Agora Verkehrswende and Stiftung Klimaneutralität*. Available online at: https://static.agora-energiewende.de/fileadmin2/Projekte/2020/2020_10_KNDE/A-EW_193_KNDE_Executive-Summary_EN_WEB_V111.pdf (accessed January 24, 2021).

Raum, S., and Potter, C. (2015). Forestry paradigms and policy change: the evolution of forestry policy in Britain in relation to the ecosystem approach. *Land Use Policy* 49, 462–470. doi: 10.1016/j.landusepol.2015.08.021

Rayner, T., and Jordan, A. (2016). "Climate change policy in the European union," in *Oxford Research Encyclopedia of Climate Science*. 1–25. doi: 10.1093/acrefore/9780190228620.013.47

Rickels, W., Proelß, A., Geden, O., Burhenne, J., and Fridahl, M. (2020). *The Future of (Negative) Emissions Trading in the European Union. Kiel Working Paper No. 2164*. Kiel: Kiel Institute for the World Economy.

Rimmer, D. (2016). *Breakdown of governance: a critical analysis of New Zealand's climate change response*. PhD thesis. Massey University, Manawatu, New Zealand.

Robiou Du Pont, Y., Jeffery, M. L., Gütschow, J., Rogelj, J., Christoff, P., and Meinshausen, M. (2017). Equitable mitigation to achieve the Paris agreement goals. *Nat. Clim. Chang*. 7, 38–43. doi: 10.1038/nclimate3186

Rodriguez, E., Lefvert, A., Fridahl, M., Grönkvist, S., Haikola, S., and Hansson, A. (2020). Tensions in the energy transition: Swedish and Finnish company perspectives on bioenergy with carbon capture and storage. *J. Clean. Prod*. 2020:124527. doi: 10.1016/j.jclepro.2020.124527

Royal Society and Royal Academy of Engineering (2018). *Report: Greenhouse Gas Removal*. Available online at: https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf (accessed January 24, 2021).

Sanchez, D. L., Amador, G., Funk, J., and Mach, K. J. (2018). Federal research, development, and demonstration priorities for carbon dioxide removal in the United States. *Environ. Res. Lett*. 13:15005. doi: 10.1088/1748-9326/aaa08f

Shue, H. (2018). Mitigation gambles: uncertainty, urgency and the last gamble possible. *Phil. Trans. R. Soc. A* 376:20170105. doi: 10.1098/rsta.2017.0105

Smith, A., and Raven, R. (2012). What is protective space? Reconsidering niches in transitions to sustainability. *Res. Policy* 41, 1025–1036. doi: 10.1016/j.respol.2011.12.012

Smith, A., Stirling, A., and Berkhout, F. (2005). The governance of sustainable socio-technical transitions. *Res. Policy* 34, 1491–1510. doi: 10.1016/j.respol.2005.07.005

Smith, A., Voß, J.-P., and Grin, J. (2010). Innovation studies and sustainability transitions: the allure of the multi-level perspective and its challenges. *Res. Policy* 39, 435–448. doi: 10.1016/j.respol.2010.01.023

Smith, K. B. (2002). Typologies, taxonomies, and the benefits of policy classification. *Policy Stud. J.* 30, 379–395. doi: 10.1111/j.1541-0072.2002.tb02153.x

Smith, P., Nkem, J., Calvin, K., Campbell, F., Cherubini, G., Grassi, V., et al. (2019). "Interlinkages between desertification, land degradation, food security and GHG fluxes: synergies, trade-offs and integrated response options," in *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* (Geneva: IPCC), 551–672.

Steinberger, P. J. (1980). Typologies of public policy: meaning construction and the policy process. *Soc. Sci. Q.* 61, 185–192.

Szulecki, K., Fischer, S., Gullberg, A. T., and Sartor, O. (2016). Shaping the 'Energy Union': between national positions and governance innovation in EU energy and climate policy. *Clim. Policy* 16, 548–567. doi: 10.1080/14693062.2015.1135100

The White House (2021). *Executive Order on tackling the Climate Crisis at Home and Abroad*. Available online at: https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/ (accessed January 24, 2021).

Torvanger, A. (2019). Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement. *Clim. Policy* 19, 329–341. doi: 10.1080/14693062.2018.1509044

UK Government (2017). *The Clean Growth Strategy: Leading the Way to a Low Carbon Future*. Available online at: https://www.gov.uk/guidance/create-woodland-overview (accessed January 24, 2021).

UK Government (2018). *Create Woodland: Overview*. Available online at: https://www.gov.uk/guidance/create-woodland-overview (accessed January 24, 2021).

UK Government (2019). *The Climate Change Act 2008 (2050 Target Amendment) Order, 2019*. Available online at: https://www.legislation.gov.uk/ukdsi/2019/9780111187654 (accessed January 24, 2021).

UK Government (2020a). *Budget 2020. Policy Paper*. Available online at: https://www.gov.uk/government/publications/budget-2020-documents/budget-2020 (accessed January 24, 2021).

UK Government (2020b). *The Ten Point Plan for a Green Industrial Revolution: Building Back Better, Supporting Green Jobs, and Accelerating Our Path to Net Zero*. Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf (accessed January 24, 2021).

Umweltbundesamt (2020). *Abschätzung der Treibhausgasminderungswirkung des Klimaschutzprogramms 2030 der Bundesregierung*. Available online at: https://www.umweltbundesamt.de/publikationen/abschaetzung-der-treibhausgasminderungswirkung-des (accessed January 24, 2021).

United Nations Environmental Program (2017). *The Emissions Gap Report 2017: A UN Environment Synthesis Report*. Nairobi: United Nations Environmental Program.

van Sluisveld, M. A., Hof, A. F., Carrara, S., Geels, F. W., Nilsson, M., Rogge, K., et al. (2020). Aligning integrated assessment modelling with socio-technical transition insights: An application to low-carbon energy scenario analysis in Europe. *Technol. Forecast. Soc. Change* 151:119177. doi: 10.1016/j.techfore.2017.10.024

Victor, D. G., Geels, F. G., and Sharpe, S. (2019). *Accelerating the Low Carbon Transition. The Case for Stronger, More Targeted and Coordinated International Action.* Brookings Institution. Available online at: https://www.brookings.edu/wp-content/uploads/2019/12/Coordinatedactionreport.pdf (accessed January 24, 2021).

Vivid Economics (2019). *Greenhouse Gas Removal Policy Options*. Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/833145/Greenhouse_Report_Gas_Removal_policy_options.pdf (accessed January 24, 2021).

vonHedemann, N., Wurtzebach, Z., Timberlake, T. J., Sinkular, E., and Schultz, C. A. (2020). Forest policy and management approaches for carbon dioxide removal. *Interface Focus* 10:20200001. doi: 10.1098/rsfs.2020.0001

VW (2020). *In Depth: Audi and Climeworks Store CO2 From the Atmosphere Underground*. Available online at: https://www.volkswagenag.com/en/news/2020/09/audi_climeworks.html (accessed January 24, 2021).

Waller, L., Rayner, T., Chilvers, J., Gough, C. A., Lorenzoni, I., Jordan, A., et al. (2020). Contested framings of greenhouse gas removal and its feasibility: Social and political dimensions. *WIREs Clim. Change* 11:e649. doi: 10.1002/wcc.649

Workman, M., Dooley, K., Lomax, G., Maltby, J., and Darch, G. (2020). Decision making in contexts of deep uncertainty - an alternative approach for long-term climate policy. *Environ. Sci. Policy* 103, 77–84. doi: 10.1016/j.envsci.2019.10.002

Woroniecki, S., Wendo, H., Brink, E., Islar, M., Krause, T., Vargas, A. M., et al. (2020). Nature unsettled: How knowledge and power shape 'nature-based' approaches to societal challenges. *Glob. Environ. Change* 65:102132. doi: 10.1016/j.gloenvcha.2020.102132

Wreford, A., Bayne, K., Edwards, P., and Renwick, A. (2019). Enabling a transformation to a bioeconomy in New Zealand. *Environ. Innov. Soc. Transit.* 31, 184–199. doi: 10.1016/j.eist.2018.11.005

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Undoing Equivalence: Rethinking Carbon Accounting for Just Carbon Removal

Wim Carton[1]*, *Jens Friis Lund*[2] and *Kate Dooley*[3]

[1] Lund University Center for Sustainability Sciences (LUCSUS), Lund, Sweden, [2] Department of Food and Resource Economics (IFRO), Copenhagen University, Copenhagen, Denmark, [3] Climate and Energy College, University of Melbourne, Parkville, VIC, Australia

Concerns are increasingly raised over the centrality of carbon removal in climate policy, particularly in the guise of "net-zero" targets. Most significantly perhaps, treating emissions and removals as equivalent obscures emission reductions, resulting in "mitigation deterrence." Yet the conflation of emission reductions and removals is only one among several implicit equivalences in carbon removal accounting. Here, we examine three other forms—carbon, geographical, and temporal equivalence—and discuss their implications for climate justice and the environmental risks with carbon removal. We conclude that "undoing" these equivalences would further a just response to the climate crisis and tentatively explore what such undoing might look like in practice.

Keywords: carbon removal, negative emissions, equivalence, carbon accounting, climate justice, net-zero

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***Correspondence:**
Wim Carton
wim.carton@lucsus.lu.se

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INTRODUCTION

Carbon removal is steadily making its way into mainstream climate governance. As countries and corporations embrace net-zero emission goals, the ambition to remove large amounts of carbon from the atmosphere is becoming an implied if not always outspoken pillar of mitigation policies. This development raises a number of, by now, well-known concerns about the feasibility of proposed "negative emission technologies" (Low and Schäfer, 2020; Waller et al., 2020) and the likely environmental and social justice impacts of their implementation (Dooley and Kartha, 2018; Doelman et al., 2020). These concerns remain largely invisible in the modeled pathways that assume large-scale deployment of negative emissions later in this century (Larkin et al., 2017; Beck and Mahony, 2018). Apprehensions are also voiced about the likely "moral hazard" or "mitigation deterrence" effects that promises of future carbon removal have on current emission reduction efforts (Anderson and Peters, 2016; McLaren, 2020; McLaren and Markusson, 2020).

To address some of these issues, McLaren et al. (2019) propose to disaggregate net-zero targets into separate objectives for carbon removal and emission reductions. Doing so, they argue, would "expose interests and politics" in the formulation of emission targets and "reveal both where negative emissions investment and development is inadequate, and where negative emissions (or future promises thereof) could undermine emissions reduction" (p. 4). McLaren et al.'s proposal reflects a long-standing social science critique of carbon accounting as an often misguided exercise in "making things the same" (MacKenzie, 2009).

This critique asserts that common carbon accounting practices are rendering disparate technologies, socioeconomic contexts, and climate change temporalities equivalent, while concerns for climate justice and environmental integrity demand that they are kept separate (Lohmann, 2009, 2011). It fundamentally questions the idea that a ton of CO_2 should be treated as functionally equivalent irrespective of how, where or when it is avoided, removed, or stored. While "a ton is a ton" might be a useful abstraction for creating and apportioning carbon budgets, the argument goes, it is a poor guide in the design of climate policy, where different options for mitigation and their distribution in time and space correspond to radically different values, socioeconomic effects, and risk profiles (Lövbrand, 2009; Corbera and Brown, 2010; Leach and Scoones, 2015; Turnhout et al., 2015). Hence, while carbon accounting fulfills an important function to create consistency and unity in assessing progress toward identified targets, the specific forms it takes are not neutral and require close consideration.

Seen in this light, the conflation of removals and emission reductions that McLaren et al. are concerned with, is one among several implicit equivalences in carbon accounting. In this perspective piece, we critically examine the social and environmental implications of three other equivalences. We argue that these too must be undone as part of a movement toward ensuring socially and environmentally just carbon removal and mitigation policies—which require that states with greater capability take the lead on climate action and that the needs of the most vulnerable are protected against the effects of climate change and of measures taken to limit it (Shue, 2019; Dooley et al., 2021). While concerns over the equivalences that we examine have long been raised in the social science literature on e.g., carbon accounting and carbon markets (Lohmann, 2009; Carton et al., 2020), they are now resurfacing under the guise of a rapidly evolving carbon removal agenda, and therefore warrant being discussed and scrutinized as part of this new conversation.

UNDOING EQUIVALENCE

We describe three common forms of equivalence in carbon accounting and discuss their implications for climate justice concerns and risks with respect to carbon removal. We then suggest what "undoing" these equivalences might look like in practice.

Carbon Equivalence

Carbon accounting often renders fossil and biotic forms of carbon, i.e., from fossil fuels vs. land use, land use change, and forestry, equivalent. Both categories of carbon are commonly included under the same climate targets, which allows fossil fuel emissions to be "offset" by increases in biological carbon sequestration. The European Union's new 2030 "net-emissions" target, for instance, now includes forests and land use within the bloc's overall mitigation target, which though constrained by accounting rules introduces a degree of flexibility between fossil and land sector emissions (Kulovesi and Oberthür, 2020). Such accounting practices are responding to political rather than scientific considerations and involve a number of risks and complexities (Lövbrand, 2004; Höhne et al., 2007), raising concerns about the weakening of targets (Climate Action Tracker, 2020). While the technical accounting difficulties with making fossil and biotic carbon equivalent have long been recognized, the social, environmental, and climate implications often remain obscured (Fogel, 2005; Dooley and Gupta, 2017).

A key concern with this equivalence pertains to the different timescales involved: fossil carbon sinks are essentially permanent (or inert) if left unused, while biotic carbon is part of the short-term (or active) carbon cycle. While accounting systems try to deal with the risk of reversal from biotic sinks in various ways, for example through temporary crediting, these solutions do not take away the long-term uncertainties involved (Brander et al., 2021). The different temporal characteristics of fossil vs. biotic carbon represent a fundamental barrier to equivalence.

Mackey et al. (2013) explain why using carbon sinks on land as a means to "offset" emissions from burning fossil fuels is scientifically flawed. Current terrestrial removal and storage potential primarily reflects the depletion of carbon sinks due to past land use. Since the capacity of forests and other ecosystems to sequester carbon is finite, increasing carbon in terrestrial sinks simply replaces carbon that has been lost to the atmosphere over past centuries. Fossil carbon, on the other hand, is permanently locked away. Thus, burning fossil fuels moves carbon from permanent storage into the active carbon cycle, causing an aggregate increase in land, ocean, and atmospheric carbon. Once added, this additional carbon cannot be removed through natural sinks on time-scales relevant to climate mitigation, leading to increased warming (Steffen et al., 2016).

Rendering biotic and fossil carbon equivalent also conflates the drivers of climate change. It obscures whether mitigation is achieved through reduced fossil emissions or increased biotic sequestration (Dooley and Gupta, 2017), suggesting that full decarbonization of the energy sector can be avoided (or delayed) by sufficient "greening" in the land sector. However, the technological, social, and economic transitions required in these sectors differ significantly, as do their relative contributions to climate change. Considering them fully fungible therefore has considerable social and environmental implications. Bioenergy with carbon capture and storage (BECCS), for example, is promoted as a biotic carbon removal solution that largely overcomes the permanence issue by geologically sequestering the carbon captured from bioenergy combustion. Yet treating BECCS as a solution to continued fossil fuel emissions implicitly shifts the burden of mitigation from energy, industry, and transport to the land use sector, with ramifications for distributional justice and ecosystem functioning (Buck, 2016; DeCicco and Schlesinger, 2018; Seddon et al., 2020).

A similar suite of issues arises from the establishment of equivalence across different biotic systems. The quality, integrity, and stability of biotic carbon stocks differs between different land-uses. Ecosystem integrity and function, including carbon storage, depends on biodiversity (Labrière et al., 2016), with diverse intact natural ecosystems known to be more resilient and stable than monocultures of non-native species (Seddon et al., 2019). Yet, carbon accounting systems do not differentiate between the "quality" of terrestrial carbon stocks on the basis of ecosystem health or diversity (Keith et al., 2021).

A just framing of carbon removal would require separate accounting and policy agendas on biotic and fossil fuel emissions. Such separation was already recommended several decades ago (WGBU, 1998) and has recently reappeared in the academic and political debate (NewClimate Institute, 2020; Skelton et al., 2020; Smith, 2021). Separation would help avoid the substitution of fossil fuel emission reductions for land-based actions that risk exacerbating climate injustices through environmental and social impacts. Rather than using biotic carbon removals to compensate for past, ongoing, or residual fossil emissions, restricting removals on a sectoral basis (e.g., land-based removals for land-based emissions) would encourage improved agricultural practices, minimize reliance on land sequestration, and force a faster transformation of sectors reliant on fossil fuels (Upton, 2019).

A further step should be to separate different land-based efforts, recognizing that these come with very different social and ecological implications. A further undoing of equivalences within the "biotic carbon" category is therefore necessary. Actions that minimize problems of impermanence through geological storage (such as BECCS) or create equivalences between terrestrial carbon stocks of different quality (such as between diverse forest ecosystems and monoculture plantations) need to be assessed for their impacts and risks related to *both* social impacts *and* biodiversity, ecosystems, and mitigation effectiveness. Taken together, this means that research and policy agendas need to distinguish between emissions avoided or removed in the land sector; the difference in quality of carbon stocks between different land-uses and ecosystems; and mitigation action in sectors reliant on fossil fuels.

Geographical Equivalence

A second equivalence embedded in carbon accounting is between carbon emissions and removals across different geographies, i.e., across locations that differ widely in terms of their biophysical and socio-political characteristics.

Climate change is commonly construed as a global problem where the spatial location of emissions and removals is irrelevant. It is also widely seen as a problem that should be mitigated at the lowest possible cost, a principle that is written into the U.N. Framework Convention on Climate Change (Article 3.3) (Boyd et al., 2009). This combination of factors makes the idea of geographical equivalence intuitively appealing. From a neoclassical economics perspective, differences in the marginal costs of mitigation efforts across the world derive from comparative advantage premised on different innate abilities and preferences, i.e., some places provide better conditions for carbon removal than others and some people prefer low-carbon lifestyles over others. This logic has given rise to a variety of mechanisms to facilitate the international exchange of mitigation responsibilities, allowing countries and corporations to finance climate action elsewhere to meet their targets. The use of carbon removal within such mechanisms is already common practice on the voluntary carbon market and is actively discussed in the context of a future trading mechanism under the Paris Agreement (Mace et al., 2021).

Carbon removal and storage does come with specific geo- and biophysical conditions that lend support to geographical equivalence and the international exchange of removal responsibilities. Geological storage capacity, for instance, is unevenly distributed across space, implying that some countries will be unable to store captured CO_2 within their jurisdictions (Kelemen et al., 2019; Wei et al., 2021). Similarly, higher biological sequestration rates in the tropics favors them as locations for afforestation/reforestation and bioenergy production in global estimates of mitigation potentials (Griscom et al., 2017). Yet prioritizing such geo- and biophysical conditions in global carbon removal estimates tends to disregard important social and political factors that put these estimates in question (Creutzig et al., 2021), and that caution against the adoption of geographical equivalence. Studies that identify "available" locations for land-based carbon removal (Griscom et al., 2017; Bastin et al., 2019; Pozo et al., 2020), for instance, commonly disregard the existing uses and users (such as pastoralists) of these areas. This amounts to a discursive marginalization of certain land uses and users and may implicitly legitimate processes of "green grabbing" (Fairhead et al., 2012).

Similarly, the notion of comparative advantage, which underpins the alleged mutual benefits of exchanging mitigation responsibilities, has been repeatedly criticized for disregarding global inequality and power structures (Sheppard, 2012; McAfee, 2016). Critics point out that the differences allowing for market exchange reflect uneven capacities and opportunities within a structurally unequal world, and are predicated on historical and present exploitation and unequal power relations (Smith, 2008). Focusing on cost-effectiveness as the driving criterion for the location of carbon removal efforts will therefore, inter alia, tend to reproduce climate injustices (Fairhead et al., 2012).

We currently see rapid growth in the use of offsetting to offer "climate neutral" products and services and/or to make good on corporate and country-level net-zero pledges (Gross, 2020; NewClimate Institute, 2020). Many of these promises build on geographical equivalence, where offsetting occurs through carbon removal—often in the form of afforestation projects—in countries in the global South. This incentivizes delay—by providing cheap alternatives to difficult or inconvenient emission reductions—and deepens climate injustice in several ways. First, by depriving poor nations and regions of "cheap" carbon removal options, making their path toward the coveted "net-zero" harder, while giving wealthy nations and regions an easier path toward realizing the same goal (Rogelj et al., 2021). Second, by limiting the livelihood opportunities afforded to poor (mostly rural) people so that a wealthy global elite can continue its ways (Shue, 2017; Gore et al., 2020). Third, by facilitating the continued release of fossil carbon into the atmosphere (Pearse and Böhm, 2014; Green, 2021), thereby contributing to future demand for carbon removal rollout as well as inflicting more severe climate damages that will shape the lives of poor and vulnerable people in the global South the most [Intergovernmental Panel on Climate Change (IPCC), 2014a].

Just climate policy requires that we abandon the notion of geographical equivalence. Undoing the equivalence between biotic and fossil carbon would contribute toward undoing geographical equivalence in practice, because much of the offsetting done by global North corporations occurs via forest offsets. However, further efforts are necessary to avoid the deepening of climate injustices entailed by global carbon markets. This involves a stronger prioritization of domestic or at least regional mitigation efforts, and a move away from global market mechanisms that neglect differentiated social and economic capabilities. Efforts to reform such mechanisms have so far failed to curb their negative social fallout as well as concerns related to additionality and leakage, among others (Asiyanbi and Lund, 2020; Cullenward and Victor, 2020; West et al., 2020). Current discussions surrounding voluntary market standards and a possible global compliance market under the Paris Agreement do not indicate a substantial break with failures of the past (Timperley, 2019; Harvey, 2021), hence offer little hope that markets can be reformed to the extent needed. Rather than relying on the principle of geographical equivalence, shared responsibility for carbon removal must start from an acknowledgment of wealthy nations' historical responsibility for climate change and a moral imperative that mandates against shifting the burden and risks associated with removal to poor and vulnerable parts of the world. Ultimately, this means decoupling support for mitigation and adaptation efforts in the global South from any trade in carbon removal claims.

Temporal Equivalence

A third prominent equivalence in discussions on carbon removal is between present (and near-term) mitigation actions, and those projected to occur in the more distant future. This temporal equivalence underpins much of the current discourse on large-scale removal but raises a number of concerns.

Proposals for large-scale removal derive from modeled pathways that seek to stay within 1.5 or 2°C warming limits. In the majority of these pathways carbon removal compensates for a temporary overshoot of the temperature target [Intergovernmental Panel on Climate Change (IPCC), 2014b, 2018]. For instance, more than 80% of scenarios in the IPCC's Special Report on 1.5°C overshoot the 1.5°C temperature threshold before returning to these levels using large-scale carbon removal in the second half of the twenty-first century [Intergovernmental Panel on Climate Change (IPCC), 2018; Rogelj et al., 2019]. This use of temperature overshoot and subsequent decline suggests that it does not matter when, over the next 80 years, mitigation actions occur, as long as the end-result by 2100 stays within agreed-upon temperature targets. It assumes substitutability between emission reductions in the near-term and further-off removals, a notion that is rapidly being institutionalized in net-zero targets. It is this equivalence that most directly lies behind concerns with "mitigation deterrence," because if it does not matter *when* we balance the carbon budget, then there might be incentives to push uncomfortable and difficult decisions and investments into the future.

The idea that future actions can straightforwardly be substituted for present ones is however problematic. For one, as Anderson and Peters (2016) point out, it neglects the different risk profiles that characterize different time horizons: we know what can be done in the present and what technologies are available, and can therefore reasonably assess their risks, flaws, and economic and political feasibility. Future removals on the other hand often rely on technologies that are hypothetical at scale and their roll-out is therefore inherently more difficult to assess. Second, significant uncertainties remain concerning future climate feedback processes and tipping points (Tokarska and Zickfeld, 2015; Lenton et al., 2019; Creutzig et al., 2021), which could affect the effectiveness of carbon removal to reduce temperatures (Rogelj et al., 2018, p. 127). If increased warming weakens natural carbon sinks (Hubau et al., 2020; Li et al., 2020; Wang et al., 2020; Duffy et al., 2021) or turns them into sources of carbon emissions (Wang et al., 2018), then assumptions about our ability to bring down atmospheric CO_2 concentrations in the second half of the century might prove overly optimistic.

Third, equating present with future actions ignores potentially important differences in the climate damages and mitigation burdens that occur as a result of different peak CO_2 concentrations. While the geophysical implications of temporary temperature overshoot remain unclear (Geden and Löschel, 2017), an increasing amount of research points to levels of sea level rise, changes in ocean circulation, and changes in other aspects of the cryosphere that exceed those under straightforward temperature stabilization scenarios and that would be difficult to reverse (Palter et al., 2018; ICCINET, 2019). In other words, while temperature overshoots might be reversible, this is not necessarily the case for other climate and geophysical dynamics. Fourth, the more societies push actions into the future, the greater the scale at which removals will need to happen, and the larger the social and economic burdens associated with mitigation [Intergovernmental Panel on Climate Change (IPCC), 2018]. Rapid short-term emission reductions also entail a significant burden, but there are clear societal co-benefits from transitioning to a renewable energy-oriented transport and industry system, and from making agricultural systems more sustainable. That is not necessarily the case with large-scale carbon removal. Technologies such as Direct Air Capture would likely be a pure cost to society, while in the case of "natural climate solutions" any co-benefits are highly dependent on the form and scale they end up taking [Intergovernmental Panel on Climate Change (IPCC), 2019; Fyson et al., 2020].

Cutting across these different concerns are the uneven intergenerational effects of temporal equivalence. As Shue (2017) notes, the conflation of present with future climate actions entails a risk-transfer to future generations, in which the people deciding that future removal is a reasonable strategy to pursue are different from those that will need to deal with any of the consequences arising should that strategy fail. Substituting near-term mitigation for future removals "sentences young people to either a massive, implausible cleanup or growing deleterious climate impacts or both' (Hansen et al., 2016, p. 578). This occurs against a background where any costs of mitigating climate change in the face of insufficient removal will be significantly larger than today, and where those costs and consequences are likely to disproportionately fall on the poorest.

A commitment to climate justice therefore demands a clear distinction between actions in the present, and more hypothetical, future promises of mitigation (mostly in the form of carbon removal). It demands the introduction of barriers to substitution, for example by moving away from the use of high discount rates in models, which value future generations less than present ones (Stanton et al., 2009) and hence facilitate substitution and bias results in favor of future removals (Emmerling et al., 2019). Foregrounding justice considerations also requires constraints on the use of overshoot scenarios (Geden and Löschel, 2017) and a carbon accounting system that internalizes the considerable added risks of delaying mitigation, for instance by institutionalizing a risk premium in mitigation pathways. For policy makers, minimizing risk transfer means much stronger prioritization of ambitious near-term actions over distant mitigation targets and open acknowledgment of the important differences between the two. This would guarantee that a majority of the mitigation burden is borne by those most responsible for the problem.

CONCLUSION

In sum, we argue that a just research and policy agenda on carbon removal needs to, first, distinguish between removals in the land use sector, and emissions from the use of fossil fuels in energy production, industry and transport. The purpose here should be to question the logic that allows biotic carbon sinks to be used as offsets for fossil fuel emissions, while also problematizing substitution between biotic sinks without regard for ecosystem quality or justice effects. Second, it needs to resist the temptations of global markets in carbon removal, where the domestic climate obligations of corporations or countries are substituted for removals in distant, often less affluent places. Such cost-shifting perpetuates existing inequalities by outsourcing the responsibility for climate action on economic grounds. Third, it needs to take a cautionary approach to tipping points, climate feedbacks, and the reversibility of climate impacts so as to avoid shifting the risks of climate change onto future generations. Taking these risks seriously would significantly constrain the use of future carbon removal as a way to compensate for continued emissions, and allow an open discussion on when such strategy might be justified, and when it is not.

In practice, the three equivalences that we have discussed are difficult to keep apart. They do not stand side by side but in numerous ways overlap and intersect with each other, and with the "net" equivalence that McLaren et al. (2019) problematize. Attention to these interrelations highlights that the problems and perverse incentives characterizing the carbon removal conversation run deeper than the conflation of removals and emission reductions alone—acknowledgment of which might help overcome some of the criticisms raised against a proposed undoing of the "net" equivalence (see Smith, 2021). Indeed, our discussion here does not exhaust the full range of concerns pervading the construction of equivalence in climate research and policy (Lohmann, 2011). Other equivalences are worthy of renewed scrutiny as well, including for example the conflation of different greenhouse gas emissions under a single CO_2 equivalent metric (see e.g., MacKenzie, 2009; Cooper, 2015). In this article, we merely sought to illustrate how common approaches to carbon accounting tend to disregard important social, environmental, and geophysical differences—among others—between different sources and sinks of greenhouse gas emissions. This accounting logic serves the interest of simplicity, substitutability, and economic flexibility but introduces important social and environmental concerns that undermine climate justice. It is time to acknowledge that carbon accounting equivalences are political choices fulfilling political functions, with important consequences for climate policy. If researchers and policy makers are serious about incorporating social and environmental justice considerations into their climate mitigation work, then models and accounting frameworks must make explicit, and indeed actively minimize, the risks involved in the creation of multiple equivalences.

Beyond separate targets for emission reductions and removals, we also need differentiated targets and policies that separate land-use from fossil fuel emissions, and that prioritize and incentivize near-term domestic actions, using existing technologies, over distant net-zero targets. This would help to direct wealthy corporations and nations—those mainly responsible for climate change and most capable of mitigating it—toward ambitious emissions reductions and just forms of carbon removal, putting us on a path toward stabilizing the climate.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

WC conceived of the article idea and drafted the introduction, the section on temporal equivalence, and the conclusion. JL drafted the section on geographical equivalence. KD drafted the section on carbon equivalence. All authors helped conceptualize the argument and contributed to extensive editing and revising of the text.

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REFERENCES

Anderson, K., and Peters, G. (2016). The trouble with negative emissions. *Science* 354, 182–183. doi: 10.1126/science.aah4567

Asiyanbi, A. P., and Lund, J. F. (2020). Policy persistence: REDD+ between stabilization and contestation. *J. Polit. Ecol.* 27, 378–400. doi: 10.2458/v27i1.23493

Bastin, J. F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., et al. (2019). The global tree restoration potential. *Science* 364, 76–79. doi: 10.1126/science.aax0848

Beck, S., and Mahony, M. (2018). The politics of anticipation: the IPCC and the negative emissions technologies experience. *Glob. Sustain.* 1:e8. doi: 10.1017/sus.2018.7

Boyd, E., Hultman, N., Timmons Roberts, J., Corbera, E., Cole, J., Bozmoski, A., et al. (2009). Reforming the CDM for sustainable development:

lessons learned and policy futures. *Environ. Sci. Policy* 12, 820–831. doi: 10.1016/j.envsci.2009.06.007

Brander, M., Ascui, F., Scott, V., and Tett, S. (2021). Carbon accounting for negative emissions technologies. *Clim. Policy* 2021, 1–19. doi: 10.1080/14693062.2021.1878009

Buck, H. J. (2016). Rapid scale-up of negative emissions technologies: social barriers and social implications. *Clim. Change* 139, 155–167. doi: 10.1007/s10584-016-1770-6

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *Clim. Change* 11, 1–25. doi: 10.1002/wcc.671

Climate Action Tracker (2020). *CAT Climate Target Update Tracker: EU*. Climate Action Tracker. Available online at: https://climateactiontracker.org/climate-target-update-tracker/eu/

Cooper, M. H. (2015). Measure for measure? Commensuration, commodification, and metrology in emissions markets and beyond. *Environ. Plann. A Econ. Space* 47, 1787–1804. doi: 10.1068/a130275p

Corbera, E., and Brown, K. (2010). Offsetting benefits? Analyzing access to forest carbon. *Environ. Plann. A Econ. Space* 42, 1739–1761. doi: 10.1068/a42437

Creutzig, F., Erb, K., Haberl, H., Hof, C., Hunsberger, C., and Roe, S. (2021). Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments. *GCB Bioenergy* 2020:gcbb.12798. doi: 10.1111/gcbb.12798

Cullenward, D., and Victor, D. (2020). *Making Climate Policy Work*. Cambridge: Polity Press.

DeCicco, J. M., and Schlesinger, W. H. (2018). Reconsidering bioenergy given the urgency of climate protection. *Proc. Natl. Acad. Sci. U.S.A*. 115, 9642–9645. doi: 10.1073/pnas.1814120115

Doelman, J. C., Stehfest, E., van Vuuren, D. P., Tabeau, A., Hof, A. F., Braakhekke, M. C., et al. (2020). Afforestation for climate change mitigation: potentials, risks and trade-offs. *Glob. Chang. Biol*. 26, 1576–1591. doi: 10.1111/gcb.14887

Dooley, K., and Gupta, A. (2017). Governing by expertise: the contested politics of (accounting for) land-based mitigation in a new climate agreement. *Int. Environ. Agreements* 17, 483–500. doi: 10.1007/s10784-016-9331-z

Dooley, K., Holz, C., Kartha, S., Klinsky, S., Roberts, T., Shue, H., et al. (2021). Ethical choices behind quantifications of fair contributions under the Paris agreement. *Nat. Clim. Change*. 11, 300–305. doi: 10.1038/s41558-021-01015-8

Dooley, K., and Kartha, S. (2018). Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *Int. Environ. Agreements* 18, 79–98. doi: 10.1007/s10784-017-9382-9

Duffy, K. A., Schwalm, C. R., Arcus, V. L., Koch, G. W., Liang, L. L., and Schipper, L. A. (2021). How close are we to the temperature tipping point of the terrestrial biosphere? *Sci. Adv*. 7:eaay1052. doi: 10.1126/sciadv.aay1052

Emmerling, J., Drouet, L., van der Wijst, K. I., van Vuuren, D., Bosetti, V., and Tavoni, M. (2019). The role of the discount rate for emission pathways and negative emissions. *Environ. Res. Lett*. 14:104008. doi: 10.1088/1748-9326/ab3cc9

Fairhead, J., Leach, M., and Scoones, I. (2012). Green Grabbing: a new appropriation of nature? *J. Peasant Stud*. 39, 237–261. doi: 10.1080/03066150.2012.671770

Fogel, C. (2005). Biotic carbon sequestration and the Kyoto protocol: the construction of global knowledge by the intergovernmental panel on climate change. *Int. Environ. Agreements* 5, 191–210. doi: 10.1007/s10784-005-1749-7

Fyson, C. L., Baur, S., Gidden, M., and Schleussner, C.-F. (2020). Fair-share carbon dioxide removal increases major emitter responsibility. *Nat. Clim. Change* 2020, 1–6. doi: 10.1038/s41558-020-0857-2

Geden, O., and Löschel, A. (2017). Define limits for temperature overshoot targets. *Nat. Geosci*. 10, 881–882. doi: 10.1038/s41561-017-0026-z

Gore, T., Alestig, M., and Ratcliff, A. (2020). *Confronting Carbon Inequality: Putting Climate Justice at the Heart of the COVID-19 Recovery* (Issue September). https://oxfamilibrary.openrepository.com/bitstream/handle/10546/621052/mb-confronting-carbon-inequality-210920-en.pdf

Green, J. F. (2021). Does carbon pricing reduce emissions? A review of ex-post analyses. *Environ. Res. Lett*. 16:043004. doi: 10.1088/1748-9326/abdae9

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., et al. (2017). Natural climate solutions. *Proc. Natl. Acad. Sci. U.S.A*. 114, 11645–11650. doi: 10.1073/pnas.1710465114

Gross, A. (2020). Carbon offset market progresses during coronavirus. *Financial Times*. Available online at: https://www.ft.com/content/e946e3bd-99ac-49a8-82c9-e372a510e87c

Hansen, J., Sato, M., Kharecha, P., Schuckmann, Karina Von, S., Beerling, D. J., et al. (2016). Young people' s burden: requirement of negative CO_2 emissions. *Earth Syst. Dyn*. 8, 577–616. doi: 10.5194/esd-2016-42

Harvey, F. (2021). Green groups raise concerns over Carney carbon credits plan. *The Guardian*. Available online at: https://www.theguardian.com/environment/2021/jan/27/green-groups-raise-concerns-over-carney-carbon-credits-plan

Höhne, N., Wartmann, S., Herold, A., and Freibauer, A. (2007). The rules for land use, land use change and forestry under the Kyoto Protocol-lessons learned for the future climate negotiations. *Environ. Sci. Policy* 10, 353–369. doi: 10.1016/j.envsci.2007.02.001

Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., et al. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* 579, 80–87. doi: 10.1038/s41586-020-2035-0

ICCINET (2019). *Cryosphere 1.5°: Where Urgency and Ambition Meet*. International Cryosphere Climate Initiative. Available online at: http://iccinet.org/wp-content/uploads/2019/12/Cryosphere1-5_191211a_high-res.pdf

Intergovernmental Panel on Climate Change (IPCC) (2014a). *Climate Change 2014: Impacts, Adaptation and Vulnerability - Contributions of the Working Group II to the Fifth Assessment Report*. doi: 10.1016/j.renene.2009.11.012

Intergovernmental Panel on Climate Change (IPCC) (2014b). *Climate Change 2014: Mitigation of Climate Change*. In Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. doi: 10.1017/CBO9781107415416

Intergovernmental Panel on Climate Change (IPCC) (2018). *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*. doi: 10.1017/CBO9781107415324

Intergovernmental Panel on Climate Change (IPCC) (2019). *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems - Summary for Policymakers*. Available online at: https://www.ipcc.ch/site/assets/uploads/2019/08/4.-SPM_Approved_Microsite_FINAL.pdf

Keith, H., Vardon, M., Obst, C., Young, V., Houghton, R. A., and Mackey, B. (2021). Evaluating nature-based solutions for climate mitigation and conservation requires comprehensive carbon accounting. *Sci. Total Environ*. 769:144341. doi: 10.1016/j.scitotenv.2020.144341

Kelemen, P., Benson, S. M., Pilorgé, H., Psarras, P., and Wilcox, J. (2019). An overview of the status and challenges of CO_2 storage in minerals and geological formations. *Front. Clim*. 1:9. doi: 10.3389/fclim.2019.00009

Kulovesi, K., and Oberthür, S. (2020). Assessing the EU's 2030 climate and energy policy framework: incremental change toward radical transformation? *Rev. Eur. Comp. Int. Environ. Law* 29, 151–166. doi: 10.1111/reel.12358

Labrière, N., Locatelli, B., Vieilledent, G., Kharisma, S., Basuki, I., Gond, V., et al. (2016). Spatial congruence between carbon and biodiversity across forest landscapes of Northern Borneo. *Glob. Ecol. Conserv*. 6, 105–120. doi: 10.1016/j.gecco.2016.01.005

Larkin, A., Kuriakose, J., Sharmina, M., and Anderson, K. (2017). What if negative emission technologies fail at scale? Implications of the Paris agreement for big emitting nations. *Clim. Policy* 3062, 1–25. doi: 10.1080/14693062.2017.1346498

Leach, M., and Scoones, I. (2015). "Political ecologies of carbon in Africa," in *Carbon Conflicts and Forest Landscapes in Africa,* eds M. Leach and I. Scoones (London: Routledge), 1–42.

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., et al. (2019). Climate tipping points - too risky to bet against. *Nature* 575, 592–595. doi: 10.1038/d41586-019-03595-0

Li, G., Cheng, L., Zhu, J., Trenberth, K. E., Mann, M. E., and Abraham, J. P. (2020). Increasing ocean stratification over the past half-century. *Nat. Clim. Chang*, 10, 1116–1123. doi: 10.1038/s41558-020-00918-2

Lohmann, L. (2009). Toward a different debate in environmental accounting: the cases of carbon and cost–benefit. *Account. Organ. Soc*. 34, 499–534. doi: 10.1016/j.aos.2008.03.002

Lohmann, L. (2011). The endless algebra of climate markets. *Capital. Nature Soc.* 22, 93–116. doi: 10.1080/10455752.2011.617507

Lövbrand, E. (2004). Bridging political expectations and scientific limitations in climate risk management - on the uncertain effects of international carbon sink policies. *Clim. Change* 67, 449–460. doi: 10.1007/s10584-004-0080-6x

Lövbrand, E. (2009). Revisiting the politics of expertise in light of the Kyoto negotiations on land use change and forestry. *For. Policy Econ.* 11, 404–412. doi: 10.1016/j.forpol.2008.08.007

Low, S., and Schäfer, S. (2020). Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling. *Energy Res. Soc. Sci.* 60, 1–9. doi: 10.1016/j.erss.2019.101326

Mace, M. J., Fyson, C. L., Schaeffer, M., and Hare, W. L. (2021). *Governing Large-Scale Carbon Dioxide Removal: Are We Ready? - An Update*. New York, NY: Carnegie Climate Governance Initiative (C2G), February 2021.

MacKenzie, D. (2009). Making things the same: gases, emission rights and the politics of carbon markets. *Account. Organ. Soc.* 34, 440–455. doi: 10.1016/j.aos.2008.02.004

Mackey, B., Prentice, I. C., Steffen, W., House, J. I., Lindenmayer, D., Keith, H., et al. (2013). Untangling the confusion around land carbon science and climate change mitigation policy. *Nat. Clim. Chang.* 3, 552–557. doi: 10.1038/nclimate1804

McAfee, K. (2016). Green economy and carbon markets for conservation and development: a critical view. *Int. Environ. Agreements* 16, 333–353. doi: 10.1007/s10784-015-9295-4

McLaren, D. (2020). Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. *Clim. Change* 162, 2411–2428. doi: 10.1007/s10584-020-02732-3

McLaren, D., and Markusson, N. (2020). The co-evolution of technological promises, modelling, policies and climate change targets. *Nat. Clim. Chang.* 10, 392–397. doi: 10.1038/s41558-020-0740-1

McLaren, D., Tyfield, D. P., Willis, R., Szerszynski, B., and Markusson, N. O. (2019). Beyond "Net-Zero": a case for separate targets for emissions reduction and negative emissions. *Front. Clim.* 1:4. doi: 10.3389/fclim.2019.00004

NewClimate Institute (2020). *Navigating the Nuances of Net-Zero Targets*. Avaialble online at: https://newclimate.org/2020/10/22/navigating-the-nuances-of-net-zero-targets/#:~:text=This%20report%20analyses%20the%20momentum,and%20enhance%20support%20towards%20them

Palter, J. B., Frölicher, T. L., Paynter, D., and John, J. G. (2018). Climate, ocean circulation, and sea level changes under stabilization and overshoot pathways to 1.5g€K warming. *Earth Syst. Dyn.* 9, 817–828. doi: 10.5194/esd-9-817-2018

Pearse, R., and Böhm, S. (2014). Ten reasons why carbon markets will not bring about radical emissions reduction. *Carbon Manage.* 5, 325–337. doi: 10.1080/17583004.2014.990679

Pozo, C., Galán-Martín, Á., Reiner, D. M., Mac Dowell, N., and Guillén-Gosálbez, G. (2020). Equity in allocating carbon dioxide removal quotas. *Nat. Clim. Chang.* 10, 640–646. doi: 10.1038/s41558-020-0802-4

Rogelj, J., Geden, O., Cowie, A., and Reisinger, A. (2021). Three ways to improve net-zero emissions targets. *Nature* 591, 365–368. doi: 10.1038/d41586-021-00662-3

Rogelj, J., Huppmann, D., Krey, V., Riahi, K., Clarke, L., Gidden, M., et al. (2019). A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* 573, 357–363. doi: 10.1038/s41586-019-1541-4

Rogelj, J., Shindell, D., and Jiang, K. (2018). Chapter 2: Mitigation pathways compatible with 1.5°C in the context of sustainable development. in *IPCC Special Report on "Global Warming of 1.5°C"*. Available online at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., and Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos. Trans. Roy. Soc. B Biol. Sci.* 375:20190120. doi: 10.1098/rstb.2019.0120

Seddon, N., Turner, B., Berry, P., Chausson, A., and Girardin, C. A. J. (2019). Grounding nature-based climate solutions in sound biodiversity science. *Nat. Clim. Chang.* 9, 84–87. doi: 10.1038/s41558-019-0405-0

Sheppard, E. (2012). Trade, globalization and uneven development: entanglements of geographical political economy. *Prog. Hum. Geogr.* 36, 44–71. doi: 10.1177/0309132511407953

Shue, H. (2017). Climate Dreaming: negative emissions, risk transfer, and irreversibility. *J. Hum. Rights Environ.* 8, 203–216. doi: 10.1038/nature18307

Shue, H. (2019). Subsistence protection and mitigation ambition: necessities, economic and climatic. *Br. J. Polit. Int. Relat.* 21, 251–262. doi: 10.1177/1369148118819071

Skelton, A., Larkin, A., Ringsmuth, A., Greiser, C., in, Fopp, D., McLaren, D., et al. (2020). 10 myths about net zero targets and carbon offsetting, busted. *Climate Home News*. Available online at: https://www.climatechangenews.com/2020/12/11/10-myths-net-zero-targets-carbon-offsetting-busted/

Smith, N. (2008). Uneven Development; Nature, Capital, and the Production of Space. Athens, GA: The University of Georgia Press.

Smith, S. M. (2021). A case for transparent net-zero carbon targets. *Commun. Earth Environ.* 2:24. doi: 10.1038/s43247-021-00095-w

Stanton, E. A., Ackerman, F., and Kartha, S. (2009). Inside the integrated assessment models: Four issues in climate economics. *Clim. Dev.* 1, 166–184. doi: 10.3763/cdev.2009.0015

Steffen, W., Fenwick, J., and Rice, M. (2016). *Land Carbon: No Substitute for Action on Fossil Fuels*. Available online at: https://www.climatecouncil.org.au/uploads/aadc6ea123523a46102e2be45bfcedc8.pdf

Timperley, J. (2019). Brazil fights attempt to cancel its old carbon credits. *Climate Home News*. Available online at: https://www.climatechangenews.com/2019/10/11/brazil-fights-attempt-cancel-old-carbon-credits/

Tokarska, K. B., and Zickfeld, K. (2015). The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Environ. Res. Lett.* 10:094013. doi: 10.1088/1748-9326/10/9/094013

Turnhout, E., Skutsch, M. M., and de Koning, J. (2015). "Carbon accounting," in *Research Handbook on Climate Governance*, eds K. Bäckstrand and E. Lövbrand (Cheltenham: Edward Elgar Publishing), 366–376. doi: 10.4337/9781783470600.00044

Upton, S. (2019). *Farms Forests and Fossil Fuels: The Next Great Landscape Transformation?* Available online at: https://www.pce.parliament.nz/media/196523/report-farms-forests-and-fossil-fuels.pdf

Waller, L., Rayner, T., Chilvers, J., Gough, C. A., Lorenzoni, I., Jordan, A., et al. (2020). Contested framings of greenhouse gas removal and its feasibility: social and political dimensions. *Clim. Change* 11, 1–17. doi: 10.1002/wcc.649

Wang, S., Zhang, Y., Ju, W., Chen, J. M., Ciais, P., Cescatti, A., et al. (2020). Recent global decline of CO_2 fertilization effects on vegetation photosynthesis. *Science* 370, 1295–1300. doi: 10.1126/science.abb7772

Wang, S., Zhuang, Q., Lähteenoja, O., Draper, F. C., and Cadillo-Quiroz, H. (2018). Potential shift from a carbon sink to a source in Amazonian peatlands under a changing climate. *Proc. Natl. Acad. Sci. U.S.A.* 115, 12407–12412. doi: 10.1073/pnas.1801317115

Wei, Y. M., Kang, J. N., Liu, L. C., Li, Q., Wang, P. T., Hou, J. J., et al. (2021). A proposed global layout of carbon capture and storage in line with a 2 °C climate target. *Nat. Clim. Change* 11, 112–118. doi: 10.1038/s41558-020-00960-0

West, T. A. P., Börner, J., Sills, E. O., and Kontoleon, A. (2020). Overstated carbon emission reductions from voluntary REDD + projects in the Brazilian Amazon. *Proc. Natl. Acad. Sci. U.S.A.* 117, 24188–24194. doi: 10.1073/pnas.2004334117

WGBU (1998). *The Accounting of Biological Sinks and Sources Under the Kyoto Protocol: A Step Forwards or Backwards for Global Environmental Protection?* Available online at: https://www.wbgu.de/en/publications/publication/die-anrechnung-biologischer-quellen-und-senken-im-kyoto-protokoll-fortschritt-oder-rueckschlag-fuer-den-globalen-umweltschutz

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Boundary Work and Interpretations in the IPCC Review Process of the Role of Bioenergy With Carbon Capture and Storage (BECCS) in Limiting Global Warming to 1.5°C

Anders Hansson[1], Jonas Anshelm[2], Mathias Fridahl[1] and Simon Haikola[3]*

[1] Unit of Environmental Change, Department of Thematic Studies, Centre for Climate Science and Policy Research, Linköping University, Linköping, Sweden, [2] Unit of Technology and Social Change, Department of Thematic Studies, Linköping University, Linköping, Sweden, [3] Unit of Technology and Social Change, Department of Thematic Studies, Centre for Climate Science and Policy Research, Linköping University, Linköping, Sweden

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Edited by:
Etsushi Kato,
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Helmholtz Centre for Environmental Research (UFZ), Germany

***Correspondence:**
Anders Hansson
anders.n.hansson@liu.se

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Paris Agreement-compatible emissions pathways produced by integrated assessment models (IAMs) often rely on large amounts of carbon dioxide removals, especially afforestation and bioenergy with carbon capture and storage (BECCS). These pathways feature prominently in the work of the Intergovernmental Panel on Climate Change (IPCC), to the extent that the IAMs have been granted an interpretative privilege at the interface between climate science, economics, and policymaking. The privilege extends to and influences climate governance, including governance of BECCS. This paper contributes to recent debates about the role of the IPCC, and its framing of BECCS, at the science-policy interface. By analyzing all BECCS-related expert review comments and author responses on the IPCC Special Report on Global Warming of 1.5°C, the paper shows that boundary work influences the representation of BECCS by authors referring to: (1) a limited scope or capacity; (2) a restrictive mandate; (3) what constitutes legitimate science, and; (4) relativizing uncertainties. The responses to the review comments indicate a significant degree of compliance on behalf of the authors. Yet, the revisions do not seem to go to the heart of the unease that runs through many of the reviewer comments, i.e., that BECCS seems to be presented as a viable CDR technology at grand scale. While several revisions serve to clarify uncertainties surrounding BECCS, some fundamental aspects of the critique are deflected, through the boundary work identified. What the analysis reveals, beyond a dissatisfaction among many reviewers with the focus on integrated assessment modeling, the associated pathway literature, and analysis of BECCS, is a disagreement about how model results should be interpreted and communicated. While acknowledging the herculean task of the IPCC and the efforts to improve the pathway literature that the SR1.5 triggered within the IAM communities, we argue that the identified boundary work also risks entrenching rather than problematize dominant framings of the feasibility of BECCS. Such entrenchment can counteract the ambition of opening up the scientific work of the IPCC to include more diversity in the process of drafting reports, and arguably also influence the governance of CDR.

Keywords: the Intergovernmental Panel on Climate Change, 1.5°C warming, bioenergy with carbon capture and storage, carbon dioxide removal, boundary work, integrated assessment models, BECCS, IAM

INTRODUCTION

Integrated assessment models (IAM) and their associated climate mitigation scenarios were key features in the Intergovernmental Panel on Climate Change's (IPCC) second assessment report, published in 1995, and their importance has increased in later years (Beck and Mahony, 2018; Gambhir et al., 2019; Hilaire et al., 2019; van Beek et al., 2020). As of 2015, the IAM community has responded to the UN Framework Convention on Climate Change's (UNFCCC) Paris Agreement by forcing their models to resolve pathways capable of holding global warming well below 2 or 1.5°C. This includes the massive deployment of negative emissions technologies (NETs) and, in particular, bioenergy with carbon capture and storage (BECCS) (on average 5–20 $GtCO_2$/yr by mid century) (e.g., Fuhrman et al., 2019; Rogelj et al., 2019). Thus, the unprecedented rate of climate mitigation scenarios intended to resolve stringent temperature targets can be understood in light of the UNFCCC's invitation to the IPCC *special report* on the impacts of *global warming of 1.5°C* above pre-industrial levels and related global greenhouse gas emission pathways (IPCC, 2016: 21§, decision 1/CP.21) and IA modelers who strive to be policy relevant. The IPCC accepted this invitation despite the fact that very few IAM-derived climate mitigation scenarios at that point in time depicted the goal as achievable (Livingston, 2018), and begun its work on what was to become its Special Report on Global Warming of 1.5°C (SR1.5), finalized in October 2018 as part of its sixth assessment cycle.

Guided by scenario estimates from SR1.5, carbon dioxide removals (CDR), achieved through deliberate deployment of negative emissions technologies (NETs), would sum to between 260 and 1,080 gigatons in the period 2020 to 2100 (IPCC, 2018). In the scenarios, BECCS would, on average, withdraw 550 gigatons accumulated over the latter half of the century, despite the method being merely in a demonstration phase (Mander, 2018). There is no scientific support for the upper ends of the range being realistic and possible to reconcile with other sustainability goals (e.g. EASAC, 2018; Carton, 2019; Haikola et al., 2019; Hu et al., 2020; Workman et al., 2020). There are currently no methods for CDRs, besides forest management and reforestation, that even approach the volumes needed to contribute to climate mitigation in any meaningful way, (Fuhrman et al., 2019). Carton et al. (2020) conclude, based on a literature review, that the forest-based CDRs are not proven at scale, and argue that the history of carbon removal, including afforestation, challenges the very idea of forest-based NETs.

The IAMs are called integrated since they combine input from many scientific disciplines to consider interlinkages between climate-, economic-, energy-, and land use systems, which perform a form of multi-criteria assessment of the economic value of various options to mitigate climate change. The nature of IAMs makes them particularly relevant for the IPCC report chapters that deal with mitigation and have a policy- or solution-oriented approach. Thus, these IAMs have an interpretative privilege at the interface between climate science, economics, and policymaking (Livingston, 2018; Haikola et al., 2019; Livingston and Rummukainen, 2020; Low and Schäfer, 2020), and have also gained an aligning role in the negotiation between science and policy (van Beek et al., 2020). van Beek's et al. (2020) review of IAMs in the science and policy interface since the 1970s show that modelers have not only been reactive to societal demands and formulated responses, but have also anticipated and helped policy makers to formulate new goals, most prominently the 1.5°C aspirational goal.

Critique has been put forth that the current generation of IAMs are black boxed or unfit for policymaking since scientific uncertainties are resolved based on arbitrary or culturally-biased assumptions, they use unrealistic input data, normativity and bias are not disclosed or dealt with, and ethical consequences are neglected (Ellenbeck and Lilliestam, 2019; Haikola et al., 2019; Low and Schäfer, 2020; Workman et al., 2020). The critique has reached beyond the role of IAMs, and extends to the scope of the IPCC, its neutrality, scientific rigor, and integrity. Another strand of criticism focuses on the possibly performative, mitigation-deterring role of IAMs that depict net negative emissions as feasible through so called overshoot scenarios, where near-term emissions reductions are postponed or even canceled because they are perceived as costly (e.g., Geden, 2015; Markusson et al., 2018; Asayama and Hulme, 2019; Carton, 2019; Ellenbeck and Lilliestam, 2019; Workman et al., 2020).

As a response to the critique, the IPCC's ambition with the SR1.5 was already from the onset to be more transparent and more interdisciplinary than previous reports. As the SR1.5 is scientifically more diverse and also more influenced by political demands and requests to be policy relevant, it has arguably become more difficult to maintain distinctions between science and policy. However, the new ideals potentially also open up for a re-negotiation of the hierarchy or traditional boundaries between different sciences and perspectives and, potentially, for leaving the more traditional and quantitative practices of the past (Livingston, 2018, see also; Sundqvist et al., 2018; Workman et al., 2020).

The aim of this paper is to contribute to recent debates about the role of the IPCC at the science-policy interface and the governance implications of how the IPCC frames and communicates the potential role of CDR in global responses to climate change (e.g., Beck and Mahony, 2018; Livingston, 2018; Haikola et al., 2019; Carton, 2020; Low and Schäfer, 2020; Workman et al., 2020). Empirically, the paper investigates the critical review comments to the second order draft of the SR1.5, related to BECCS, and the author responses. Through the lens of the concept boundary work (the rhetoric to distinguish one thing from another thing, e.g., Gieryn, 1983), and in particular in relation to IAMs and BECCS, we will first briefly summarize the critical comments put forth by the reviewers and then analyze how the SR1.5 authors responded by delimiting relevant and accurate science. Finally, we conclude with a discussion of responses to the general critique of IAMs put forth both within and beyond the IAM communities, and what challenges we can see from having the type of boundary work observed influence the IPCC review processes. Thus, by investigating scientific discussions on BECCS in climate mitigation scenarios and in relation to IAMs and how the forwarded critique is dealt with in the IPCC's review process, insights can also be gained into how the increased ambitions for interdisciplinarity play out (i.e., Callaghan et al., 2020). Even though all review comments and IPCC author responses are publicly available already, the sheer amount of comments arguably makes the central conversations difficult to comprehend and assess for a reader. Thus, by the summary this paper also contributes to the transparency of the review process.

BACKGROUND: THE IPCC'S MANDATE AND INTEGRATED ASSESSMENT MODELS

The IPCC is governed by principles that specify its mandate, procedures, and organization (IPCC, 2013), including its specific mandate: "to assess on a comprehensive, objective, open and transparent basis the scientific, technical, and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation" (6§). Importantly, the IPCC reports should be "neutral with respect to policy" (6§) but are allowed to "deal objectively with scientific, technical and socio-economic factors relevant to the application of particular policies" (6§). This, for short, has been termed the principle of providing policy-relevant yet policy-neutral assessments. Sundqvist et al. (2018) and Thoni and Livingston (2021) make clear that the consensus approach and tight coupling of science and policy often lead to the marginalization of alternatives, and that the often-narrow definitions of science in the IPCC contexts lead to a scientific reductionism.

If first constrained by a specific climate objective or other types of assumptions, the IAMs can be run to generate least cost pathways for transitioning the world in a manner that is compatible with the model constraints. This has resulted in a prioritization of BECCS among the NETs in the IAM-derived scenarios aimed at the most stringent targets (RCP1.9), and only 0.1% of these scenarios represent NETs other than BECCS, afforestation, or reforestation (Workman et al., 2020)[1]. As noted by Gambhir et al. (2019), BECCS has made "some of the most stringent mitigation targets achievable in the framework of the IAMs" (p. 2). While BECCS was originally proposed as a backstop technology to manage risks (Obersteiner et al., 2001) and later featured in a minority of IAMs to resolve more stringent targets during the IPCC's fourth review cycle (Tavoni and Socolow, 2013), it has now become vital as an equation solver for the Paris Agreement's temperature goal (Fuss et al., 2014; Minx et al., 2017; Gambhir et al., 2019).

Livingston and Rummukainen (2020) argue that the science-policy interactions of the SR1.5 are unusual, in addition to the fact that this was the first IPCC report to include all three working groups, in the sense that science and policy were even more blurred regarding both institutional set up and processes than was the case for previous reports. They conclude that the consideration of the 1.5°C aspirations made climate change as an object of governance more complicated, subjective, and multiple, not the least because of a lack of agreement from both a scientific and a political perspective on the suitability of actually including 1.5°C in the Paris Agreement in 2015. Their interviews with IPCC authors reveal that the unexpected and unusual request from the UNFCCC to the scientific community, to investigate the novel more stringent targets, confirm the observation that these targets were considered unrealistic by many scientists (see also van Beek et al., 2020). This may illustrate an inverted process compared to first settling the science and then opening up for political deliberations. Thus, the UNFCCC aspirational goal to limit global warming to 1.5°C, and how it was scientifically assessed, challenged the traditional norms of the IPCC.

METHODOLOGY

Boundary Work and the IPCC Review Process

IPCC reports must balance scientific validity with policy relevance, and that relation is produced and reproduced discursively (Huitema and Turnhout, 2009). Like Low and Schäfer's (2020) interview study of the contested authority of IAMs and the feasibility of BECCS, our paper departs from boundary work as an analytical framework. Boundary work entails rhetorical strategies—applied intentionally as well as unintentionally—to distinguish one thing from another thing, for example to distinguish relevant science and knowledge and to structure language between the positive and negative and between what is included and excluded (Gieryn, 1983; Friman, 2010). Boundary work also entails distinguishing boundaries between science and politics and also distinguishing the objective from the subjective, and that kind of boundary work has arguably recently become more salient in the recent debates on the IPCC's work processes (see also Frickel, 2004; van der Sluijs, 2005; Livingston, 2018). The procedural structure and work that takes place during revisions of an IPCC report indicate the frame for the boundary work, as they instruct the types of texts to

[1]The number 0.1% was assessed from the IIASA 1.5 scenario explorer in May 2019 by Workman et al. (2020).

include or exclude, what terminology to use, and how to define the overarching scope and aim of the report. Nonetheless, the instructions are interpreted by the IPCC authors and reviewers, and are also often referred to, implicitly or explicitly, by the actors in their boundary work. We will investigate how boundary work took place in the drafting of the SR1.5 report by looking at how critical comments are taken care of in general, and more importantly also the arguments presented in the cases when assessed as not being a basis for modifying the draft text or being possible to integrate.

The initial step in drafting an IPCC report is taken at a closed scoping meeting at which experts draft a report outline. The experts are selected by the relevant WG bureau from a list of nominees solicited from governments, observer organizations, and IPCC bureau members (IPCC, 2013). After the scoping meeting, the bureaux of the WGs and Task Force selects authors to be engaged in drafting the report(s). Criteria such as mix of expertise, gender balance, geographical origin, and previous experience in IPCC work are to be considered when selecting scoping meeting experts as well as authors. The authors then proceed to assess the scientific literature on issues within its mandate and the scope of the report. At the first lead author meeting, the authors also receive instructions on appropriate IPCC procedures, the type of sources that may or may not be included in the assessments, and how to calibrate uncertainty language (Mastrandrea et al., 2011; IPCC, 2013).

The review process is generally done in three steps: an expert review of the first order draft of the longer report(s), government and expert review of the second order draft(s), and government review of the summaries for policymakers (SPMs) and overview chapters and/or the synthesis report of the longer underlying reports prepared by each WG. Expert reviewers self-nominate and are then selected by the IPCC on the basis of expertise. The technical support units of the IPCC's WGs may also identify people with relevant expertise and directly invite them to nominate themselves as reviewers (IPCC, 2013). Every chapter is designated review editors, who attend lead author meetings and raise issues and concerns during the two review rounds. The review editors have continuous contact with the lead author teams regarding responses to review comments. The review editors also publish a final report for each chapter in order to describe the review process, describe the main areas of concern arising from the review comments, and confirm that contentious and controversial issues have been addressed and how they have been handled (IPCC, 2013, 2017, 2019a).

From 541 nominations, 91 coordinating lead authors, lead authors, and review editors from 44 countries were singled out for the SR1.5[2]. In addition, 133 contributing authors were invited by the chapter teams to provide specific input. As the comprehensive amount of review comments—40 001 in total, contributed by 796 individual reviewers and 65 governments—and author responses are very well-documented (IPCC, 2019b,c,d), and the authors clearly and systematically motivate their responses to all comments, this material constitutes exemplary material to scrutinize the boundary work at the interface of science and policy and in-between various sciences and perspectives.

Method and Analysis

The empirical focus in this paper is limited to a qualitative analysis of the critical reviewer comments and author responses to three chapters of the second draft, and not the final versions, however we include the authors' claims on how the texts were revised in the final versions, but we do not assess whether those revisions were undertaken or not. The material is publicly available, and the IPCC editors have presented all review comments and author responses in a transparent and accessible way (IPCC, 2019b,c,d). The dialogue between reviewers and authors is of primary analytical relevance for the analysis, and we have no reason to believe that the stated revisions were not undertaken.

The three chapters were selected due to their reliance on IAMs and the relatively high share of the acronym BECCS of the total word content: Summary for Policymakers, Chapter 2, and Chapter 4 (see **Table 1** below for an overview of the chapters and comments). All comments ($n = 717$) including BECCS were read (The term "Bioenergy with carbon capture" did not appear in isolation from BECCS in the documents). Recurring themes and topics in the second reading were identified and ordered into categories applying a bottom-up approach, i.e., critique of bias in favor of BECCS; critique of how BECCS ecological, social, political, and economic consequences are described and analyzed; BECCS feasibility; BECCS and IAMs; land-use; and BECCS in relation to natural CDRs. The themes in the third reading were reduced to "reviewers' critique of biased framings," "lack of realism," "criticism of assumptions," and "neglect of alternatives." The themes overlap somewhat and are not mutually exclusive and single comment, especially the longer comments, can be ordered into several categories. Minor comments on e.g., language, missing space, and punctuations or inconsistencies and lack of clarity that are easily addressed are omitted from the analysis. An overall impression of the critical comments including BECCS is that they often convey a coherent questioning of not only the prominent position BECCS received in the draft but also bring attention to crucial issues concerning the meaning of feasibility, framings and interpretations of the main message the report presents, the role of assumptions and methodology, as well as boundary settings. The analysis was inter-coded by two of the article authors, and a third author cross-checked a larger sample of references at a later stage.

The author comments have been ordered into four categories that can be seen as illustrations of boundary work. Also the reviewers perform boundary work, but the present study is analytically limited to the authors' boundary work because authors must respond explicitly to all review comments (which enables a more transparent analysis) and also make the final decisions on how to revise the report, i.e., draw the boundaries. The strength of the inductive approach is that it allows for sensitivity to how the authors responded to critical comments, in contrast to defining and applying boundary work categories already identified in previous research. Boundary work is context dependent and previous research suggests that the

[2]List of authors and editors: https://www.ipcc.ch/sr15/authors.

TABLE 1 | The share of the acronym BECCS of the total content of the review comments and responses to the first order draft of the Summary for Policymakers and individual chapters of the second order draft of the full report.

Chapter	Comments with references to BECCS	BECCS share of the total word content [‰]	Review comments[a] (total/of substance)[b]
Summary for Policymakers[c]	**133**	**0.3**	**NA**
Chapter 1: Framing and context	33	0.1	11 074/NA
Chapter 2: Mitigation pathways compatible with 1.5°C in the context of sustainable development	**350**	**0.6**	**3 724/2 088**
Chapter 3: Impacts of 1.5°C of global warming on natural and human systems	41	0.1	4 209/3 874
Chapter 4: Strengthening and implementing the global response	**234**	**0.3**	**4 409/NA**
Chapter 5: Sustainable development, poverty eradication and reducing inequalities	45	0.1	2 299/NA

[a] *IPCC, 2019b,c,d).*
[b] *IPCC (2019a). Review comments that are not of substantive nature are, for example, editorial in nature, pertain to references, or relate to the use of uncertainty language.*
[c] *Chapters marked in bold are those that have been selected for analysis.*

TABLE 2 | The four boundary work modes.

Boundary work mode	Examples of rhetoric and coding
1) Remitting or referring to a limited scope or capacity.	Selection of literature argued to be not in line with the scope of the chapter; impacts on a certain SDG are outside the scope of the report or chapter; the issue is too complex for the authors; space restrictions.
2) Claiming to be beyond the mandate: subjective and policy prescriptive.	Land-use issues are within the mandate of another forthcoming IPCC report; excluding BECCS from the analysis is policy prescriptive/subjective; the mandate is to reflect assessments in the scientific literature only.
3) Restricting and defining what is legitimate science.	A certain field of literature (i.e., the pathway literature) defines what is relevant to include, cannot conduct an analysis beyond what is already conducted in the relevant literature; the reviewer's suggested literature does not meet scientific criteria.
4) Relativizing uncertainties.	A specific problem/challenge/obstacle is also valid, or worse, for another alternative; a global energy transition will involve a large land footprint regardless of whether BECCS is implemented or not; most CDRs are untested.

work procedures of the IPCC, contentious topics and views on uncertainty and policymaking change over time (e.g., Livingston and Rummukainen, 2020), thus the inductive approach opens up for a more open-minded exploration of boundary work not already discussed in the literature. We inductively constructed four boundary work modes (see **Table 2**), and as will be elaborated on in the Discussion (chapter 5), they are not mutually exclusive and some modes often interact or overlap. The boundary work modes were constructed by reading the authors' rebuttals or partial rebuttals of critical comments, but the complying responses were not analyzed. Taken together the four modes hopefully convey most rhetorical means that were deployed. One can argue that a fifth mode could have been added—neglecting a comment—but instead we decided to merely mention when that occurred. The table above (**Table 2**) shows the four boundary work modes and exemplifies how they were coded and identified.

ANALYSIS AND RESULTS

This chapter exclusively summarizes content of the comments and responses. The first sub-section (The reviewers' critique of BECCS) presents the reviewer comments and the second sub-section (The authors' responses) thematically structures salient and recurring themes derived from the review comments and author responses in the three analyzed chapters[3]. The latter section, based on the author responses, also discusses the material but in relation to four inductively-derived boundary work modes: (1) remitting or referring to a limited scope or capacity, (2) claiming to be beyond the mandate: subjective and policy prescriptive, (3) restricting and defining what is legitimate science, and (4) relativizing uncertainties. **Table A1** shows the 15 reviewers that submitted the largest number of critical comments.

The Reviewers' Critique of BECCS

A central line of the critique raised by reviewers is that the second order draft of SR1.5 is strongly biased in favor of BECCS, and that the report underplays fundamental uncertainties related to technical, socio-political, and ecological aspects. Some reviewers

[3]References to review comments and responses follow the unique numbering assigned by the IPCC review editors with prefix letters added to facilitate the identification of the context in which the comments have been given; "A" denotes a reviewer or author comment to the SPM (IPCC, 2019b), "B" denotes chapter 2 (IPCC, 2019c), and "C" denotes chapter 4 (IPCC, 2019d). The list of references is illustrative and not exhaustive.

have even gone so far as to claim that the unwarranted focus on BECCS in the draft conflicts with the IPCC's intention to present comprehensive and unbiased assessments[4]. This, however, is framed in somewhat different terms in the chapters analyzed in the present paper. Comments to chapter 2 are the most technically oriented, while they also highlight perceived problems with how BECCS is represented in IAMs. Similarly, comments to the SPM also aim to incorporate caveats and limitations in IAMs and is concerned with the overall impression given by that chapter, which, according to some reviewers, gives a dangerously favorable impression of the real potential of BECCS that is not substantiated by the science. Comments to chapter 4 more often tend to focus critically on the feasibility aspect of BECCS and draw more attention to issues of policy and governance[5].

Many reviewers argue that portrayal of BECCS as necessary for achieving the 1.5°C target is unfounded and over-emphasized, or that the report itself does not support the heavy reliance on BECCS in the pathways. Several comments stress that BECCS is not proven at scale and conclude that should be clearer communicated. Additional comments state that it is irresponsible or even unethical, to let scenarios compatible with 1.5°C rely so heavily on BECCS and afforestation as the only CDR methods without explaining this single-minded focus[6]. The reason for the bias is occasionally claimed to be the IAMs' internal logic, which according to reviewers privilege large-scale techno-fixes and foster technological determinism or results in systematic neglect of alternatives[7]. The draft report is also criticized for cherry-picking or highlighting scenarios that rely heavily on BECCS, even though scenarios without BECCS or with only small proportions of BECCS and other NETs are available. Some reviewers argue for re-phrasing or removing wording that suggests all scenarios need BECCS in order to reach 1.5°C[8].

A wide array of what is argued to be less speculative CDR alternatives to BECCS is put forth in comments by reviewers. These methods sometimes described as more natural, include land-use management, changed agricultural practices, and restoration of ecosystems including forests, and are seldom or never included in the IAMs. Several reviewers argue that the so called natural CDRs are more ecologically sustainable, tested at larger scale, less expensive, involve fewer risks, and may enhance food and water supply security[9]. Also other CDR methods, such as direct air carbon capture and storage (DACCS), afforestation and regenerative agriculture, are suggested in one comment to be "preferable" but insufficiently covered in the IAMs in spite of being, they argue, more feasible, desirable and ethical than BECCS at scale[10]. Other—more mature, less costly and far less speculative—mitigation options and paths to decarbonization are claimed by reviewers to be unwarrantedly ignored, such as improved solar and wind power, scaling down of agri-food systems, forest restoration, methane and nitrification inhibition, reduced energy demand, and nuclear power[11]. An important problem with the draft, as identified by reviewers, is that its reliance on integrated pathways literature, and bias or neglect of options in the IAMs underpinning the mitigation pathways, means many mitigation methods are not analyzed[12].

Some reviewers also criticize what they perceive as the presentation, in the draft, of afforestation and BECCS as equally feasible. This, they claim, is misleading as the former has already been implemented at scale and provides several co-benefits. The future cost of BECCS is understood by some reviewers to be inherently impossible to estimate, while afforestation, in contrast, is argued to be possible to cost-efficiently scale-up[13]. Both methods entail land-use problems, the reviewers argue, and some suggest that claims that BECCS is better than afforestation should firmly be avoided[14].

Several reviewers criticize what they perceive as a lack of transparency in general, or regarding how the range of scenarios were selected. Many call for more transparent discussion about the strength and weaknesses of IAMs and crucial model assumptions[15], including discount rates, natural sinks, land-use effects and land-use trade-offs[16], hydrological and water aspects and nutrient loss from soils[17], biomass productivity rates and crop yields[18], and technological learning and economies of scale[19]. For some, the extremely high levels of BECCS deployment in reviewed scenarios depend on calculations that are either untraceable, unrealistic, or rest on flawed assumptions. Some of these comments forward that if these calculations and assumptions are not dealt with in a scientifically robust manner, together with the general limitations, biases and strengths of IAMs[20], the narrative of a BECCS-dominated path to 1.5°C is either not trustworthy or comprehensible[21].

According to some comments to chapter 4, where the most colorful remarks are to be found, the draft text is suffused with magical thinking because it treats model results as reality, or does not explain how the apparent contradiction between what is feasible in the models and feasible in reality should be interpreted[22]. According to several reviewers, the lack of transparency around climate scenarios and their underlying assumptions results in a potentially deceptive impression of the maturity and feasibility of BECCS. Because of the draft report's reliance on IAMs, some argue, BECCS is represented as feasible

[4]e.g., A19436, B51036, B53970, B55468, B55478.

[5]e.g., C13342, C31658, C60780.

[6]A42862, A42912, A43810, A43858, A43738, A50414, A51160, B51038, cf. B53260, B53492.

[7]A19360, A19362, B51036, B55478, C51048.

[8]A19436, A56512, A62906, C19708, C19756, C24386, C53268, C55700.

[9]A19002, A29556, A50036, A51072, A51074, A51166, B19614, B19628, B51038, B53970, B54512, B55480.

[10]A43858, A43810.

[11]B2072, B3198, B19614, B19628, B51038, B53970, B54512, B55468, B59926, C52072.

[12]A19436, B11824, B19614, B51038, B59926, B55478, B55468.

[13]A29182, A30100, B53260, B59998, C18618, C39300, C53264, C53266, C56052.

[14]C18618, C51522, C53266, cf. C62786.

[15]B11708.

[16]B11700, B11708, B11800, B19310, B19624, B27962, B51036, B51148, B56872.

[17]B13924, B15730, B53262.

[18]B18110, B37376.

[19]B2072, C37212.

[20]A19360, A19362, B51036, B51038, C51044, C51196, C53248, B55468.

[21]A49532, A56506, A59256, B11700, B37398, B55468, C51044, C53250, C53258.

[22]C51044, C53246, C53258, C53264, C53268, see also A19362, B11700, B18010, B37398.

at an unrealistic scale or in a way that is contradicted even by findings reported on elsewhere in the SR1.5 draft[23].

If, some reviewers argue, the conclusion is that the 1.5°C target is only possible to achieve with large scale BECCS deployment, the risks related to relying on an unproven method with low feasibility should be clearly spelled out[24]. Several reviewers call for explicit accounts of the lack of scientific support for anything but very limited or slow implementation of BECCS[25]. A few reviewers comment on what they see as a neglect and underestimation of severe limitations to BECCS deployment, as well as questionable statements that BECCS would entail positive side-effects (e.g., lower food prices)[26].

The availability of land is another frequently raised concern. Several reviewers observe as remarkable the assumption made for some pathways, e.g., that 25–46% of the available arable land will be included in future BECCS systems. Such land use would, they note, significantly impact the potential to achieve other SDGs or result in forest degradation, social tensions, biodiversity losses, or reduced food security, conflicts many reviewers argue need to be explained in more detail[27]. In chapter 4, one reviewer, the director at the NGO "The Partnership for Policy Integrity," argues that some pathways entail land areas for biomass production that "would strike most people as insane," but that the report treats these numbers as unproblematic[28].

The scenarios' heavy reliance on bioenergy use is a point of concern for reviewers, not only for what this reliance implies in terms of land use change, but also for the wider energy system repercussions when limited bioenergy resources are devoted to BECCS. This would supposedly make fossil phase-out more difficult if it means less bioenergy available to substitute for fossil fuels in other sectors. This is one additional factor that reviewers identify as a risk for fossil lock-in due to an overreliance on BECCS, besides the neglect of alternative ways for decarbonization[29]. In addition to impacts on food security and biodiversity, the land-use associated with biomass production for large-scale BECCS is occasionally suggested to imply substantial governance challenges, including potentially negative economic and political consequences[30].

All these comments are often summed up in the frequently recurring message that massive implementation of BECCS has been envisioned as achievable only because extensive problems associated with its implementation have not been taken into account. Several reviewers emphasize that detrimental land-use effects, economic costs, and other systemic risks associated with large-scale BECCS are of such a magnitude that BECCS must be rejected as an option for removing CO_2 at scale. Instead some argue that alternative CDRs, that pose lower risks, are more readily available. Thus, the option to cope with only low levels of CDR, or without CDR entirely, should, according to some comments, be presented as preferable[31].

The harsh, comprehensive, and intense criticism that several reviewers articulate is obviously an expression of fundamental disagreements, even though they are for the most part conveyed in a restrained manner. However, some voices diverge (two university professors and two NGO representatives) from this pattern by use of a more contentious rhetoric. Among these voices, accusations that the report does not at all rest on scientific objectivity, rationality, and policy neutrality are recurrent. On the contrary, the draft is said to be permeated with irrational and unfounded beliefs. A few reviewers maintain that the report's reliance on BECCS resembles the belief in "fairy dust"[32] or "magical thinking" and "is frankly absurd" [33], or being "practically a fantasy"[34], and another understands this reliance on BECCS as a result of a "teleological determinism" [35] in the IAMs, and that singling out BECCS as the main option for negative emissions "makes no sense"[36]. The two latter reviewers also claim that the IAMs relied upon in the draft include "insane" assumptions,[37] or present "crazy numbers"[38]. In a similar manner, another reviewer argues that the narratives and messages concerning BECCS and negative carbon systems appear to be "a house of cards"[39].

The polemical tone and the provocative statements of some reviewers bear witness to the contentiousness of BECCS in the review process and to the importance that was attributed to the draft's analysis of BECCS. It was partly against this backdrop of harsh criticism, sometimes couched in polemical language, that boundary work guided the revised version of the report toward scientific rigor and objectivity as well as policy neutrality.

The Authors' Responses

The reviewer comments are generally met with at least some degree of compliance by the authors, who in most cases clearly acknowledge the validity of the comment in question. In many instances, authors also claim to have responded accordingly by making the required revisions to the text. This is true for the many comments that point to the need to further highlight the fact that BECCS remains unproven at scale, while the feasibility claims are nuanced by insertion of caveats and clarifications that certain results rest on pathway literature, or by authors highlighting that BECCS is more uncertain and harder to assess than for example low-energy scenarios[40]. In chapter 4, especially, authors claim to have developed or clarified the feasibility

[23] A19436, A19360, A49532, B30878, B30880, B53492, B55468, A56506, A59256, C12292, C30976, C51044, C51196, C53246, C53248, C57876.
[24] C22774, C57876.
[25] C28472, C51044, C51196, C53248, C57876, C60780.
[26] B28054, B 53978, B55646, C18612, C37470, C61014.
[27] A4450, A32624, A54764, B10286, B28002, B37376, B37382, B51134, C18612, C39232, C51196, C51516, C53154, C53250, C54732, C57864, C57876.
[28] C53250.
[29] B11844, C51516, C60678, C63270.
[30] B37382.
[31] A43858, A43810, A51138, A51158, A51160, A51166, B51036, B51038, B51134, B53970, B53978.
[32] A19362.
[33] C53266.
[34] C53264, C53268.
[35] C51048.
[36] C51048.
[37] C53250.
[38] C51044.
[39] B37398.
[40] A51166, B3198, B18010, B18006, B19614, B27998, B51036, B51038, B53260, C53264, B53970, B53978, B54512, B55478.

discussions and scaling issues substantially[41], and further state they have assessed the literature about side-effects or long term storage[42]. On several occasions in chapter 4, the authors briefly confirm that suggested re-formulations and literature have been taken into account and revised accordingly[43], while a few rebuttals or partial rebuttals are made due to limited space in the report[44].

Authors further acknowledge a mistake in unwittingly presenting BECCS and afforestation as equally feasible and revise potentially misleading formulations accordingly. Additional clarifications of the differences and similarities between the two methods have been added by the authors, explicitly including statements of the methods being at different maturity levels, with BECCS merely in the demonstration phase[45].

The frequently voiced critique of a BECCS bias in the report is never explicitly addressed by the authors. Instead, they respond to the comments calling for inclusion of a broader variety of CDRs, and those criticizing a perceived neglect of non-CDR scenarios, by explaining that the draft has been revised to state that most but not all pathways include BECCS[46]. The heavy reliance on BECCS and afforestation is also claimed to be balanced with explanations that several mitigation options not included in the climate mitigation models are in fact available and that a broad variety of mitigation options actually are preferable, despite the clear prioritization of BECCS in the integrated pathway literature. The heavy reliance on integrated pathway literature in chapter 2 is also claimed to be in line with the scope of that chapter[47].

Authors additionally respond to critique on certain figures downplaying BECCS' negative impacts on the environment and food security by revising or removing them. A more general rephrasing is conducted throughout the three chapters, as nuances are added about the environmental consequences of BECCS and bioenergy in general. Comments about relations between land-use and BECCS in IAMs, as well as the relation between bioenergy and BECCS in 1.5°C pathways, have also led to the addition of a discussion and an explanatory box[48]. Additional comments have also been inserted explaining that many of the impacts associated with BECCS are in fact also valid, or even worse, for several of the alternatives that the reviewers present[49].

The general pattern of the authors' responses is thus an addition to the text rather than subtraction, and to clarify where reviewers call for it. Even the more critical comments in chapter 4 are met with acknowledgment and often result in revisions. However, the deeply critical verdicts of that chapter, which question the scientific rigor and fundamentals of crucial assumptions and methods without pinpointing specific figures, numbers, or calculations that can be easily amended, are sometimes passed over without remark.

Nevertheless, despite the consistently appeasing tone, some fundamental points of the critique are deferred through the boundary work we presented in the introduction of this chapter, i.e., (1), remitting or referring to a limited scope or capacity, (2) claiming to be beyond the mandate: subjective and policy prescriptive, (3) restricting and defining what is legitimate science, and (4) relativizing uncertainties. While acknowledging that BECCS would have an impact on the fulfillment of a number of SDG and deleting statements to the contrary, the authors' general response is to claim that SDG conflicts, land-use competition and assessment of technological assumptions are outside the scope of the report, too complex for the author teams to engage with, or simply impossible to address due to space restrictions (boundary work mode 1: remitting or referring to a limited scope or capacity). When such critique appears in comments to chapter 2, on the other hand, it is commonly argued by the authors that sustainability aspects will be dealt with exclusively in other chapters (while briefly referred to also in chapter 2)[50]. Another recurring argument is that the pathway literature defines which options to include, and that an in-depth analysis beyond what is already conducted in the referred literature falls outside the scope (boundary work mode 3: restricting and defining what is legitimate science)[51]. The overall impression is that the four boundary work modes were equally common.

Boundary work mode 1 is also seen in response to calls for clarifications about land-use-related trade-offs resulting from large-scale BECCS. This discussion is acknowledged by authors as important but outside the scope of SR1.5 and, while certain minor revisions are made, they commonly, refer land-use issues to the forthcoming IPCC Land-use Report due in 2019, 1 year after the SR1.5[52]. When critique is rebutted in this manner, it is not always clear whether it is a matter of boundary work mode 1 (limited scope/capacity) or a matter of restricted mandate (subjective and policy prescriptive), i.e., boundary work mode 2, since both aspects are sometimes implied. So, for example, the request to exclude massive implementation of BECCS from the report due to infeasibility is met with the argument that doing so would not only require complex but also subjective assessments[53]. In response to this and similar requests, the authors point out that, in line with the mandate of the IPCC, the report is not to provide policy prescriptions or feasibility judgements, but instead only to reflect assessments in the scientific literature[54].

Similarly, boundary work modes 2 and 3 are often used in conjunction with each other. This is especially the case concerning comments about land-use and bioenergy issues in chapter 2 and the request to broaden the literature scope, which

[41] C51516, C53248, C56062.
[42] C18618, C28546, C51196, C57876.
[43] C1644, C18616, C31556, C51516, C53248, C53254, C54068, C56052, C58184.
[44] A19360, C39244, C51522, C53252.
[45] A51072, C39300, C51048, C51522, B53260, C53264, C53266, C56052.
[46] A19436, A51158, A51160, A56512, A62906, B51148, B53492, C19756, C24386, A43738, C55700.
[47] B51038, B55468, B55478, B56872, B59904.
[48] B11700, B18118, B56036.
[49] A49528, A50036, A53876, B53260, B59998.
[50] B10286, B11824, B19628, B53970, B53978, B59938.
[51] B51036, B51038.
[52] A29556, B11788.
[53] B51134.
[54] B53980, C28472, C51516, see also A43810.

the authors in general are slightly more reluctant to respond to favorably. The critique of land-use-related sustainability issues—when these are not argued by authors to have already been included elsewhere in the report or addressed with clearly expressed caveats—is rebutted with the argument that the report exclusively rests on scientific, peer-reviewed results. Review comments on this topic are thus often dismissed either because they are deemed to be based on literature that does not meet scientific criteria, or because the referenced papers are judged to not deal explicitly with these issues, and therefore, the authors would move beyond their mandate if they drew broader conclusions based on these studies[55]. The authors claim to be restricted to making solidly scientific and objective assessments without favoring any specific options or technologies or prescribing specific policies. When called upon to sharpen a formulation about constraints to large-scale BECCS, for example, the authors respond that doing so would be policy prescriptive, since it lacks wide support in the reviewed scientific literature: "Reject. Qualifying the constraints would be perceived as policy prescriptive and judgmental, and is not supported by the width of the literature."[56]

Boundary work mode 3 is also used to justify the lack of comparison with natural CDRs. Authors of chapter 2 refer to—and regret—that the investigated literature does not assess alternative CDRs, which disqualifies several methods from inclusion in the chapter. More specifically, the authors agree that it is a flaw that only BECCS, afforestation, and DACCS are included among the NETs. However, they emphasize that the selection in chapter 2, was made since these are the only NETs available in the reviewed "integrated pathways literature" or that the other options do not feature strongly[57]. However, boundary work mode 1 is sometimes also used to clarify why natural CDR options and land management are excluded, as the authors argue that those methods instead fall under the scope of the forthcoming special report on Climate Change and Land Use, to be published in the autumn of 2019[58].

Furthermore, critical comments about the relation of BECCS to other CDRs, as well as its relation to bioenergy usage without CCS, is also deferred by authors, who resort to boundary work mode 4, i.e., relativizing uncertainties. In the SPM, for example, requests to compare BECCS to other, natural and according to reviewers ecologically less risky and more proven CDRs are often met with acknowledgment and revisions, but the responses are sometimes followed by a comment that natural CDRs demand equal or even larger land areas than BECCS and have other constrains of importance. Similar arguments are used in a more general defense of the way that the SPM is written. Authors, while acknowledging the need to further clarify potential environmental risks from large-scale BECCS, add that all forms of bio-energy use are associated with the same fundamental land-use problems. In the SPM, comments to the effect that large-scale BECCS will entail land competition with other land uses and CDRs, are responded to with the claim that a global energy transition will involve a large land footprint regardless of whether BECCS is implemented or not[59]. This boundary work mode is also evident in chapter 4. Responding to a request to clarify that BECCS is untested at scale, the authors reply that while this is true, the same applies to many CDR technologies[60].

DISCUSSION

The responses to the critical reviewer comments indicate a significant degree of compliance on behalf of the author team. Comments are often met with acknowledgment of their relevance, and a large number of revisions are made. Yet, such revisions do not seem to go to the heart of the unease that runs through many of the comments, i.e., that BECCS is presented as a viable, or feasible, CDR technology at a gigaton-scale in the future. While several revisions are made to further clarify uncertainties surrounding BECCS, many of the more fundamental aspects of the critique are deflected rather than incorporated, through the boundary work described in the previous sections.

There are two key junctures at which the boundary work operates to deflect fundamental criticism of the way that BECCS is represented in the draft IPCC report. The modes of boundary work in play arbitrate, first, arguments over *what constitutes relevant science* in relation to the report, and second, arguments over *what constitutes an accurate representation of science*. At both these junctures, review comments aim to broaden the scope of the text while the authors deploy different boundary work modes to hold in place what they define as the boundaries for their role as scientific interpreters. In this concluding discussion, we will highlight how boundary work by the authors sometimes tends toward abstract and reductionistic treatment of BECCS, and, finally, what challenges we can see from permitting this type of boundary work to influence the outcome of the review process. The discussion-section ends with a reflection on the key challenges of communicating the IPCC report's scientific results in a "policy-relevant yet policy-neutral" manner and the role of IAMs in IPCC assessments.

What Constitutes Relevant Science?

The report authors of chapter 2 explicitly assert that the integrated pathway literature should be given most weight without clearly stating whether this is due to issues of scientific validity and relevance or if it is due to time limits. This strict limitation to a certain type of literature, that rely on IAMs, cannot be fully explained by the draft outline decided at the scoping meeting, which in vague terms calls for considering "[t]echnological, environmental, institutional, and socio-economic opportunities and challenges related to 1.5°C pathways" (IPCC, 2016, p. 19). The scoping meeting decision also instructs authors to consider the recommended focus as "indicative" (IPCC, 2016: Decision IPCC/XLIV-4, §4), which

[55] B33578, B55468.
[56] C28472.
[57] B51038, B55468, see also B2072, B18010, B55478.
[58] A29556, B11788, B18110.
[59] A11372, A11376, A49528, A50036, A53876, A56028, B53260.
[60] C22774, see also C53264.

provides flexibility for the authors to decide what literature they consider relevant for which chapters.

As illustrated in the section "The authors' responses," sometimes authors respond to requests for broadening the scope of the literature review by claiming that only peer-reviewed papers are to be included in the review, while comments indicate the existence of peer-reviewed, relevant literature that casts doubt on several of the assumptions made in the pathway and IAM literature preferred by the authors. Thus, the boundary work modes 1 (scope and capacity) and 3 (legitimate science) blend, as authors sometimes point to the limited scope of the report or chapter being discussed as reason for not including certain suggestions, while the reference to the peer-review criterion sometimes implies this to be the motive for excluding certain suggestions.

The demarcation between assertions of limited scope and relevance is further blurred by the way authors sometimes motivate excluding certain statements about alternative CDRs or mitigation options, land-use impacts, or conflicts with SDGs. In addition to omitting certain critique based on assertions of the limited scope of the report, the capacity of the author team due to the complexity of the request and the lack of relevant literature, the authors also relativize the uncertainties and risks associated with BECCS (boundary work mode 4). Requests for analyses of how other biomass-based mitigation options are related to and could conflict with a deployment of BECCS on a gigaton-scale are often responded to with the assertion that their land-use effects would be equally or even more severe than those of BECCS. Thus, it is implied that while the focus on BECCS in the literature is unfortunate, avoiding BECCS or referring to a broader palette of alternatives would not make a substantial difference to the report's conclusions, since doing so entails equally troublesome or even worse consequences for agriculture, land-use, and forestry.

What Constitutes an Accurate Representation of Science?

The same tendency to avoid delving into some of the specifics of BECCS is evident also in discussions between authors and reviewers about the proper way to represent the science that is assessed by the IPCC. Critical commenters often urge that BECCS be reframed as a highly speculative technology. The critics call for a much sharper distinction between the real-world potential for BECCS deployment and the levels depicted in the imaginary climate mitigation scenarios. This includes elaborating a nomenclature that clarifies the meaning of the term feasibility when used in connection to integrated assessment modeling as opposed to real-world deployment potentials (see also Low and Schäfer, 2020). While acknowledging the speculative nature of BECCS and making some linguistic adjustments, the IPCC authors tend to respond to such requests by referring to boundary work mode 2, i.e., they are restricted by their mandate to assess existing literature while being "neutral with respect to policy" (IPCC, 2013, §2). Following this logic, the literature would be used in a restricted sense for its conclusions about theoretical possibilities or feasibility rather than as a base for "policy prescriptive" judgements about how feasible these deployment levels are. However, the boundary between what constitutes unwarranted policy prescription and what constitutes a legitimate scientific review is apparently not clearly defined.

Our analysis reveals certain ambiguities and inconsistencies in how report authors respond to reviewers that can partly be explained as a consequence of recent changes of the IPCC work processes and attempts to be more inclusive, as described by Gambhir et al. (2019), Thoni and Livingston (2021), and Workman et al. (2020). The IPCC has a reductionistic tendency deeply rooted in its history as an institution that favors quantitative models and data and results from the natural or economic sciences over less quantitative methods and perspectives (Bjurström and Polk, 2011; Hulme, 2011; Fløttum et al., 2016; Haikola et al., 2019; Low and Schäfer, 2020; Thoni and Livingston, 2021). The SR1.5, meanwhile, was set-up to be the most transparent, inclusive, and interdisciplinary of all IPCC reports, and many IPCC actors welcomed the increased plurality. However, the practical drafting of an IPCC special report must deal with conflicting ontological and epistemological demands at the interfaces of different scientific disciplines as well as between science and policy. This would force a tradeoff between embracing complexity and the reductionism that is often required by the conventional methodologies favored by the IPCC and its consensus ideal (IPCC, 2013: §10; see also Livingston, 2018; Thoni and Livingston, 2021). The boundary work studied in the present paper could be seen as a response to being torn between strengthened ideals of openness concerning the IPCC work processes and the institutional path dependency that regulates the work of the IPCC. These new ideals for more inclusive scientific assessments and less reductionist tendencies seem to invite the type of critical arguments for embracing uncertainty and complexity, which the IPCC historically had a culturally ingrained tendency to reduce[61].

It could well be that this review process has lived up to being billed as the most open IPCC report to date. There are, nevertheless, some challenges attached to the type of boundary work that operates in managing some of the more critical review comments. BECCS goes through a two-step abstraction because the relativization of BECCS at scale coincides with the treatment of pathway literature in the reductionist tradition identified by Hulme (2011) and Thoni and Livingston (2021). The treatment of the IAM literature as a detached, separately existing body of scientific work to be assessed as objective science is especially problematic since the modeling communities that produce this literature are also encouraged by the IPCC to produce these same scenarios/pathways and optimize them toward politically pre-set targets (see Livingston, 2018; Carton et al., 2020; Workman et al., 2020, see also van Beek et al., 2020).

By thus detaching the 1.5°C pathway literature from the institutional and political contexts in which it is embedded, and from the contested assumptions it departs from, the authors' boundary work risks normalizing what is in fact a highly speculative option in the portfolio of mitigation and CDR

[61] See Haikola et al. (2019) for guidance on literature on the historic role of models and IAMs in relation to climate science.

alternatives (see also e.g., Geden, 2015; Faran and Olsson, 2018; Carton, 2019; Ellenbeck and Lilliestam, 2019; Haikola et al., 2019). If SR1.5 is regarded as merely one type of statement, intended to be viewed in a context of a series of reports, as indeed is suggested by authors in the review process, the chosen approach appears perfectly sound. However, to do so would assume a very high level of awareness and knowledge about scientific uncertainties, the nature of IAMs, and the concept of feasibility, among the many actor groups that use and rely on the findings of IPCC assessment reports.

Concluding Reflections

Communicating uncertainty to non-specialized audiences while maintaining the "policy-relevant yet policy-neutral" stance of the IPCC has become a key challenge for the organization (Hollin and Pearce, 2015). The readability of the SPMs has proven to be poor (Barkemeyer et al., 2015), and the standardized nomenclature used by the IPCC to communicate probability and uncertainties is prone to misinterpretation and differing interpretations (Budescu et al., 2014; Low and Schäfer, 2020). Fløttum et al. (2016) also show that the standardized probability language reinforces natural science framings in all of the IPCC working groups, at the expense of social science framings and perspectives that include critical remarks on the governance implications of global BECCS deployment at large scale (see also Carton et al., 2020). The emphasis on policy-relevance in the sixth assessment cycle would also seem difficult to reconcile with a strengthening of uncertainty communication and the concurrent requests for inclusion of a plurality of scientific perspectives.

The communication challenge is made even more difficult by the IPCC's heavy reliance on IAMs in their narration of assessment reports, as IAMs have long been criticized precisely for their tendency toward reductionism and lack of transparency. The IAM communities have reacted to such critique and the SR1.5 arguably acted as a trigger, and the main response has been to conclude that it is not fruitful to abandon IAMs since they have been proven to be useful tools and are highly demanded by policy-makers and other actors concerned with the transformation, distribution, costs, and use of energy resources. Instead, the IAM communities' recommendations seem to favor supplementing the IAMs with additional analytical models and methods, e.g., improve representation of behavioral and lifestyle changes, and include additional CDRs or minimize the use of BECCS (see e.g., Grubler et al., 2018; van Vuuren et al., 2018; van Beek et al., 2020).

Thus, incremental changes are favored from within the IAM communities: by aiming at including more scientific perspectives and connecting qualitative evidence to quantitative in a more systematic way (e.g., Gambhir et al., 2019; Hilaire et al., 2019; van den Berg et al., 2019; De Cian et al., 2020), initiating model intercomparison projects (e.g., Rickels et al., 2019), and by including a broader span of NETs, technological diffusion dynamics, political constraints, and socio-cultural changes in the models (Fuhrman et al., 2019; Workman et al., 2020). Currently self-reflection and meta-studies to improve the understanding of mitigation pathways and enhance the models' utility and credibility are underway (Fuhrman et al., 2019; Gambhir et al., 2019; Hilaire et al., 2019; Rickels et al., 2019).

What our analysis reveals, beyond a dissatisfaction among many reviewers with the focus on integrated assessment modeling, the associated pathway literature, and the analysis of BECCS, is a disagreement about how model results should be interpreted and communicated. Perhaps, however, there is a limit to how well-uncertainty in highly complex computer models can be communicated to anyone beyond experts on models. While the review process itself is obviously open to a highly critical examination of BECCS and its theoretical presuppositions, the scientific foundation on which central chapters of SR1.5 rests, i.e., primarily the integrated pathway literature, as well as interpretations of the IPCC's scope, tend to partly filter out this highly critical discussion through boundary work.

Therefore, in addition to initiating a more comprehensive analysis of BECCS within the pathway and IAM literature, the review process might also have the opposite effect to what was intended. It may also risk entrenching, rather than problematize, a contested representation of the potential of BECCS (se also e.g., Beck and Mahony, 2018; Carton, 2019; Ellenbeck and Lilliestam, 2019; Workman et al., 2020). We see a challenge related to the type of boundary work observed in this paper influencing the outcome of the IPCC assessment processes, as it does little to mitigate the problems associated with such a heavy reliance on IAM literature that easily tend to include the massive deployment of BECCS. Doing so decreases the total modeled cost of the transition necessary to limit global warming. This can be misinterpreted and have implications for governance and policy making since it risks legitimizing a more relaxed fossil decarbonization in the near term by building belief in speculative future CDR. This moral hazard, while not empirically verified, could obscure the critical need for increased ambition in the near-term global response to climate change (Hilaire et al., 2019; see also Asayama and Hulme, 2019; Carton et al., 2020).

A more optimistic interpretation of the role of IAMs, in line with van Beek et al. (2020) argumentation, is that the IAM community has been able to adapt to new demands at the science-policy interface by remaining up-to-date and developing its provision of policy relevant knowledge while also anticipating, or even help shaping, the demands of policy makers. Since the IAM communities are populated by a relatively small group of researchers there is a risk attached to letting this group not only define the boundaries of relevant science but also influence how that science should be interpreted and translated to policies (see also Hughes and Paterson, 2017). A critique of IAMs is their lack of ability to conceive of more radical societal transformations, which is suggested by van Beek et al. (2020) to be solved by a closer engagement with social sciences and humanities for example by conceptualizing human behavior in the IAMs beyond the rational choice model. However, what we have revealed in the review of the interaction between critical reviewers and IPCC authors is that the critique very seldom is about lack of social sciences or humanities in the pathway literature or the IPCC assessment reports, but instead a questioning of what is considered unrealistic input data for IAMs, representations of technologies and basic assumptions about resource availability. Thus, the critique is not predominantly formulated from social scientific or humanities perspectives, but instead from perspectives asking for more realistic assumptions and for natural complexities to be taken more seriously, often accompanied by a questioning of the privileged position of the IAM literature in the assessment processes. Perhaps the responses to the critique formulated within the IAM community are misguided—at least they do not respond to the request from many reviewers: to balance the privileged status of IAMs in IPCC assessments with a profoundly more diverse representation of potential climate transition pathways. A true pluralization of perspectives in the IPCC assessment report series would therefore not entail merely adding perspectives as complements to the IAM core. Rather, it would mean creating space for alternative perspectives (cf. Markusson et al., 2020)—not at all necessarily only from within the social sciences and humanities but from within the natural and engineering sciences as well—to make claims about future mitigation paths without having to relate them to IAMs.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/07/SR15FOD_Summary_for_Policymakers_Comments_and_Responses.pdf; https://www.ipcc.ch/site/assets/uploads/sites/2/2019/07/SR15SOD_Chapter2_Comments_and_Responses.pdf; https://www.ipcc.ch/site/assets/uploads/sites/2/2019/09/SR15SOD_Chapter4_Comments_and_Responses.pdf. Readers are requested to contact the corresponding author for more information regarding coding, inter-coding and the four analytical categories.

AUTHOR CONTRIBUTIONS

AH is the lead author and coordinator and designed the research. AH and JA analyzed the data. MF performed the cross-checking. AH, MF, and SH contributed to the contextualization, background, and discussion chapters. All authors made a substantial and intellectual contribution to the text and approved the submitted version.

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REFERENCES

Asayama, S., and Hulme, M. (2019). Engineering climate debt: temperature overshoot and peak-shaving as risky subprime mortgage lending. *Clim. Policy* 19, 937–946. doi: 10.1080/14693062.2019.1623165

Barkemeyer, R., Dessai, S., Monge-Sanz, B., Renzi, B. G., and Napolitano, G. (2015). Linguistic analysis of IPCC summaries for policymakers and associated coverage. *Nat. Clim. Chang.* 6, 311–316. doi: 10.1038/nclimate2824

Beck, S., and Mahony, M. (2018). The politics of anticipation: the IPCC and the negative emissions technologies experience. *Global Sustain.* 1, 1–8. doi: 10.1017/sus.2018.7

Bjurström, A., and Polk, M. (2011). Physical and economic bias in climate change research: a scientometric study of IPCC Third Assessment Report. *Clim. Change.* 108, 1–22. doi: 10.1007/s10584-011-0018-8

Budescu, D. V., Por, H.-H., Broomell, S., and Smithson, M. (2014). The interpretation of IPCC probabilistic statements around the world. *Nat. Clim. Chang.* 4, 508–512. doi: 10.1038/nclimate2194

Callaghan, M. W., Minx, J. C., and Forster, P. M. (2020). A topography of climate change research. *Nat. Clim. Chang.* 10, 118–123. doi: 10.1038/s41558-019-0684-5

Carton, W. (2019). "Fixing" climate change by mortgaging the future: negative emissions, spatiotemporal fixes, and the political economy of delay. *Antipode* 51, 750–769. doi: 10.1111/anti.12532

Carton, W. (2020). Carbon unicorns and fossil futures. whose emission reduction pathways is the IPCC performing? In *Has it Come to This? The Pitfalls and Promises of Geoengineering on the Brink*, eds J. P. Sapinski, H. J. Buck, and A. Malm A (New Brunswick: Rutgers University Press).

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *WIREs Clim. Chang.* 11:e671. doi: 10.1002/wcc.671

De Cian, E., Dasgupta, S., Hof, A. F., van Sluisveld, M., Köhler, J., Pfluger, B., et al. (2020). Actors, decision-making, and institutions in quantitative system modelling. *Technol. Forecast. Soc. Change.* 151:119480.

EASAC (2018). *EASAC Report on Negative Emissions Technologies. Policy Report 35.* Halle: European Academies Science Advisory Council.

Ellenbeck, S., and Lilliestam, J. (2019). How modelers construct energy costs: discursive elements in energy system and integrated assessment models. *Energy Res. Soc. Sci.* 47, 69–77. doi: 10.1016/j.erss.2018.08.021

Faran, T., and Olsson, L. (2018). Geoengineering: neither economical, nor ethical – a risk-reward nexus analysis of carbon dioxide removal. *Int. Environ. Agree.* 18, 63–77. doi: 10.1007/s10784-017-9383-8

Fløttum, K., Gasper, D., and St Clair, A. L. (2016). Synthesizing a policy-relevant perspective from the three IPCC "Worlds"—a comparison of topics and frames in the SPMs of the Fifth Assessment Report. *Global Environ. Chang.* 38, 118–129. doi: 10.1016/j.gloenvcha.2016.03.007

Frickel, S. (2004). Building an interdiscipline: collective action framing and the rise of genetic toxicology. *Soc. Probl.* 51, 269–287. doi: 10.1525/sp.2004.51.2.269

Friman, M. (2010). Understanding boundary work through discourse theory: inter/disciplines and interdisciplinary. *Sci. Technol. Stud.* 23, 5–19. doi: 10.23987/sts.55250

Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W., and Clarens, A. F. (2019). From zero to hero?: Why integrated assessment modeling of negative emissions technologies is hard and how we can do better. *Front. Clim.* 1:11. doi: 10.3389/fclim.2019.00011

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., et al. (2014). Betting on negative emissions. *Nat. Clim. Chang.* 4, 850–853. doi: 10.1038/nclimate2392

Gambhir, A., Butnar, I., Li, P.-H., Smith, P., and Strachan, N. (2019). A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS. *Energies* 12, 1–21. doi: 10.3390/en12091747

Geden, O. (2015). Climate advisers must maintain integrity. *Nature* 521, 27–28 doi: 10.1038/521027a

Gieryn, T. F. (1983). Boundary-work and the demarcation of science from non-science: strains and interests in professional ideologies of scientists. *Am. Sociol. Rev.* 48, 781–795. doi: 10.2307/2095325

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., et al. (2018). A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. *Nat. Energy* 3, 515–527. doi: 10.1038/s41560-018-0172-6

Haikola, S., Hansson, A., and Fridahl, M. (2019). Map-makers and navigators of politicised terrain: expert understandings of epistemological uncertainty in integrated assessment modelling of bioenergy with carbon capture and storage. *Futures* 114:102472. doi: 10.1016/j.futures.2019.102472

Hilaire, J., Minx, J. C., Callaghan, M. W., Edmonds, J., Luderer, G., Nemet, G., et al. (2019). Negative emissions and international climate goals—learning from and about mitigation scenarios. *Clim. Chang.* 157, 189–219 doi: 10.1007/s10584-019-02516-4

Hollin, G. J. S., and Pearce, W. (2015). Tension between scientific certainty and meaning complicates communication of IPCC reports. *Nat. Clim. Chang.* 5, 753–756. doi: 10.1038/nclimate2672

Hu, B., Zhang, Y., Teng, Y., and Yue, W. (2020). Can bioenergy carbon capture and storage aggravate global water crisis? *Sci. Total Environ*. 714:136856. doi: 10.1016/j.scitotenv.2020.136856

Hughes, H. R., and Paterson, M. (2017). Narrowing the climate field: the symbolic power of authors in the IPCCs Assessment of Mitigation. *Rev. Policy Res.* 34, 744–766. doi: 10.1111/ropr.12255

Huitema, D., and Turnhout, E. (2009). Working at the science–policy interface: a discursive analysis of boundary work at the Netherlands Environmental Assessment Agency. *Env. Polit*. 18, 576–594. doi: 10.1080/09644010903007427

Hulme, M. (2011). Reducing the future to climate: a story of climate determinism and reductionism. *Osiris* 26, 245–266. doi: 10.1086/661274

IPCC (2013). *Principles Governing IPCC Work. Approved at the Fourteenth Session (Vienna, 1-3 October 1998) on 1 October 1998, Amended at the Twenty-First Session (Vienna, 3 and 6-7 November 2003), The Twenty-Fifth Session (Mauritius, 26-28 April 2006), The Thirty-Fifth Session (Geneva, 6-9 June 2012) and The Thirty-Seventh Session (Batumi, 14-18 October 2013)*. Available online at: https://www.ipcc.ch/site/assets/uploads/2018/09/ipcc-principles.pdf (accessed October 28, 2019).

IPCC (2016). *Decision IPCC/XLIV-4. Sixth Assessment Report (AR6) Products, Outline of the Special Report on 1.5°C.* Geneva: The Intergovernmental Panel on Climate Change (IPCC).

IPCC (2017). *Guidance Note of the Role of Review Editors of the Special Report on Global Warming of 1.5°C.* Geneva: The Intergovernmental Panel on Climate Change (IPCC).

IPCC (2018). *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. eds V. P. Masson-Delmotte et al. (Cambridge: Cambridge Univeristy Press).

IPCC (2019a). *Final Report from IPCC Special Report on Global Warming of 1.5°C Review Editor (RE)*. Available online at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Final_RE_Reports_All.pdf (accessed April 13, 2021).

IPCC (2019b). *IPCC WGI SR15 Second Order Draft Review Comments And Responses - Summary for Policy Makers*. Available online at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/07/SR15FOD_Summary_for_Policymakers_Comments_and_Responses.pdf. (accessed December 17, 2021).

IPCC (2019c). *IPCC WGI SR15 Second Order Draft Review Comments And Responses - Chapter 2*. Available online at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15SOD_Chapter2_Comments_and_Responses.pdf. (accessed December 17, 2021).

IPCC (2019d). *IPCC WGI SR15 Second Order Draft Review Comments And Responses - Chapter 4*. Available online at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/09/SR15SOD_Chapter4_Comments_and_Responses.pdf (accessed December 17, 2021).

Livingston, J. (2018). *Climate Science for Policy? The Knowledge Politics of the IPCC After Copenhagen*. Lund: Lund University.

Livingston, J., and Rummukainen, M. (2020). Taking science by surprise: the knowledge politics of the IPCC Special Report on 1.5 degrees. *Environ. Sci. Policy* 112, 10–16. doi: 10.1016/j.envsci.2020.05.020

Low, S., and Schäfer, S. (2020). Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling. *Energy Res. Soc. Sci.* 60, 1–9. doi: 10.1016/j.erss.2019.101326

Mander, S. (2018). "The climate-change mitigation challenge," in *Biomass with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions.* eds C. Gough, N. Vaughan, S. Mander, P. Thornley, and A. Lea-Langton (Oxford: John Wiley and Sons Ltd.), 187–204. doi: 10.1002/9781119237716.ch9

Markusson, N., Balta-Ozkan, N., Chilvers, J., Healey, P., Reiner, D., and McLaren, D. (2020). Social science sequestered. *Front. Clim.* 2:2. doi: 10.3389/fclim.2020.00002

Markusson, N., McLaren, D., and Tyfield, D. (2018). Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Global Sustain.* 1:e10. doi: 10.1017/sus.2018.10

Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Edenhofer, O., Stocker, T. F., Field, C. B., et al. (2011). The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups. *Clim. Chang.* 108, 675–691. doi: 10.1007/s10584-011-0178-6

Minx, J. C., Callaghan, M., Lamb, W. F., Garard, J., and Edenhofer, O. (2017). Learning about climate change solutions in the IPCC and beyond. *Environ. Sci. Policy* 77, 252–259 doi: 10.1016/j.envsci.2017.05.014

Obersteiner, M., Azar, C., Kauppi, P., Möllersten, K., Moreira, J., S., Nilsson, et al. (2001). Managing climate risk. *Science* 294, 786–787. doi: 10.1126/science.294.5543.786b

Rickels, W., Merk, C., Reith, F., Keller, D. P., and Oschlies, A. (2019). (Mis)conceptions about modeling of negative emissions technologies. *Environ. Res. Lett*. 14:104004. doi: 10.1088/1748-9326/ab3ab4

Rogelj, J., Huppmann, D., Krey, V., Riahi, K., Clarke, L., Gidden, M., et al. (2019). A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* 573, 357–363 doi: 10.1038/s41586-019-1541-4

Sundqvist, G., Gasper, D., St. Clair, A. L., Hermansen, E., Yearley, S., and Øvsteb, ø, Tvedten I, Wynne, B. (2018). One world or two? Science–policy interactions in the climate field. *Crit. Policy Stud*. 12, 448–468. doi: 10.1080/19460171.2017.1374193

Tavoni, M., and Socolow, R. (2013). Modeling meets science and technology: an introduction to a special issue on negative emissions. *Clim. Chang*. 118, 1–14 doi: 10.1007/s10584-013-0757-9

Thoni, T., and Livingston, J. (2021). Going beyond science-policy interaction? : an analysis of views among intergovernmental panel on climate change actors. *Critic. Policy Stud.* 15, 37–54. doi: 10.1080/19460171.2019.1665564

van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D., and Cassen, C. (2020). Anticipating futures through models: the rise of integrated assessment modelling in the climate science-policy interface since 1970. *Global Environ. Chang.* 65:102191. doi: 10.1016/j.gloenvcha.2020.102191

van den Berg, N. J., Hof, A. F., Akenji, A., Edelenbosch, O. Y., van Sluisveld, M., Timmer, V. J., et al. (2019). Improved modelling of lifestyle changes in integrated assessment models: cross-disciplinary insights from methodologies and theories. *Energy Strategy Rev*. 26:100420. doi: 10.1016/j.esr.2019.100420

van der Sluijs, J. (2005). Uncertainty as a monster in the science–policy interface: four coping strategies. *Water Sci. Technol.* 52, 87–82. doi: 10.2166/wst.2005.0155

van Vuuren, D. P., Stehfest, E., Gernaat, D., van den Berg, M., Bijl, D., Sytze de Boer, H., et al. (2018). Alternative pathways to the 1.5 C target reduce the need for negative emission technologies. *Nat. Clim. Chang.* 8, 391–397. doi: 10.1038/s41558-018-0119-8

Workman, M., Dooley, K., Lomax, G., Maltby, J., and Darch, G. (2020). Decision making in contexts of deep uncertainty: an alternative approach for long-term climate policy. *Environ. Sci. Policy* 103, 77–84. doi: 10.1016/j.envsci.2019.10.002

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.

APPENDIX

TABLE A1 | List of the reviewers with the largest number of reviewer comments coded as critical.

Reviewer	Affiliation/position	No. of comments
Mary Booth, United States of America	Director at The Partnership for Policy Integrity (PFPI)	22
Doreen Stabinsky, United States of America	Professor of Global Environmental Politics at the College of the Atlantic in Bar Harbor, USA/Uppsala University, Sweden	20
Jennifer Morgan, Netherlands	Executive Director, Greenpeace International	16
Linda Schneider, Germany	Senior Programme Officer for International Climate Policy at the Heinrich Böll Foundation's head office in Berlin	13
United States of America	N/A	10
Andy Reisinger, New Zealand	Vice chair IPCC, and Deputy Director of the New Zealand Agricultural Greenhouse Gas Research Centre	10
United Kingdom (of Great Britain and Northern Ireland)	N/A	9
Andrea Tilche, Belgium	European Commission, Head of Unit DG R&I, Brussels, Belgium	9
Peter Carter, Canada	The Climate Emergency Institute	7
Helmut Haberl, Austria	Professor and director of the Institute of Social Ecology Vienna, Alpen-Adria Universität, Austria	7
Elenita Daño, Philippines	Co-Executive Director, ETC-Group	6
Kate Dooley, Australia	PhD, University of Melbourne	6
Germany	N/A	5
Eleanor Johnston, United States of America	Climate Interactive, Washington, DC, United States of America	3
Simon Bullock, United Kingdom (of Great Britain and Northern Ireland)	Tyndall Centre for Climate Change Research	3

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Policy Options for Deep Decarbonization and Wood Utilization in California's Low Carbon Fuel Standard

Daniel L. Sanchez[1]*, *Kevin Fingerman*[2], *Claudia Herbert*[1] *and Sam Uden*[3]

[1] Department of Environmental Science, Policy and Management, University of California, Berkeley, Berkeley, CA, United States, [2] Environmental Science and Management, Humboldt State University, Arcata, CA, United States, [3] School of Earth and Environmental Sciences, University of Queensland, Brisbane, QLD, Australia

California's Low Carbon Fuel Standard (LCFS) is one of the most important policies to develop and deploy low-carbon and carbon-negative fuels. Yet, because the LCFS is designed to deliver the lowest-cost carbon intensity (CI) reductions possible in the transportation fuel system, it may fail to deliver technologies that would be poised to offer deeper decarbonization or other ancillary benefits to California's people and environment. We contemplate administrative changes to the LCFS to further stimulate the commercialization of promising low-carbon and carbon-negative fuels. To do so, we examine promising technical pathways, their barriers to commercialization, and recent administrative actions by the CA Air Resources Board (ARB) under the LCFS to promote novel lower-carbon fuels. We propose three actions that ARB could undertake to promote commercialization within existing authorities. To commercialize low-carbon and carbon negative fuel, including those derived from forest residue feedstocks, ARB could: (1) embrace the most up-to-date science regarding lifecycle greenhouse gas emissions, (2) create additional, targeted incentives for very low-carbon or carbon-negative fuels through a volumetric technology carve-out or credit multiplier, and (3) ensure that the LCFS stimulates the best-performing fuels across a variety of sustainability parameters.

Keywords: carbon dioxide removal, climate policy, forest biomass, California, low carbon fuel standard

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Royal Institute of Technology, Sweden

****Correspondence:***
Daniel L. Sanchez
sanchezd@berkeley.edu

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INTRODUCTION

Deep Decarbonization in California's Low Carbon Fuel Standard

California's Low Carbon Fuel Standard (LCFS) is emerging as one of the most important policies to develop low-carbon and carbon-negative fuels, which have a very low or negative carbon intensity (CI) based on lifecycle assessment. Offering one of the highest carbon prices of any emissions market in the world, the LCFS is spurring the development of cutting-edge low-carbon fuel pathways that might otherwise never come to market. The years 2019 and 2020 saw the announcement of numerous commercial-scale cellulosic biofuel, bioenergy with carbon capture and sequestration (BECCS), landfill and dairy biogas, and direct air capture (DAC) projects, many of which explicitly cited revenues from CA's LCFS as a motivation (Aemetis, 2019; Rathi, 2019). These fuels play a pivotal role in California, national, and international action to address climate change (The White House, 2016; Rogelj et al., 2018).

Yet successful commercialization of low-carbon and carbon-negative fuels is far from certain, despite policy support from the LCFS. Commercial-scale cellulosic biofuels, for instance, have seen several high-profile failures in recent years (Lynd et al., 2017). Most negative emissions technologies face challenges related to both technical and commercial immaturity (Lomax et al., 2015). Without modifications to the LCFS, these promising technologies might be locked out by more established and cheaper, but less carbon-reducing alternatives. Indeed, lack of "demand pull" has been cited as a primary barrier to the deployment of carbon-negative bioenergy within national climate change policies (Fridahl et al., 2020; Schenuit et al., 2021).

The transportation sector represents 41% of total GHG emissions in California, and recently surpassed electric power to become the largest emissions sector nationwide (CARB, 2019a). This is because emissions from electric power generation, long the most significant sector, are comparatively easy and inexpensive to reduce. Emissions reductions from transport, on the other hand, are comparatively challenging to achieve. Necessary change in this sector is inhibited by market barriers such as technology lock-in, the low price elasticity of fuel demand, and the need for coordination among fuel producers, distributors, and consumers. Furthermore, the marginal abatement cost of transportation emission reductions—especially through fuel switching—is comparatively high, meaning an economy-wide carbon price, while an economically efficient approach to emission abatement, is unlikely to achieve significant near-term reductions from transport at politically-acceptable carbon prices (Lutsey and Sperling, 2009; van der Zwaan et al., 2013). For example, U.S. government analysis of the American Clean Energy and Security Act of 2009 determined that a nationwide cap-and-trade system would yield almost no emission reduction in the transport sector, which would account for over 50% of total emissions nationwide in 2050 (Fawcett, 2010).

Spurring near-term emission reductions through transportation fuel switching is the reason the LCFS is necessary. The November 2020 credit price under CA's cap & trade system averaged $16.93, while the credit price in the LCFS credits averaged $199 per metric ton (CARB, 2021a,b). This implies that the changes being spurred by the LCFS would indeed not come about through an economy-wide carbon price alone. The LCFS and other sector-specific policies are necessary to drive the development of technologies and markets that will ultimately be necessary for deeper emissions reductions, meeting California's goal of carbon neutrality in 2045 (Baker et al., 2019). As has been shown before in the renewable energy space, these near-term costs can ultimately stimulate technology development leading to cost reductions such that these targeted policies are no longer needed. One key element in the pursuit of deep emissions cuts from transportation will be the deployment of low-carbon alternative fuels, an outcome that is the direct target and result of California's LCFS.

A carbon price mechanism will deliver the cheapest mitigation available in the system. However, as Vogt-Schilb and Hallegatte, point out, this can create a conflict between what they refer to as "cheap" and "deep" abatement options (Vogt-Schilb and Hallegatte, 2014). They state that "the measures required to achieve ambitious emission reductions cannot be implemented overnight, the optimal strategy to reach a short-term target depends on longer-term targets. For instance, the best strategy to achieve Europe's −20% by 2020 target may be to implement some expensive, high-potential, and long-to-implement options required to meet the −75% by 2050 target. Using just the cheapest abatement options to meet the 2020 target can create carbon-intensive lock-in and make the 2050 target too expensive to reach."

This is the reason the LCFS exists was adopted by California's Air Resources Board all; it will help spur early action on deeper abatement pathways that will be necessary in the long run (Exec. Order No. S-01-07 by Governor Arnold Schwarzenegger, 2007; Farrell et al., 2007). However, this problem also exists *within* the LCFS system, as it is also a market designed to deliver the cheapest fuel carbon intensity reductions possible today rather than those capable of delivering the deepest decarbonization in the long term. Just as California requires the LCFS policy to stimulate action in the transportation fuels space—action that will eventually be necessary to reach deep mitigation targets—the State may also require action within the LCFS program to spur development of technologies capable of deeper mitigation than those that are emerging currently from the LCFS market. It is also worth considering whether the LCFS can be leveraged to achieve broader state goals beyond only fuel carbon intensity (CI) reduction, such as wildfire risk reduction.

Put more plainly, the LCFS has not yet led to wide-scale commercialization of very low-carbon or carbon-negative fuels. Instead, early targets were met by blending conventional crop-based biofuels (**Figure 1**) that were able to deliver 1–5% average fuel CI reductions but do not have a low enough carbon footprint to play a role in reaching 10–20% reduction targets. Compliance has shifted to lower carbon first-generation fuels such as biodiesel and renewable diesel from recycled vegetable and other waste oils, but these are supply-limited, hampering their ability to drive deep decarbonization (Christensen and Hobbs, 2016). As demand for these costly fuels has increased, credit prices have risen dramatically.

The Low-Carbon Fuel Landscape in California

California and its neighbors have numerous commercial-scale low-carbon and carbon-negative fuels production facilities in various stages of development (**Table 1**). These include biofuels from very low-carbon biomass feedstocks—especially residues from sustainable forest management—and those using carbon capture and sequestration (CCS) technologies to make low-carbon and carbon-negative fuels.

The Forest/Fuel/Air Quality Nexus in California

California's forest management crisis has important implications for public safety, biodiversity conservation, water resource management, air quality, climate change, and the state's

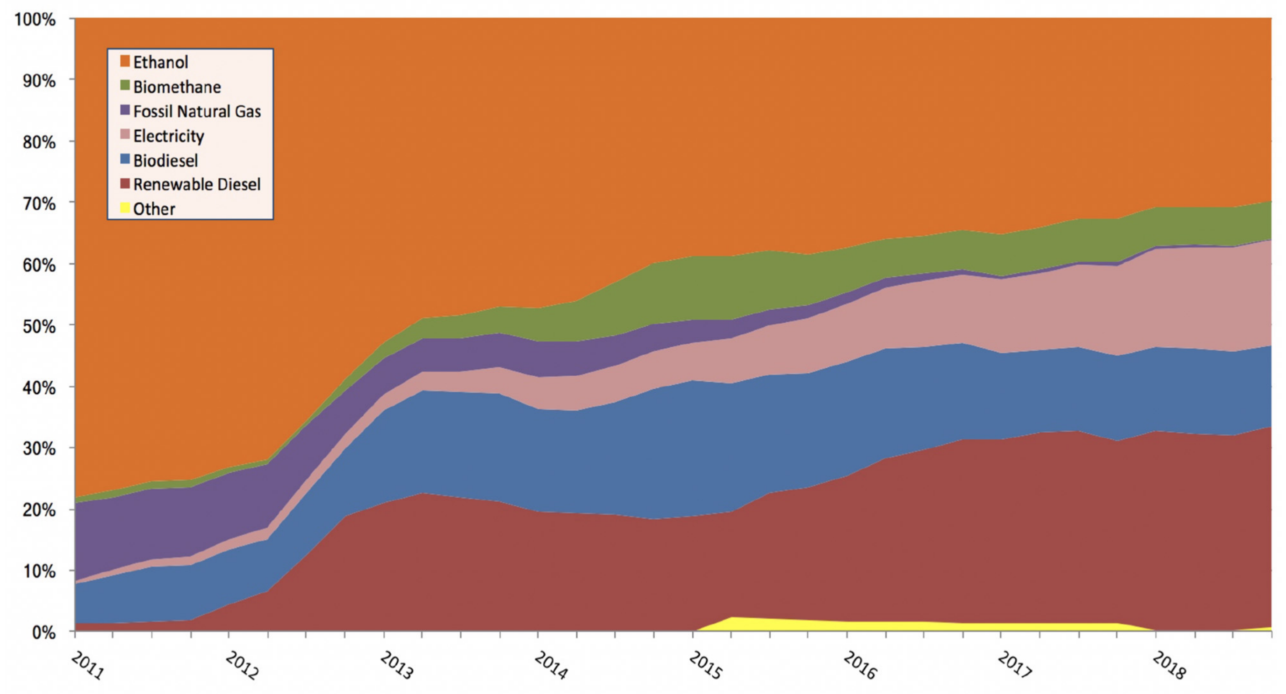

FIGURE 1 | Yearly rolling average percentage of credits by fuel type from Q1 2011 to quarter 3 (Q3) 2019. Total credits generated grew more than 10-fold over this period from 328,000 metric tons in quarterly in 2011 to 3.48 million metric tons quarterly. Reproduced from CARB (2021c).

TABLE 1 | Characterization of low-carbon and carbon-negative pathways proposed in California.

Product	Feedstock required	Example	Carbon removal	TRL[i] (1–9)	CRL[ii] (1–9)	Project location	Capital cost ($ million)
Biofuels from woody biomass, including biofuels with CCS							
Fischer-Tropsch Fuels	160,000 BDT/year	Red Rock Biofuels	Possible (CCS)	7	6–7	Lakeview, OR	>200[a]
Ethanol via gas fermentation	133,000 BDT/year	Aemetis Inc.	No	8	6	Riverbank, CA	158[b]
Renewable natural gas	250,000 BDT/year	GTI Stockton	Possible (CCS)	6	5	Stockton, CA	340[c]
Renewable hydrogen	45,000 BDT/year	Clean Energy Systems	Proposed (CCS)	7	5–6	Multiple locations in CA	>100

[a]*Dihn and Manternach, 2019.*
[b]*Lane, 2018.*
[c]*GTI, 2019.*
i: Technology Readiness Level.
ii: Commercial Readiness Level.

economy[1]. Wildfires in California during the 2018 fire season released about 68 million tons of CO_2 equivalent. This accounts for 15% of California's total carbon footprint and is comparable in magnitude to emissions from the state's electricity generation in the same year. The 2018 Camp Fire alone is estimated to have cost $16.5 billion in economic losses (Löw, 2019).

Because of these cross-cutting impacts, especially in the wake of 2 years of severe wildfires, significant political and economic resources are now being mobilized to promote sustainable management of California's forests. Historically, restoration treatments have been "carried" economically by the concurrent harvest of merchantable sawlogs as part of the management plan. Where this is not feasible, other sources of funding must be applied to support forest management.

Recent research by the Board of Forestry's Joint Institute for Wood Products Innovation has found that the LCFS could be an important source of revenue for forest restoration in California (Sanchez et al., 2020). In short, innovative wood products, including low-carbon and carbon-negative fuels, hold the potential to support carbon-beneficial, sustainable forest management in California. Innovative wood products can

[1]Little Hoover Commission, 2018.

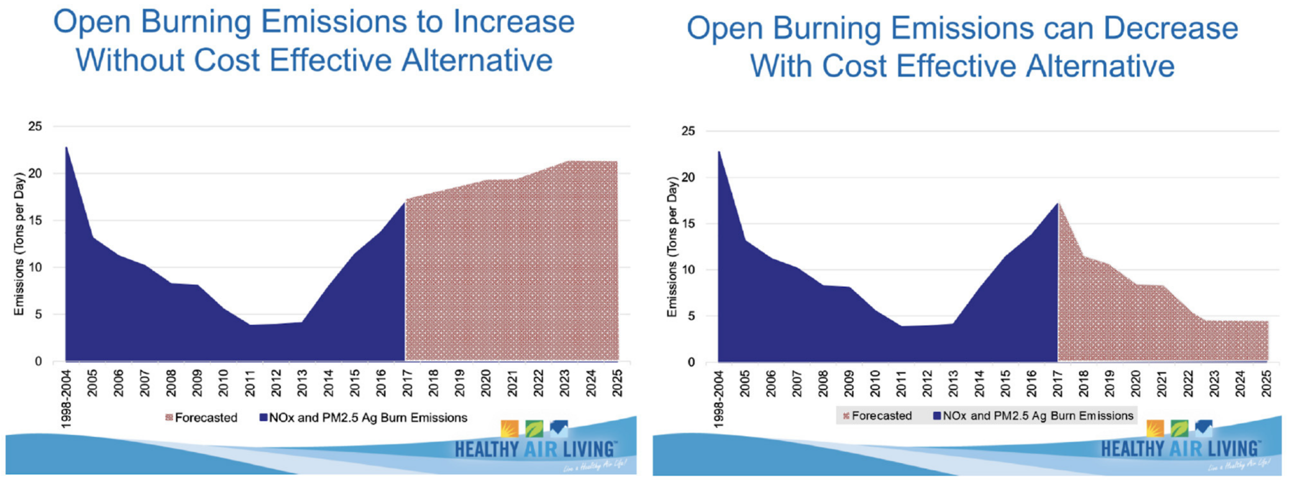

FIGURE 2 | Expected emissions of key health-impacting air pollutants from agricultural burning in the San Joaquin Valley. Reproduced from Olsen (2017).

support the state of California in increasing the pace and scale of forest management and restoration efforts, building local capacity, strengthening regional collaboration, supporting innovation, and promoting carbon storage.

It is important to note these technologies can employ either woody forest biomass or agricultural biomass, such as orchard and vineyard wastes. Agricultural biomass has numerous economic and logistical advantages over forest biomass: it is often cheaper, closer to existing infrastructure, and co-located with suitable geology for geologic CO_2 sequestration.

There is a significant air quality benefit of diverting otherwise-burned biomass. From 2005–2012, open burning of agricultural residue in the San Joaquin Valley had been reduced by over 80%, but drought and the shutdown of six biopower facilities in the region led to a significant increase in open burning, bringing it back above 2005 levels. Most of this increase is from open burning of biomass from pruning and removal of orchard trees. Under business-as-usual projections, open burning of agricultural residues—and the resultant emissions of health-harming air pollutants—are expected to increase, as indicated in **Figure 2**.

Working to find alternatives to open burning of agricultural waste is a major stated priority for the San Joaquin Valley Air Pollution Control District and other Air Districts (San Joaquin Valley Air Pollution Control District, 2018). Not only is this a public health concern, but it is also a significant environmental justice consideration, as recognized disadvantaged communities are disproportionately exposed to the emissions from these open burns (OEHHA, 2017). Pile burning of forest residues, as well as exposure to wildfire smoke, are similarly significant public health concerns, but under the current LCFS structure, there is no way to support pathways that offer reductions in criteria pollutant emissions.

We note that other sources of biomass have less favorable environmental impacts than those we consider in this paper. Potentially negative impacts related to forest residue removal include degradation of ecosystem condition and reduction of biodiversity (Camia et al., 2021). Managing these complex tradeoffs in forest-based climate change mitigation is subject to intense debate amongst academics, NGOs, and policymakers.

CCS Technologies

In addition to biomass-based processes, it is possible to create low-carbon and carbon-negative fuels using carbon capture and sequestration (CCS) in fuels production processes. Opportunities include carbon capture and sequestration of existing CO_2 emissions from fuels production. When ARB announced its 2019 changes to the LCFS, they pointed out that the CCS protocol would be particularly useful for ethanol producers, allowing producers to reduce CI by up to 40% (CARB, 2018a). To date, there is one CCS project submitted to ARB for approval. This project is part of an existing starch ethanol facility in North Dakota that will capture about 181,000 metric tons of CO_2 annually from starch fermentation and inject into a geologic formation 6,500 ft below the ethanol facility (Red Trail Energy, LLC, 2019; CARB, 2020a).

Despite the large financial incentives for low-carbon and carbon-negative fuels in California, these fuels may require additional support to be successfully commercialized. This is because low-carbon and carbon-negative fuels have not overcome the so-called "commercialization valley of death," which can occur for technologies that have already demonstrated proof of concept but still require large capital infusions to demonstrate that their design and manufacturing processes can be brought to full commercial scale (e.g., a first-of-a-kind full-scale power plant or manufacturing facility) (Jenkins and Mansur, 2011). Possible reasons for this outcome include low technical and commercial maturity, high capital costs, feedstock supply uncertainty for forest biomass, stability of revenues and LCFS credit prices, and permitting challenges.

Relevant Administrative Actions Under LCFS

Prior administrative action by ARB can inform feasible LCFS interventions to promote deep decarbonization. Most notably, in 2018, ARB board members amended the LCFS to broaden the program's focus and promote engineered carbon removal technologies (CARB, 2018a). Taking effect January 1, 2019, the re-adoption of the LCFS extended the program to 2030 with a targeted 20 percent CI decrease from 2010 levels. Additionally, the re-adoption imposed a CI gasoline and diesel standard for all post-2030 years that keeps the CI from increasing over time (CARB, 2020b). Along with extending the timeline for LCFS, the re-adoption expanded credit-generation opportunities to include non-alternative fuel pathway crediting, encompassing carbon capture and sequestration (CCS), low-carbon electricity generation, and building infrastructure for Zero Emissions Vehicles. The decision to extend the market to 2030 signaled ARB's commitment to the LCFS framework[2]. More recently, Governor Newsom directed ARB to develop and propose strategies to continue the State's current efforts to reduce the carbon intensity of fuels beyond 2030 (Exec. Order No. N-79-20, 2020).

Inclusion of Carbon Capture in LCFS

Project Based Crediting for CCS, a non-fuel credit-generating pathway, was added in 2018 (Townsend and Havercroft, 2019). This was the result of a multi-year process at ARB to integrate CCS with state climate policies, including 2050 state climate goals (CARB, 2017). To qualify for this protocol, a project must be part of a low carbon fuel pathway (Tier 2 pathway), a refinery investment (e.g., steam methane reforming), innovative crude (e.g., co-gen at oil field), or direct air capture (CARB, 2018b). CCS projects must inject the carbon into a saline reservoir, depleted oil and gas reservoirs, or oil and gas reservoirs used for CO_2-enhanced oil recovery and secure the carbon belowground for at least 100 years, meeting the permanence requirement (CARB, 2019b). Before credits are issued, a permanence certification needs to be issued, which includes a sequestration site certification and a CCS project certification. Both of these certifications require third-party review, and take an estimated 6 months for crediting (CARB, 2018b).

The LCFS CCS protocol provides flexibility on where projects can occur and allows stacking tax credits to promote maximum development and deployment of CCS technologies. Projects can occur anywhere in the world, but non-DAC projects must be associated with fuel sold in California. Projects can claim both LCFS credits and the federal 45Q tax credit for carbon oxide sequestration, increasing the value of CCS to ∼$250/ton CO2 sequestered (Credit for Carbon Oxide Sequestration, 2011).

Zero Emissions Vehicle Infrastructure Capacity

Prior to the 2018 amendments, electric utilities could opt-in to participating in the LCFS, producing electricity as a transportation fuel and supporting electric vehicles (EV). Utilities were eligible to generate LCFS credits for electricity they provided to charge EVs, and used credit revenue to provide a one-time, post-purchase rebate to utility customers who had purchased an EV. The 2019 amendments expanded the role of electricity providers and support for EVs, by expanding credit-generating opportunities based on supporting both EV charging infrastructure and purchasing. The 2019 amendments did not change how LCFS counts utility electricity generation, but it does have two notable contributions to changing LCFS credit generating opportunities: awarding credits for capacity rather than dispensed fuel, and further prioritizing deployment of EVs through a point-of-purchase EV rebate (Zheng, 2019a).

The zero emissions vehicle (ZEV) amendments to LCFS cover Hydrogen Refueling Infrastructure (HRI) and Direct Current Fast Charging Infrastructure (FCI) per Executive Order B-48-18 and Board Resolution 18-17 (CARB, 2018c). As of October 30, 2020, 52 hydrogen stations and 436 DC fast chargers at 91 sites have been approved for ZEV infrastructure crediting (CARB, 2021d). As stations reach full utilization, credits decrease in value, creating some first mover advantage (CARB, 2018c). By the end of 2025, these credits will sunset and, throughout its lifetime, are not to exceed 5% of program deficits (Witcover, 2018). The point-of-purchase rebate is still under development but is intended to further incentivize Californians purchasing EVs, now better supported by EV charging infrastructure (Zheng, 2019b).

Credit Clearance Market

ARB can also create price certainty through the Credit Clearance Market (CCM). The CCM is used to create a price cap, creating an annual market that allows deficit holders to trade at a set maximum ($200 in 2016 dollars) with credit holders that have agreed to participate (Stillwater Associates L. L. C, 2018; CARB, 2019c). This CCM prevents daily trades from exceeding too far above this $200/T ceiling because deficit holders have either the CCM or deficit banking opportunities at the end of the compliance year to settle deficits. As CI standards decline and it becomes more difficult to comply with LCFS fuel averages, the CCM will become increasingly important. Staff at ARB have indicated that the CCM should be used for cost containment to prevent demand-driven price spikes.

The price cap is maintained through granting electric utilities LCFS credits in the current year that are "borrowed" from that utility's future EV charging credit generation. The utilities are then obligated to sell these credits in the CCM and to invest proceeds from these "holdback" credits into subsidies for new EV purchases (the Clean Fuel Rewards program) and in the installation of EV charging infrastructure in disadvantaged communities (CARB, 2019d).

Changes to Target Stringency and End Date

Another policy design impacting price certainty is target stringency—or the ambition of CI targets—and the rate of ratcheting down CI averages. To encourage large capital investments and changes in supply-chains necessary for decarbonizing transportation, it is important for the policy to have high target stringency so that regulated entities have the necessary market certainty to stimulate investment. In 2018, ARB made minor changes to the short-term CI targets leading

[2]Extrapolating the trend in historic weekly averages of LCFS credits prices leading up to the announcement of the market extension (5/2/2016-9/17/2018) to forecast the price a year from the announcement for linear forecasting, the expected value is $169 and the actual market value was $195.

up to 2020 and signaled major commitment to the LCFS by extending the market to 2030.

ACTIONABLE RECOMMENDATIONS

We discuss three actions that ARB could undertake to promote commercialization of low-carbon and carbon-negative biofuels within their existing authorities.

Ensure Up-To-Date Accounting of Avoided Emissions Benefits

Lifecycle assessment as a regulatory tool is a complex topic, which often involves normative choices (Breetz, 2017). For instance, CA has included indirect land use change in its lifecycle carbon accounting under the LCFS, while the European Union has excluded it under its Renewable Energy Directive (Camia et al., 2021). Using best-available science around the lifecycle benefits and drawbacks of biofuels can guide future ARB action.

The LCFS carbon accounting framework currently does not account for emissions of biogenic carbon. While appropriate for some agricultural biofuels for which the time period of carbon sequestration is short (i.e., $<$1-year), it raises concerns when applied to forest biomass, which may sequester carbon for decades. Additionally, the framework also fails to account for avoided emissions from pile burning or decay of woody biomass, which is common practice in much of California (Springsteen et al., 2015). These emissions should be quantified in pathway CI calculations, providing additional incentives based on the actual emissions reductions from these feedstock sources.

Further, ARB should pursue research internally and externally to identify and reduce uncertainties related to these avoided emissions scenarios. For example, the frequency with which woody biomass, particularly forest residues, are pile burned in California is not currently tracked despite its obvious importance to fire risk, carbon storage, air quality and other environmental concerns. Tracking business-as-usual fate of woody biomass will aid in accurate accounting for the emissions avoided by their utilization. Finally, there is little empirical data on methane emissions from biomass piles—either in the field or at industrial facilities (California Board of Forestry Fire Protection, 2020). Given methane's importance as a GHG, this question warrants empirical study in the California context in order to accurately account for the net emissions impact of residue mobilization.

Provide Additional Incentives for Very Low-Carbon and Carbon Negative Fuels

Additional incentives to promote deeper decarbonization technologies could take several forms within the LCFS. In this section, we highlight two possibilities: a volumetric technology carve-out and a credit multiplier.

Volumetric Technology Carve-Out

A volumetric technology carve-out could be applied to a target fuel, such as one achieving a very low or negative CI score, or one made from biomass that would otherwise have been burned, leading to significant air quality impairments. A carve-out could require blenders to procure some fraction of their fuel from that source (or pay someone else to do so). Similar carve-outs are commonly used in Renewable Portfolio Standard (RPS) policies to deliver priority goals. While an RPS is generally designed to be technology-neutral like the LCFS, such carve-outs require regulated entities to procure a set percentage or amount of their power from operations of a certain type. This allows policymakers to use the RPS to achieve goals such as the development of emerging renewable energy technologies or support for local manufacturing. A similar approach could be implemented in the LCFS. Such an approach could allow CA to reduce the unintended consequences of an expansion of forest-biomass fuels, including use of biomass with less desirable environmental impacts.

For example, if the State identifies a priority, such as the creation of a renewable hydrogen industry utilizing diversion of woody forest residues that would otherwise have been open pile burned, or avoided flaring of landfill gas, the LCFS could mandate a fixed or rising number of MJ of fuel be generated from this source annually, obligating parties to purchase their "share" of these fuels or credits. The key challenge posed in this case is that such a "quantity" measure does not control cost. If a very small set of facilities are able to produce the qualifying fuel, the cost of these credits could rise rapidly. A carve-out could be more appropriate once the industries in question have reached commercial maturity, in order to use the LCFS system to drive further deployment of operational technologies.

Credit Multiplier

If a certain type of fuel or feedstock source is found to deliver priority goals, additional LCFS credits could be offered to manufacturers of that fuel, e.g., 1.2 or 1.5 MJ of credit for every MJ of fuel delivered. Specific credit multiplier values would be determined based on current market conditions and cost of production. One down-side of such a policy is that it reduces the actual GHG reductions delivered by the LCFS, since it would in effect create credits for low-carbon fuels that were not delivered.

This is not a novel concept. For example, the US Corporate Average Fuel Economy (CAFE) Standard is designed to increase the fuel economy of the vehicles sold in the US. However, the policy has also been leveraged to incentivize fuel switching. Electric vehicles sold into US markets are counted as 1.5 vehicles in calculating a manufacturer's average fuel economy. This means that a car maker would need to sell 50% more conventional vehicles than EVs with the same fuel economy to reach their target in a given year. This mechanism has been successful in driving more alternative fuel vehicles into US markets. Credit multipliers have arguably been less successful in the European Union Renewable Energy Directive, where there have been significant market distortions for feedstocks such as used cooking oil.

This credit multiplier could also be applied on a sliding scale to further incentivize very low carbon fuels. An operator could receive, e.g., 1.1× credit value per MJ for fuels from 30 g CO_2e/MJ down to 20 g/MJ, 1.2× from 20 down to 10, 1.3× from 10 down to 0, and 1.5× for any negative C pathway. This would both accelerate the production and uptake of very low C fuel pathways

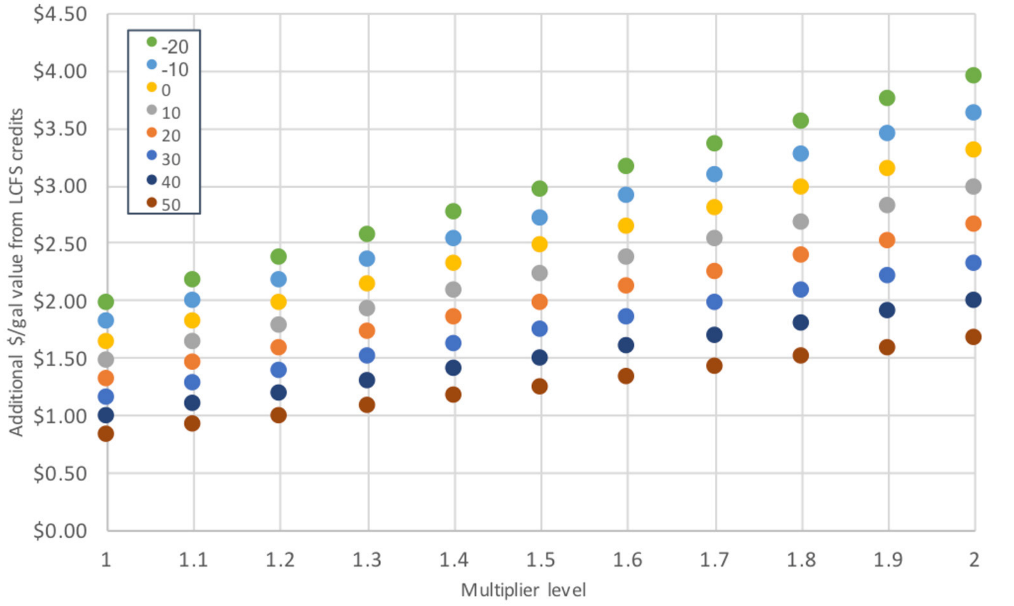

FIGURE 3 | Value of LCFS credits for delivery of a gallon of fuel as a function of that fuel's CI and the multiplier level applied to that fuel type. We assume a fuel energy content of 81.51 MJ/gal LHV, a LCFS credit price of $200/tCO$_2$e, and displacement of California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) with CI = 101.69 MJ/gal LHV.

that will be critical for meeting future goals while still retaining the LCFS model of CI-dependent subsidy level.

The level of multiplier necessary to achieve the intended uptake of target fuel types would need to be determined through further study. It would be necessary to conduct a detailed technoeconomic analysis of facility profits at different multiplier levels to assess the multiplier necessary to drive significant uptake. **Figure 3** presents the de facto per gallon subsidy created by the LCFS at different fuel CI values and different multiplier levels.

Implementing these additional incentives would mean reaching beyond the direct LCFS policy structure to achieve broader state goals. There is precedent, however, for using LCFS credits to incentivize activities not strictly within the bounds of the LCFS market. As discussed above, the allocation of credits for hydrogen fueling and fast EV charging infrastructure on a capacity rather than a delivery basis enables ARB to leverage the LCFS program to achieve broader ZEV goals. As with a carve-out, this policy would also reduce the amount of GHG reduction actually delivered by the LCFS program.

Provide Additional Incentives for Ancillary Benefits

ARB could provide additional incentives for very low-carbon and carbon negative fuel pathways which offer ancillary benefits to emissions reductions, such as wildfire risk reduction and air quality benefits. For example, it is clear that mobilizing woody forest residues that would otherwise be burned in open piles leads to a significant reduction in health-harming particulate emissions. ARB could consider offering additional incentives which recognize this benefit, especially where these residues would otherwise have been burned in non-attainment airsheds and/or near disadvantaged communities. ARB could also consider additional incentives for forest residue mobilization from designated high-hazard wildfire zones. However, in each of these cases, which reward local benefits, consideration would need to be given to interstate commerce and international trade issues. Further legal analysis is needed to determine how to reward benefits that are geographically limited without contravening potential limitations.

More broadly, ARB could ensure that the LCFS stimulates the best performing fuels across a variety of sustainability parameters. Fuels incentivized by the LCFS can offer significant environmental benefit, but this can't be taken as a given. Concerns abound regarding feedstock sourcing and its impacts on ecosystems, biodiversity, water resources, soil erosion, and other metrics of concern. Many of these considerations may be captured via the rigorous supply chain traceability already applied in the LCFS. However, others may not be tied to—or may even be inversely correlated with—lifecycle CI. ARB could consider third-party certification to ensure best practices are followed in feedstock sourcing across a variety of parameters, and also as a prerequisite to access additional LCFS incentives.

DISCUSSION

California's Low Carbon Fuel Standard (LCFS) is emerging as one of the most important policies to develop low-carbon and carbon-negative fuels. Yet, because the LCFS is designed to deliver the lowest-cost carbon intensity (CI) reductions possible in the transportation fuel system, it may fail to deliver technologies that would be poised to offer deeper decarbonization or other ancillary benefits to California's people and environment. This article contemplates administrative changes to the LCFS to further stimulate the commercialization of promising low-carbon and carbon-negative fuels. To do so, we examine promising technical pathways, their barriers to commercialization, and recent administrative actions by the CA ARB under the LCFS to promote novel lower-carbon fuels.

We propose three actions that ARB could undertake to promote commercialization within existing authorities. To commercialize low-carbon and carbon negative fuel, including those derived from forest residue feedstocks, ARB could: (1) embrace the most up-to-date science regarding lifecycle greenhouse gas emissions, (2) create additional, targeted incentives for very low-carbon or carbon-negative fuels through a volumetric technology carve-out or credit multiplier, and (3) ensure that the LCFS stimulates the best-performing fuels across a variety of parameters.

California's efforts to commercialize carbon-negative fuels could hold large implications for global efforts to fight climate change. California's success could bolster the performance of the federal Renewable Fuels Standard (RFS), which also promotes lower-carbon fuels. Bioenergy with carbon capture and sequestration (BECCS) will likely play a large role in global efforts to address climate change. Yet successful commercialization of low- and carbon-negative fuels from forest biomass is far from certain, despite policy support from the LCFS. Absent intervention, the State risks missing an opportunity to develop and deploy these fuels, with global implications.

AUTHOR CONTRIBUTIONS

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

REFERENCES

Aemetis, Inc. (2019). *Aemetis Receives USDA Conditional Commitment for $125 Million, 20-Year Financing of Riverbank Biorefinery*. Available online at: Available online at: http://www.aemetis.com/aemetis-receives-usda-conditional-commitment-for-125-million-20-year-financing-of-riverbank-biorefinery/ (accessed February, 2021).

Baker, S. E., Peridas, G., Stolaroff, J. K., Goldstein, H. M., Pang, S. H., Lucci, F. R., et al. (2019). *Getting to Neutral: Options for Negative Carbon Emissions in California (No. LLNL-TR-796100)*. Livermore, CA: Lawrence Livermore National Lab. (LLNL) doi: 10.2172/1597217

Breetz, H. L. (2017). Regulating carbon emissions from indirect land use change (ILUC): U.S. and California case studies. *Environ. Sci. Policy* 77, 25–31. doi: 10.1016/j.envsci.2017.07.016

California Board of Forestry and Fire Protection. (2020). *Joint Institute Recommendations to Expand Wood and Biomass Utilization in California*. Available online at: https://www.bioenergyca.org/wp-content/uploads/2020/11/Joint-Institute-Wood-and-Biomass-Utilization-Recommendat.pdf (accessed February, 2021).

Camia, A., Giuntoli, J., Jonsson, R., Robert, N., Cazzaniga, N.E., Jasinevicius, G., et al. (2021). *The Use of Woody Biomass for Energy Production in the EU*. Ispra: Joint Research Centre.

CARB (2017). *Carbon Capture and Sequestration Program: 2016 Progress and Future Plans*. Available online at: https://ww2.arb.ca.gov/sites/default/files/2018-12/CCS_Summary_Paper_April_2017.pdf (accessed February, 2021).

CARB (2018a). *CARB Amends Low Carbon Fuel Standard for Wider Impact*. Available online at: https://ww2.arb.ca.gov/news/carb-amends-low-carbon-fuel-standard-wider-impact (accessed February, 2021).

CARB (2018b). *Public Workshop to Discuss Implementation of LCFS*. Available online at: https://ww3.arb.ca.gov/fuels/lcfs/lcfs_meetings/112818presentation.pdf (accessed February, 2021).

CARB (2018c). *2018 Proposed Amendments to the Low Carbon Fuel Standard Regulation and to the Regulation on Commercialization of Alternative Diesel Fuels*. Retrieved from: https://ww3.arb.ca.gov/board/books/2018/092718/18-7-4pres.pdf (accessed February, 2021).

CARB (2019a). *California Greenhouse Gas Emissions for 2000 to 2017 Trends of Emissions and Other Indicators*. Available online at: https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2017/ghg_inventory_trends_00-17.pdf (accessed February, 2021).

CARB (2019b). *Carbon Capture and Sequestration Project Eligibility*. Available online at: https://ww2.arb.ca.gov/sites/default/files/2019-09/ccs_project_eligibility_faq_9-12-19.pdf (accessed February, 2021).

CARB (2019c). *2018 LCFS Compliance Information and Credit Clearance Market Information*. Available online at: https://ww3.arb.ca.gov/fuels/lcfs/2018compliance-ccm_051519.pdf (accessed February, 2021).

CARB (2019d). *Low Carbon Fuel Standard Workshop, July 31, 2019*, Sacramento, C. A. Available online at: https://ww3.arb.ca.gov/fuels/lcfs/lcfs_meetings/073119presentation.pdf (accessed February, 2021).

CARB (2020a). *Staff Summary Application No. D0005*. Available online at: https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/comments/tier2/d0005_summary.pdf (accessed February, 2021).

CARB (2020b). *Low Carbon Fuel Standard*. Available online at: https://ww2.arb.ca.gov/sites/default/files/2020-09/basics-notes.pdf

CARB (2021a). *California Cap-and-Trade Program Summary of California-Quebec Joint Auction Settlement Prices and Results*. Available online at: https://ww2.arb.ca.gov/sites/default/files/2020-08/results_summary.pdf (accessed February, 2021).

CARB (2021b). Weekly LCFS Credit Transfer Activity Report. Available online at: https://ww3.arb.ca.gov/fuels/lcfs/credit/lrtweeklycreditreports.htm (accessed February, 2021).

CARB (2021c). *Low Carbon Fuel Standard Reporting Tool Quarterly Summaries*. Available online at: https://ww3.arb.ca.gov/fuels/lcfs/lrtqsummaries.htm (accessed February, 2021).

CARB (2021d). LCFS ZEV Infrastructure Crediting. Available online at: https://ww3.arb.ca.gov/fuels/lcfs/electricity/zev_infrastructure/zev_infrastructure.htm (accessed February, 2021).

Christensen, A., and Hobbs, B. (2016). A model of state and federal biofuel policy: feasibility assessment of the california low carbon fuel standard. *Appl. Energy* 169, 799–812. doi: 10.1016/j.apenergy.2016.01.121

Credit for Carbon Oxide Sequestration. (2011). 26 U.S. Code § 45Q. Available online at: https://www.govinfo.gov/app/details/USCODE-2011-title26/USCODE-2011-title26-subtitlechap1-subchapA-partIV-subpartD-sec45Q (accessed February, 2021).

Dihn, M., and Manternach, J. (2019). *DOE Bioenergy Technologies Office 2019 Project Peer Review*. Red Rock Biofuels. Available online at: https://www.energy.gov/sites/prod/files/2019/04/f61/Woody%20Biomass%20Biorefinery%20Capability%20Development_EE000DPA2.pdf (accessed February, 2021).

Exec. Order No. N-79-20. (2020). Available online at: https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-text.pdf (accessed February, 2021).

Exec. Order No. S-01-07 by Governor Arnold Schwarzenegger (2007). Available online at: https://web.archive.org/web/20081026081001/http://gov.ca.gov/executive-order/5172/ https://ww3.arb.ca.gov/fuels/lcfs/lrtqsummaries.htm (accessed February, 2021).

Farrell, A. E, Sperling, D., Brandt, A., Eggert, A., Farrell, A., Haya, B., et al. (2007). *A Low-Carbon Fuel Standard for California Part 2: Policy Analysis. UC Berkeley: Transportation Sustainability Research Center.* Retrieved from https://escholarship.org/uc/item/1hm6k089 (accessed February, 2021).

Fawcett, A. A. (2010). *Supplemental EPA Analysis of the American Clean Energy and Security Act of 2009 H.R. 2454 in the 111th Congress Appendix*. Available online at: https://19january2017snapshot.epa.gov/sites/production/files/2016-07/documents/epasupplementalhr2454analysisappendix.pdf (accessed February, 2021).

Fridahl, M., Bellamy, R., Hansson, A., and Haikola S. (2020). Mapping multi-level policy incentives for bioenergy with carbon capture and storage in Sweden. *Front. Clim*. 2:604787. doi: 10.3389/fclim.2020.604787

GTI. (2019). *Low-Carbon Renewable Natural Gas (RNG) from Wood Wastes*. Available online at: https://www.gti.energy/wp-content/uploads/2019/02/Low-Carbon-Renewable-Natural-Gas-RNG-from-Wood-Wastes-Final-Report-Feb2019.pdf (accessed February, 2021).

Jenkins, J., and Mansur, S. (2011). *Bridging the Clean Energy Valleys of Death Helping American Entrepreneurs Meet the Nation's Energy Innovation Imperative. Breakthrough Institute*. Available online at: https://s3.us-east-2.amazonaws.com/uploads.thebreakthrough.org/legacy/blog/Valleys_of_Death.pdf (accessed February, 2021).

Lane, J. (2018). *Commercial time: Aemetis embarks on $158 million cellulosic ethanol project in California*. Biofuels Digest. Available online at: https://www.biofuelsdigest.com/bdigest/2018/03/08/commercial-time-aemetis-embarks-on-158-million-cellulosic-ethanol-project-in-california/ (accessed February, 2021).

Little Hoover Commission. (2018). *Fire on the Mountain: Rethinking Forest Management in the Sierra Nevada. Report #242.* Available online at: https://lhc.ca.gov/sites/lhc.ca.gov/files/Reports/242/Report242.pdf (accessed February, 2021).

Lomax, G., Lenton, T. M., Adeosun, A., and Workman, M. (2015). Investing in negative emissions. *Nat. Clim Change* 5, 498–500. doi: 10.1038/nclimate2627

Löw, P. (2019). *The Natural Disasters of 2018 in Figures: Losses in 2018 Dominated by Wildfires and Tropical Storms*. Munich, R. E. Available online at: https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/the-natural-disasters-of-2018-in-figures.html (accessed February, 2021).

Lutsey, N., and Sperling, D. (2009). Greenhouse gas mitigation supply curve for the United States for transport versus other sectors. *Transport. Res. Part D* 14, 222–229. doi: 10.1016/j.trd.2008.12.002

Lynd, L.R., Liang, X., Biddy, M.J., Allee, A., Cai, H., Foust, T., et al. (2017). Cellulosic ethanol: status and innovation. *Curr. Opin. Biotech*. 45, 202–211. doi: 10.1016/j.copbio.2017.03.008

OEHHA. (2017). SB 535 Disadvantaged Communities. Available online at: https://oehha.ca.gov/calenviroscreen/sb535 (accessed February, 2021).

Olsen, J. (2017). *San Joaquin Valley Air Pollution Control District. Presentation at the Central Valley Summit on Alternatives to Open Burning of Agricultural Wastes, November 2017.* Available online at: http://valleyair.org/cvsummit/documents/presentations/Session02-Jessica-Olsen.pdf (accessed February, 2021).

Rathi, A. (2019). The Story behind the World's First Large Direct Air Capture Plant. Quartz. Available online at: https://qz.com/1638096/the-story-behind-the-worlds-first-large-direct-air-capture-plant/ (accessed February, 2021).

Red Trail Energy, LLC. (2019). *Red Trail Energy Low Carbon Fuel Standard (LCFS) Design-Based Pathway Application – Carbon Capture and Storage Integrated with Ethanol Production.* Available online at: https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/comments/tier2/d0005_report.pdf (accessed February, 2021).

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., et al. (2018). "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development," in *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*eds, eds V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla (Geneva: IPCC), 93–174.

San Joaquin Valley Air Pollution Control District. (2018). *2017-2018 Report to the Community San Joaquin Valley Air Pollution Control District*. Available online at: https://www.valleyair.org/General_info/pubdocs/2017-18-Annual-Report.PDF (accessed February, 2021).

Sanchez, D., Zimring, T., Mater, C., Harrell, K., Muszynski, L., Edwards, B., et al. (2020). *Joint Institute for Wood Products Innovation: Evaluation of Literature, Research Gaps, Partnerships, and Priorities. Board of Forestry and Fire Prevention.* Available online at: https://bof.fire.ca.gov/media/9512/1-draft_jiwpi-report_152020_ada.pdf (accessed February, 2021).

Schenuit, F., Colvin, R., Fridahl, M., McMullin, B., Reisinger, A., Sanchez, D. L., Smith, S. M., Torvanger, A., Wreford, A., and Geden O. (2021). Carbon dioxide removal policy in the making: assessing developments in 9 OECD cases. *Front. Clim*. 3:638805. doi: 10.3389/fclim.2021.638805

Springsteen, B., Christofk, T., York, R. A., Mason, T., Baker, S., Lincoln, E., et al. (2015). Forest biomass diversion in the sierra nevada: energy, economics and emissions. *cal Ag* 69, 142–149. doi: 10.3733/ca.v069n03p142

Stillwater Associates, L. L. C. (2018). *The LCFS Credit Clearance Market: What Might Happen?* Available online at: https://www.stillwaterpublications.com/wp-content/uploads/2018/11/CCM-Analysis-11-2018-hfw9723k.pdf (accessed February, 2021).

The White House. (2016). *United States Mid-Century Strategy for Deep Decarbonization.* Available online at: https://unfccc.int/files/focus/long-term_strategies/application/pdf/us_mid_century_strategy.pdf (accessed February, 2021).

Townsend, A., and Havercroft, I. (2019). *The LCFS and CCS Protocol: An Overview for Policymakers and Project Developers. Global CCS Institute.* Available online at: https://www.globalccsinstitute.com/wp-content/uploads/2019/05/LCFS-and-CCS-Protocol_digital_version.pdf (accessed February, 2021).

van der Zwaan, B., Keppo, I., and Johnsson, F. (2013). How to decarbonize the transport sector? *Energy Policy* 61, 562–573. doi: 10.1016/j.enpol.2013.05.118

Vogt-Schilb, A., and Hallegatte, S. (2014). Marginal abatement cost curves and the optimal timing of mitigation measures. *Energy Policy* 66, 645–653. doi: 10.1016/j.enpol.2013.11.045

Witcover, J. (2018). *Status Review of California's Low Carbon Fuel Standard, 2011—2018 Q1 September 2018 Issue, UC Davis: Institute of Transportation Studies.* Available online at: https://escholarship.org/uc/item/445815cd (accessed February, 2021).

Zheng, S. (2019a). *Is California's Low Carbon Fuel Standard Incentivizing Electric Vehicle Deployment? Clean Energy Finance Forum.* Available online at: https://www.cleanenergyfinanceforum.com/2019/05/29/is-californias-low-carbon-fuel-standard-incentivizing-electric-vehicle-deployment (accessed February, 2021).

Zheng, S. (2019b). *Is California's Low Carbon Fuel Standard Helping EV Deployment? GreenBiz.* Available online at: https://www.greenbiz.com/article/californias-low-carbon-fuel-standard-helping-ev-deployment (accessed February, 2021).

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Governing Net Zero Carbon Removals to Avoid Entrenching Inequities

Peter Healey[1]*, *Robert Scholes*[2†], *Penehuro Lefale*[3] *and Pius Yanda*[4]

[1] Institute for Science Innovation and Society, University of Oxford, Oxford, United Kingdom, [2] Global Change Institute, University of the Witwatersrand, Johannesburg, South Africa, [3] Pacific Centre for Environment and Sustainable Development, University of the South Pacific, Suva, Fiji, [4] Institute of Resource Assessment, University of Dar es Salaam, Dar es Salaam, Tanzania

Climate change embeds inequities and risks reinforcing these in policies for climate change remediation. In particular, with policies designed to achieve "net zero" carbon dioxide, offsets may be considered inequitable if seen to avoid or delay gross emission reductions; offsets to emissions through technologically mature methods of carbon dioxide removals (CDR) require natural resources at scales threatening food security; knowledge of the potential of immature CDR is largely a global north monopoly; and CDR in particular environments is ill-understood and its implications for development unexamined. The use of CDR to contribute to robust progress toward Paris climate goals requires global agreement on simultaneously reducing emissions and enhancing removals, equity in burden sharing, and an interdisciplinary effort led by individual jurisdictions and focused on the co-development of technologies and governance to create CDR portfolios matched to local needs.

Keywords: net zero, carbon removals, countering inequities, offsets, polycentric governance

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Edited by:
Oliver Geden,
German Institute for International and Security Affairs (SWP), Germany

Reviewed by:
Alina Brad,
University of Vienna, Austria
Barry McMullin,
Dublin City University, Ireland
Adeniyi Asiyanbi,
University of Calgary, Canada

***Correspondence:**
Peter Healey
peter.healey@insis.ox.ac.uk

†Deceased

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INTRODUCTION

Bellamy and Geden (2019) make a case for the consideration of the potential contribution of CDR approaches to achieving 1.5–2.0°C pathways. They further propose that assessment proceeds technique by technique and locality by locality.

However, the sufficiency of local governance of carbon dioxide removal (CDR), although undeniably important, applies only where CDR actions are taken within the jurisdiction where the credits are to be accrued. This is quite unlikely to be the case for CDR roll-out of the magnitude required for global "net zero," to the extent that these use the most likely current land-based technologies. The big-emitter countries, where the gap between easily-achievable emission reductions and net zero is largest, do not have enough affordable or re-allocatable land to plug the gap using land-based CDR, including forestry and bioenergy with carbon capture and storage, BECCS. Implicitly or explicitly, directly or indirectly, they would need to rely on developing countries to do it for them, on terms which may limit their food and energy supplies in the host countries and may not be seen as a fair global distribution of the burdens of managing climate change. The outcome would inevitably be compared with attempts to distribute burdens on an overall least-cost basis, on the lines used in integrated assessment models, or on approaches based on equity principles such as cumulative per capita emissions or current ability to pay (Fyson et al., 2020).

The scope and framing of these climate-related distributional issues have developed over time. Schlosberg and Collins (2014) have traced how the breadth of concerns of the environmental justice movement—rooted in studies of local pollution largely in the USA, defining the environment to include the places where people live and work and incorporating social justice—in turn influenced conceptions of climate justice. The pursuit of "just sustainability" (Agyeman, 2013) involves managing the distribution of benefits and harms not only between developed and developing countries but also between different communities and generations, with potentially different values. Policy needs to reflect that what is marginal land to a developed world policymaker or business in search of land-based offsets may have a different value to his or her counterpart in a developing country government and be different again from its significance to those who actually live on it. The issues at stake here go beyond the significance of large-scale CDR for energy supply and food security but biodiversity and the survival of a whole range of livelihoods and cultural practices, assuming CDR works and itself is not reversed through climate change (Dooley and Kartha, 2018). From a legal perspective, Tsosie (2007) argues for a right to environmental self-determination for indigenous peoples. It is against the background of these distributional concerns that we look critically at how CDR might be employed in the context of net zero policies and how potential inequities might be forestalled.

POLICY OPTIONS AND IMPLICATIONS

Potential Limits of Net Zero Framings

As Bellamy and Geden (2019) point out, the first misframing of CDR in climate policy occurred when "bioenergy with carbon capture and storage" (BECCS)—at that point a putative and undemonstrated combination of two techniques—was used in integrated assessment and climate policy models to fill the gap between overall carbon budgets and what could be achieved in a particular timeframe through emissions reductions. This was counterproductive in four respects:

- It led to over-optimism for the early achievement of carbon budgets.
- Particularly in the UK, it overestimated the role that BECCS could play and worked against critical analysis of this approach.
- The symbolic substitution of BECCS for all CDRs led to insufficient attention being given to other CDR techniques.
- It established a false sense of security, especially for the most climatically vulnerable communities.

We are now seeing the emergence of a second counterproductive misframing. It relates to the role of CDR in delivering national "net zero" targets. It is important to recognize that net zero is not an objective of Paris but an interim objective on the way to net-negative emissions sufficient to achieve temperature stabilization of well below 2°C above pre-industrial levels. Net zero CO_2 emissions, in the IPCC 1.5° Report definition, are achieved "when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period" (IPCC, 2018). The scenarios in this report suggest that CDR might typically be used to bring down net emissions faster than they would otherwise be achieved and in advance of the achievement of global "net zero." The problematic issue arises around the circumstances under which CDRs could constitute a "moral hazard" or "mitigation deterrence effect" (Markusson et al., 2018), for instance by delaying or diluting other mitigation efforts.

There are some circumstances of CDR use in which moral hazard would not apply because the contributions of CDRs and emission reductions would be temporally as well as physically distinct. Thus, when emissions have been cut to zero, climate stability will still require the removal of residual greenhouse gases from the atmosphere, which have already locked in future temperature increases, and this is a task that only CDR techniques can perform. In addition, in cases where CDRs are more expensive, considered less safe, or less politically palatable than emission reduction, the risk of moral hazard and displacement does not arise. However, for several land-based CDR techniques, including afforestation, BECCS, and biochar, none of these circumstances may apply.

The potential for CDRs to deter other mitigation efforts has long been anticipated. The Royal Society Report on Geoengineering[1] (The Royal Society, 2009) recommended that "Geoengineering methods are not a substitute for climate change mitigation and should only be considered as part of a wider package of options for addressing climate change" (recommendation 3, p. 58), and the Royal Society/Royal Academy of Engineering Report on Greenhouse Gas Removal (The Royal Society and the Royal Academy of Engineering, 2018) (GGR/CDR) concludes "the goals of Paris can only be achieved if GGR is pursued alongside rapid and substantial emissions reductions… Large-scale GGR is challenging and expensive and not a replacement for reducing emissions" (recommendation 1, p. 114).

Despite these admonitions, the way in which "net zero" is currently framed in climate policy discourse, primarily considers CDRs as a simultaneous and fully substitutable ("fungible") offsets to avoid gross emissions reductions. Moral hazard has moved from the realm of abstract risk to that of prospective operational mechanisms. The IPCC 1.5° Report makes clear that offsetting residual emissions is one role of CDR, along with shaving off a temperature peak:

> "CDR would be used to compensate for residual emissions, and in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak[2]."

Indeed, it could be argued that the "net zero" concept loses much of its meaning and attraction unless there is a large measure of substitutability between emissions reductions and CDR offsets. McLaren et al. (2019) have advocated separate, non-fungible targets for emissions reductions and CDR sequestrations, yet, as far as we are aware, only one jurisdiction to date has so far

[1] *Geoengineering Governance Research Project Briefing Note 6*. Available online at: https://web.archive.org/web/20160619032848/http://geoengineering-governance-research.org/perch/resources/cgg-briefing-note-6geresearch-1.pdf.
[2] IPCC 2018, Summary for Policymakers, C3.

embraced such an approach. This exception is Sweden, which, within its "net zero by 2045" overall strategic policy, has adopted separate targets for emission reductions and for something that is called "supplementary measures." The latter includes both negative emissions *via* enhanced action in the land use, land-use change, and forestry (LULUCF) sector and specifically through BECCS, but it also includes international offsetting (including international negative emissions)[3,4]. Thus, even in Sweden, the option of using CDR schemes in other countries to offset domestic emissions remains available.

For the majority of high emitting countries, fungibility between emissions and CDR sequestration targets provides a temptation to delay efforts with the more lifestyle-challenging or expensive policies of emission reduction, by ramping up CDR offsets either domestically or internationally. Alternatively, we might see another round of what Geden (2015), drawing on Brunsson (2007), has called "targetism," by which setting unrealistic targets is primarily about making claims for legitimacy within climate policy processes and becomes dissociated from the need to deliver precision in defining climate action. The perceived political value to policymakers of constructive ambiguity (Geden, 2018) might provide an incentive not to look too closely at the effectiveness of CDR techniques or the unintended consequences of particular policy pathways toward their deployment. Non-state or sub-state actors, such as companies or cities, may feel even less constrained. We already have a clear warning of the dangers of similar climate policy fudges, as for instance regarding "reduction of emissions through degradation and deforestation" (REDD) programmes. These promote cynicism regarding the integrity of climate negotiations (Dooley et al., 2011), especially among environmental NGOs, and deliver very dubious long-term benefits to the climate system as well as to local communities (Jagger et al., 2014; Jagger and Rana, 2017). There will be strong benefits in attempting to learn from such past controversies and policy failures (Carton et al., 2020), recognizing that there may be particular problems in trying to rapidly scale up CDR (Buck, 2016) and that pursuit of environmental justice needs to go beyond a framework based on solely token adherence to the norms of transparency, equity, and legitimacy (Isyaku et al., 2017).

Do the Oxford Offsetting Principles Help to Mitigate the Risks?

A degree of cynicism about national actions may suggest a greater challenge to the myriad of non-state and sub-state actors to expand their actions in emissions reduction and in voluntary offset arrangements. Studies of voluntary standard setting in analogous contexts in the production of biofuels (Neville, 2015; Winickoff and Mandou, 2016) and palm oil (Clapp and Scott, 2018) suggest some potential hazards of such a course: continual contestation over discourses and narratives that frame governance, with alignment of interests between producers and consumers being particularly powerful (Dauvergne, 2018). Allen et al. (2020) have sought to counter the broad risks—as well as specific failures in carbon accounting and storage and unintended consequences to humans and the environment—by the adoption of a set of principles designed to ensure "high-quality" offsets incorporating removals rather than substitution for emissions and incorporating long-term storage. They present these proposals as part of a program of "net zero aligned offsetting." In their model, "a net zero society" has become the climate policy goal, and that means an expansion of existing voluntary carbon offsetting by "companies, organizations, cities, regions, and financial institutions."

The detailed proposals in Allen et al. (2020) could make a significant impact if embedded in institutional arrangements with sufficient authority to review and enforce—see *ACTIONABLE RECOMMENDATIONS: THE CO-DEVELOPMENT OF APPROPRIATE CDR AND ITS GOVERNANCE IN THE CONTEXT OF LOCAL VALUES AND PRIORITIES* and *CONCLUSIONS: ROBUST AND EQUITABLE PROGRESS IN THE DEVELOPMENT OF CDR*. However, we consider their idea of a "net zero society" that presents significant governance challenges of its own, especially if delivered in a highly decentralized manner, with market power as its primary instrument:

- Net zero can be achieved in theory at any level of gross emissions, provided balancing removals are available as offsets. Achieving any level of offsets simply by developing a carbon market, initially through an accumulation of market signals, would give too much economic power to the high-emitting countries of the global north, which favor offsets. It risks that removals may be unreasonably prioritized over food production, biodiversity, or other sustainable development goals in the global south or that the financial or other terms of the deal may be inequitable.
- As already indicated, it is asking a too much of voluntary codes such as these to create a consistent, fair, and widely observed set of standards to be applied to processes and outcomes. It is not clear whether such voluntary arrangements are supposed to replace the role of governments under the Paris process, by constituting the means of implementation of NDC commitments or otherwise what the means of articulation of the national and non-state systems might be.
- The relationship of the short-term goal of a "net zero society" to a state of minimizing gross emissions, at least until Paris temperature targets are achieved and stabilized, is also unclear. Some effective global cap-and-trade system, with a shrinking cap applying both to emissions themselves and the trading of them, might be the way to secure further progress post mid-century. There is a scope for this within Paris Article 6, but a range of views among the parties as to its desirability was indicated in failure to make progress on mechanisms at COP25. There is of course an inherent tension between the need for governments to bear down on emissions and their delegation of that role to the market.
- Furthermore, there is a substantial chance that the achievement of any form of net zero will reduce the incentives

[3] http://www.swedishepa.se/Environmental-objectives-and-cooperation/Swedish-environmental-work/Work-areas/Climate/Climate-Act-and-Climate-policy-framework-/.
[4] Fridahl, M., personal communication, 25 November 2019.

for policymakers to progress further toward minimizing gross emissions, at least without some technological breakthrough that significantly reduces the costs of such measures.

ACTIONABLE RECOMMENDATIONS: THE CO-DEVELOPMENT OF APPROPRIATE CDR AND ITS GOVERNANCE IN THE CONTEXT OF LOCAL VALUES AND PRIORITIES

To understand the impact of international CDR policy on those lower-emitting and still developing countries, we have to understand the challenges posed by a large dependence of the global climate policy regime on greenhouse gas removals. One arises from the very different states of technology readiness of different CDR approaches. The second derives from the principle of "common but differentiated responsibilities" of states to protect the climate as a global public good under international law in line with their capacities (Reynolds et al., 2018), an approach that is foundational to the UNFCCC and the Paris Agreement mechanism of nationally determined contributions (NDCs). Given this policy architecture of Paris, political realism would seem to suggest that more ambitious climate actions are most likely to be adopted if they are congruent with both national development aims and the full array of sustainable development goals (SDGs). Yet, the development of first-generation biofuels, as well as REDD+ programs as noted above, already provides examples of innovation to the detriment of local community rights, as well as to food security, and in some cases also the balance of greenhouse gas production (Mohr and Raman, 2013). By analogy, a balance between competing requirements on CDR will only be struck if clear governance principles are in place. These need to specify that CDR approaches are to be deployed if they are not only demonstrated to be effective, cost-effective, accountable, and safe by international standards but also interact with the local environment, culture, and economy in ways acceptable to each jurisdiction where they are to be deployed or where they will have impacts (CGG, 2014).

How might such a broad principle be developed into equitable global CDR policy? For lower-emitting, developing countries, where often CDRs do not yet have much of a place in climate policy, achieving a meaningful and sustainable role for CDRs will need to be based on careful and sensitive programs of technical assessment and stakeholder and public engagement. This relatively slow response to CDR provides a current window of opportunity for these assessments. They would need to consider *local* options, constraints, and goals and be informed by locally initiated research and governance. Achieving this, against a background where CDR research is largely concentrated in the Global North-West and is typically assessed only in technical and global terms that obscure national differences (for example, a reduction in the global mean temperature rise), will itself be a huge challenge, requiring a major development in local assessment and governance capacities. It risks being made politically more difficult if—as a result of unconditionally fungible "net zero" emissions framings—CDRs are seen as the rich country escape route from assuming a historically fair share of gross emissions reductions. In order to speed widespread assessment, development, and take-up of CDR in the developing world, unconditionally fungible "net zero" emission framings need to be replaced or circumscribed so as to address and mitigate such perceptions. We suggest below some key principles and mechanisms for doing so. We recognize that given the interests of political and industrial incumbents, to be effective, any measures of this kind will need to be underpinned by strong international commitment to redress power inequalities in global climate policy, notably by recognition of local and indigenous rights and claims to land and resources.

CONCLUSIONS: ROBUST AND EQUITABLE PROGRESS IN THE DEVELOPMENT OF CDR

The challenges of achieving North-South justice of course are not confined to "net zero" framings or indeed to climate policy, and of course attempts to mitigate such risks should be based on principles and protocols that have a wider application. In summary, on the basis of the arguments presented, it is our assessment that robust but equitable progress in the development of CDR can be achieved through a number of such key developments in the governance and research system.

A first element should be a global agreement of the need to both reduce gross emissions and enhance removals at the fastest possible rate in pursuit of Paris objectives, coupled with a common view of what constitutes equity in national burden sharing in achieving these goals both in their overall scope and the process by which they are delivered.

A second element must be to ensure that those countries whose natural and social resources are targeted by others for large-scale CDR possess the capacities required to make them equal partners in their scientific assessment and governance of all options, in the context of their development needs and pathways (Workman et al., 2020).

The third element would be the introduction of a set of principles to protect the interests of local communities in the development CDR. These would be analogous to those applied to REDD+ by the Cancun safeguards (UNFCCC, 2011), which were designed to ensure the protection of the rights of indigenous peoples, the protection of natural forests, transparency, and accountability. In developing these, CDR would need to improve on and learn from the inadequacies of REDD+ safeguards.

Two innovations in the machinery of research and governance would buttress and implement these approaches.

An interdisciplinary, social-natural science, research, and policy effort would be the instrument for mitigating national inequalities in scientific and governance capacity in line with the second element above. This would be led by the policymakers and stakeholders of individual jurisdictions or through their voluntary networks and would center on the need for CDR policies to serve also wider economic and social needs, especially in developing countries. It would mobilize the scientific and governance capacities of the developed world—the sharing of these capacities to be seen as part of the "common but differentiated responsibilities" of the developed world (see also United Nations, 2012)—and focus these on the rapid co-development of technologies and governance in creating portfolios of CDR matched to local circumstances and needs. The current authors declare an interest in this approach as members of an international network committed in principle to such work.

This would be complemented by, and iterated with, a small but effective global CDR governance machinery. This might be best established as an independent intergovernmental organization, analogous to IPCC but on a smaller scale, which would be able to bring together expertise to assess individual governments' policies and practices as the Climate Change Committee is mandated to do within the UK. Its main role would be to lead an international dialogue aimed at vertically integrating systems for the assessment and governance of CDR so that progress toward and beyond "net zero" can be independently and consistently assessed and global standards and codes for best practice distilled. One detailed contribution this organization could make would not only be to underwrite or organize insurance to protect the supplier of any offsets but also to specify minimum contractual standards for monitoring, reporting, and verification of all CDR schemes, to protect offset purchasers.

These changes would have wider effects on the ways we assess the role of CDR in climate policy. Instead of each CDR technique being considered individually for its potential contribution at a global scale, using approximations of the environmental resources it would need to draw on, each technique would face the rigor of being evaluated comparatively in relation to other methods and in its approach being tested in real jurisdictions. The ambitious range of policies that some countries seek to integrate with climate action will provide additional challenges to the design of multilevel governance.

At the global level, instead of the pathway of removals being composed of technology wedges, allocated to countries top-down, it would be built bottom-up from the geopolitical wedges put forward by individual countries, based on local needs (Bellamy and Healey, 2018). This geopolitical anchoring of CDR plans should make them more realistic and sustainable and help them to make the maximum responsible contribution to climate action.

AUTHOR CONTRIBUTIONS

PH and RS made substantial contributions to the text as joint first authors. PL and PY contributed to the text. All authors approved the work for publication.

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DEDICATION STATEMENT

We dedicate this article to Professor Bob Scholes, news of whose untimely death reached us during this article's production. He has passed away at a time when his scientific contribution to climate science is sorely needed. He will be remembered for his scientific leadership globally and specifically in the African continent.

REFERENCES

Agyeman, J. (2013). *Introducing Just Sustainability: Policy, Planning and Practice.* London: Zed Books.

Allen, M., Axelsson, K., Caldecott, B., Hale, T., Hepburn, C., Hickey, C., et al. (2020). *The Oxford Principles for Net Zero Aligned Carbon Offsetting*. University of Oxford; Smith School of Enterprise and the Environment. Available online at: https://www.smithschool.ox.ac.uk/publications/reports/Oxford-Offsetting-Principles-2020.pdf (accessed April 9, 2021).

Bellamy, R., Geden, O. (2019). Govern CO2 removal from the ground up. *Nat. Geosci.* 12, 874–876. doi: 10.1038/s41561-019-0475-7

Bellamy, R., and Healey, P. (2018). 'Slippery slope' or 'uphill struggle'? Broadening out expert scenarios of climate engineering research and development. *Environ. Sci Policy* 83, 1–10. doi: 10.1016/j.envsci.2018.01.021

Brunsson, N. (2007). *The Consequences of Decision-Making*. Oxford: Oxford University Press.

Buck, H. J. (2016). Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change* 139, 155–167. doi: 10.1007/s10584-016-1770-6

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *WIREs Climate Change* 11:e671 doi: 10.1002/wcc.671

CGG (2014). What should we expect from geoengineering research? Climate

Clapp, J., and Scott, C. (2018). The global environmental politics of food. *Glob. Environ. Politics* 18, 1–11. doi: 10.1162/glep_a_00464

Dauvergne, P. (2018). The global politics of the business of "sustainable" palm oil. *Glob. Environ. Politics* 18, 34–50. doi: 10.1162/glep_a_00455

Dooley, K., Griffiths, T., Francesco, M., and Saskia, O. (2011). *Smoke and Mirrors: A Critical Assessment of the Forest Carbon Partnership Facility.* Moreton-in-Marsh: FERN and Forest Peoples' Programme.

Dooley, K., and Kartha, S. (2018). Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *Int Environ Agreements* 18, 79–98. doi: 10.1007/s10784-017-9382-9

Fyson, C. L., Baur, S., Gidden, M., and Schleussner, C. F. (2020). Fair-share carbon dioxide removal increases major emitter responsibility. *Nat. Clim. Chang.* 10, 836–841 doi: 10.1038/s41558-020-0857-2

Geden, O. (2015, December 14). Paris climate deal: the trouble with targetism. *The Guardian*. https://www.theguardian.com/science/political-science/2015/dec/14/the-trouble-with-targetism (accessed January 1, 2021).

Geden, O. (2018). Politically informed advice for climate action. *Nat. Geosci.* 11, 380–383 doi: 10.1038/s41561-018-0143-3

IPCC (2018). *Intergovernmental Panel on Climate Change: Global Warming of 1.5°*. Geneva: IPCC.

Isyaku, U., Arhin, A. A., and Asiyanbi, A. P. (2017). Framing justice in REDD+ governance: centring transparency, equity and legitimacy in readiness implementation in West Africa. *Environ. Conserv*. 44:212. doi: 10.1017/S0376892916000588

Jagger, P., Brockhaus, M., Duchelle, A. E., Gebara, M. F., Lawlor, K., Resosudarmo, I. A. P., et al. (2014). Multi-level policy dialogues, processes, and actions: challenges and opportunities for national REDD+ safeguards measurement, reporting, and verification (MRV). *Forests* 5, 2136–2162. doi: 10.3390/f5092136

Jagger, P., and Rana, P. (2017). Using publicly available social and spatial data to evaluate progress on REDD+ social safeguards in Indonesia. *Environ. Sci. Policy* 76, 59–69. doi: 10.1016/j.envsci.2017.06.006

Markusson, N., McLaren, D., and Tyfield, D. (2018). *Global Sustainability*. Cambridge: Cambridge University Press.

McLaren, D., Tyfield, D., Willis, R., Szerszynski, B., and Markusson, N. (2019). Beyond "net-zero": a case for separate targets for emissions reduction and negative emissions. *Front. Climate* 1:4. doi: 10.3389/fclim.2019.00004

Mohr, A., and Raman, S. (2013). Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. *Energy Policy*. 63, 114–122. doi: 10.1016/j.enpol.2013.08.033

Neville, K. J. (2015). The contentious political economy of biofuels. *Glob. Environ. Politics* 15, 21–40. doi: 10.1162/GLEP_a_00270

Reynolds, J. L., Gerrard, M. B., and Hester, T. (2018). *Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal*. Cambridge: Cambridge University Press. p. 124.

Schlosberg, D., and Collins, L. B. (2014). From environmental to climate justice. *Wires Climate Change* 5, 359–374. doi: 10.1002/wcc.275

The Royal Society (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. London: The Royal Society.

The Royal Society and the Royal Academy of Engineering (2018). *Greenhouse Gas Removal*. London: The Royal Society. p. 114.

Tsosie, R. (2007). Indigenous people and environmental justice: the impact of climate change. *U. Colorado Law Rev*. 78:1625.

UNFCCC (2011). *The Cancun Agreements Dec 1/CP.16*. Bonn: United Nations Framework Convention on Climate Change. p. 1–31.

United Nations (2012). *Report of Special UN Rapporteur, Farsda Shaheed, in the Field of Cultural Rights: the Right to Enjoy the Benefits of Scientific Progress and Its Applications*. UN Dec A/HRC/20/26. New York, NY: United Nations.

Winickoff, D. E., and Mandou, M. (2016). *The problems of epistemic jurisdiction in global* governance: the use of sustainability standards for biofuels. Social Studies of Science. doi: 10.1177/0306312716667855

Workman, M., Dooley, K., Lomax, G., Maltby, J., and Darch, G. (2020). Decision making in contexts of deep uncertainty - an alternative approach for long-term climate policy. *Environ. Sci. Policy* 103, 77–84. doi: 10.1016/j.envsci.2019.10.002

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POLICY AND PRACTICE REVIEWS
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Who Is Paying for Carbon Dioxide Removal? Designing Policy Instruments for Mobilizing Negative Emissions Technologies

Matthias Honegger[1,2,3]*, *Matthias Poralla*[1], *Axel Michaelowa*[1,4] *and Hanna-Mari Ahonen*[1]

[1] *Perspectives Climate Research gGmbH, Freiburg im Breisgau, Germany,* [2] *Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, Netherlands,* [3] *Institute for Advanced Sustainability Studies (IASS) Potsdam, Potsdam, Germany,* [4] *Department of Political Science, University of Zurich, Zurich, Switzerland*

Carbon dioxide removal (CDR) poses a significant and complex public policy challenge in the long-term. Presently treated as a marginal aspect of climate policy, addressing CDR as a public good is quickly becoming essential for limiting warming to well below 2 or 1.5°C by achieving net-zero emissions in time – including by mobilization of public and private finance. In this policy and practice review, we develop six functions jointly needed for policy mixes mobilizing CDR in a manner compatible with the Paris Agreement's objectives. We discuss the emerging CDR financing efforts in light of these functions, and we chart a path to a meaningful long-term structuring of policies and financing instruments. CDR characteristics point to the need for up-front capital, continuous funding for scaling, and long-term operating funding streams, as well as differentiation based on permanence of storage and should influence the design of policy instruments. Transparency and early public deliberation are essential for charting a politically stable course of action on CDR, while specific policy designs are being developed in a way that ensures effectiveness, prevents rent-seeking at public expense, and allows for iterative course corrections. We propose a stepwise approach whereby various CDR approaches initially need differentiated treatment based on their differing maturity and cost through R&D pilot activity subsidies. In the longer term, CDR increasingly ought to be funded through mitigation results-oriented financing and included in broader policy instruments. We conclude that CDR needs to become a regularly-provided public service like public waste management has become over the last century.

Keywords: mitigation policy instruments, climate finance, carbon markets, negative emissions, Paris Agreement, net-zero emissions, nationally determined contributions, carbon dioxide removal

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***Correspondence:**
Matthias Honegger
honegger@perspectives.cc

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INTRODUCTION

The ultimate objective of international climate policy is to stabilize atmospheric greenhouse gas (GHG) concentrations at levels that prevent dangerous interference with the climate system, according to the UN Framework Convention on Climate Change (United Nations Framework Convention on Climate Change, 2015). The Paris Agreement's long-term goal is to limit warming well below 2°C and pursue efforts to limit warming to 1.5°C by achieving a peak on global GHG emissions as soon as possible and achieving net-zero emissions globally in the second half of this century. The Paris Agreement sets a collective quantitative constraint on cumulative net emissions of GHGs at the global level. The Agreement furthermore provides qualitative indications (with room for interpretation) regarding the respective contributions of countries, sectors or of emissions reductions vs. carbon dioxide removal (CDR) therein (Honegger et al., 2021). In recent years, net-zero emission targets have emerged as an organizing principle of climate policy on various levels (Schenuit et al., 2021). While offering a long-term perspective and potential alignment with the Paris Agreement's collective goals, such targets are not sufficient on their own. They need to be operationalized on the level of specific decision-makers in all economic sectors and underpinned by specific policy instruments. In this paper, we address characteristics such policy instruments should (jointly) have and develop a set of necessary conditions for Paris-alignment with regard to CDR policy instrument mixes.

The Possible Roles of CDR

While afforestation and restoration projects have long served to remove and store carbon dioxide (CO_2) (Kupfer and Karimanzira, 1990), the idea of combining biomass energy generation with carbon capture and storage (BECCS) (Möllersten et al., 2003) was included in integrated assessment models (IAM) only in the late 2000s (Van Vuren et al., 2011). Direct air capture and storage (DACCS) (Keith et al., 2006) was added even later. Initially met by climate change scholars with skepticism, such CDR is increasingly viewed as essential for meeting net-zero emissions targets at national and regional as well as the global level. The readiness of, and support for CDR approaches varies widely from already implemented and low-regret (e.g., restoring mangrove vegetation) to low or unknown (in particular open-ocean-based) approaches [see Honegger et al. (2020) for an assessment of the impacts of various CDR approaches on the Sustainable Development Goals, Gattuso et al. (2021)]. At least three rationales are frequently put forward for considering CDR in public policy (Geden and Schenuit, 2020; Morrow et al., 2020): (a) balancing out residual emissions from effectively-impossible-to-decarbonize sectors (like agriculture) for achieving a permanent steady state of net-zero emissions, (b) temporarily balancing out residual emissions from hard-to-decarbonize sectors (like construction, heavy industry, and heavy transport), while solutions for these sectors are being developed and just transformations with job-transitions are taking place (Buck et al., 2020), and/or (c) to return to historical CO_2 concentrations through a phase of global net-negative emissions after achievement of complete decarbonization. Additionally, there is d) a moral argument interpreting well-established principles of distributive justice such that countries with significant historical emissions and technological capacities ought to act as first movers and attempt to drive down the cost of CDR so that others have access to a larger set of mitigation options (Fyson et al., 2020; Pozo et al., 2020).

These reasons all characterize the continuous and large-scale removal of CO_2 into permanent storage as a public good, which in many cases requires a systematic long-term public intervention. Yet, to date governmental action – beyond early-stage research and development funding – appears to be lagging and causing a systematic "incentive gap" (Fridahl et al., 2020). Calls for examining and mobilizing various CDR potentials are growing (e.g., Bellamy, 2018; Geden et al., 2019) and an increasing number of private companies and philanthropies are starting to voluntarily mobilize CDR. Yet so far CDR has not commonly been established as a necessary public service of similar nature as the treatment of solid or liquid wastes. This is despite the increasingly well-evidenced public-good nature of CDR services – as would be the case for the public service of disposing of liquid or solid wastes, which without government intervention would pile up on the street or pollute water, soil and air. While such a narrative holds promise for framing and guiding public policy, its historical context suggests that the associated policies may face continuity challenges (Buck, 2020).

Operational CDR Definitions Needed for Funding and Public Policy Instruments

Only recently have scientific definitions of CDR (overnmental Panel on Cli, 2018, p. 544) been operationalized with greater clarity, which is a precondition for designing appropriate instruments for mobilizing it. Through four principles, Preston Aragonès et al. (2020) differentiate CDR from other mitigation activities roughly as follows: (1) atmospheric CO_2 is physically removed, (2) then permanently stored out of the atmosphere, (3) all up- and downstream GHG flows are considered in the calculations, and (4) the atmospheric net-CO_2 flow balance is negative.

The Paris Agreement obliges its Parties to pursue "mitigation of climate change," which includes both emissions reductions and CDR (Honegger et al., 2021). Parties are to furthermore communicate their planned "mitigation" efforts via regularly updated nationally determined contributions (NDCs), long-term low greenhouse gas emission development strategies (LTS-LEDS), and their actually observed emission and removals via GHG inventory reports. Parties' mitigation efforts are to become increasingly comprehensive (including all emission sources and sinks, all GHGs, and all economic sectors) and ambitious in line with the collective net-zero emissions goal. Consequently, governmental action is needed to pursue CDR in addition to rapidly cutting emissions and private sector actors are likely to play an important role in the execution.

Differentiation Needed Based on CDR Characteristics

A key feature – and challenge – of CDR is that the storage of CO_2 needs to be 'durable' (overnmental Panel on Cli, 2018, p. 544) or permanent. The innate permanence of CO_2 stored in biological systems (soil- and plant biomass or biochar) is much lower than the innate permanence of CO_2 stored deep underground and/or in mineralized form (Möllersten and Naqvi, 2020). While permanence may overall be achieved in both cases through suitable measures, permanence of chemically stable compositions is dramatically higher. Emission reductions are innately permanent and do not face a risk of reversal. Policy instruments need to account for such differences in order to be compatible with net-zero ambitions, by differentiating results based on their permanence levels [e.g., recognizing temporary removals without relying on them in the long term; Ruseva et al. (2020)] or limiting their role within mitigation targets by further enhancing the pace and scale of emissions reductions accordingly.

Another important difference between CDR approaches is their present and projected future financial structure, where few approaches are already – or may be in the future – benefiting from non-carbon revenue sources, while most may largely or exclusively have to rely on continuous carbon-related revenues. Policy instruments need to account for differences in long-term funding needs. Several reports and studies have examined cost projections of various CDR types, yet the empirical basis remains very narrow and comparability between projections of future CDR costs is limited (Fuss et al., 2018; Lehtveer and Emanuelsson, 2021).

Policy, furthermore, needs to be based on an encompassing and long-term view of the results: In some cases, the same type of activity can have widely different mitigation results, ranging from a net increase in emissions, a reduction in net emissions, all the way to varying degrees of net-negative emissions. It is therefore not sufficient to create generic categories of CDR activities whose effects can robustly be predicted by standardized calculation methodologies, but carbon flows need to be projected on a case-by-case basis and appropriately measured ex-post.

Outline and Approach

In this policy and practice review, we first identify a set of CDR-specific policy design needs emerging from the particularities of CDR (in contrast to conventional mitigation through emissions reductions activities). Building on those needs and situated within the emerging CDR policy literature, we then identify a set of six necessary functions for CDR policy mixes to fully aligned with the objectives of the Paris Agreement. Against the backdrop of these functions, we examine prominent examples of current policy elements at international and national levels as well as private sector initiatives which may offer (partial) steps toward fulfilling the identified functions in the way they contribute to mobilizing and financing CDR. Finding shortfalls – even among the perhaps best case approaches toward individual policy functions – we observe a near-universal lack of a systematic approach to fulfilling these functions jointly. Based on relevant lessons from climate change mitigation policy, we then offer actionable recommendations to start addressing the gaps and risks identified, and to transparently advance a set of dedicated policy instruments in collaborative fashion. Our recommendations target international climate negotiators, national mitigation planners, and private sector actors engaged in voluntary CDR efforts. We propose a stepwise approach that allows both the necessary differentiation between CDR approaches in the short-term and an increasingly level playing field for all kinds of CDR in the long-term. The objective would be that CDR efforts and mitigation efforts overall are enabled to credibly achieve Paris-aligned net-zero emissions targets at national and global levels.

CDR FINANCING NEEDS AND PROJECTIONS

Differentiating Cost-Revenue Projections

For design of efficient mitigation policy instruments a distinction has to be made between those mitigation options that require full-, partial-, or no public funding to be implemented. As a first differentiation we therefore suggest three categories of CDR approaches: (I) those that cannot generate revenues in the absence of dedicated financial support, (II) those which might generate some (but not sufficient) revenues or cost savings from co-benefits, and (III) those that may be profitable even in the absence of dedicated interventions (regulatory, market-making or fiscal policy instruments or voluntary efforts). **Table 1** offers an overview of potential revenue streams and marginal-cost categorization of various CDR approaches.

Technologies in group I – "pure climate technologies" – do not come with significant (or any) monetizable co-benefits: their sole purpose is to limit the rise in atmospheric CO_2 concentrations. The direct capture of CO_2 from ambient air and subsequent underground storage (DACCS) is the clearest example. Retrofitting capture technology to existing biomass-energy plants combined with underground storage (BECCS) (and some other CDR approaches) are further examples, where at least some necessary elements in the value-chain are solely dedicated to the purpose of CDR and thus do not generate revenue.

Group II and III technologies are not always as clearly identifiable; their separation requires a case-by-case examination for the determination of their so-called "additionality" – as has been done under the Clean Development Mechanism (CDM) of the Kyoto Protocol (Michaelowa et al., 2019a). While some (Cames et al., 2016) questioned the additionality of the majority of CDM activities. Others, however, contested their results, given that Cames et al. chose a very narrow definition of additionality based on the degree of increase of attractiveness of the activity induced by the carbon credits. Moreover, Cames et al. (2016) did not take the international regulation for treatment of host country mitigation policies under the CDM into account (Federal Ministry of the Environment, Nature Conservation, Housing, and Reactor Safety (BMUB), 2017). Afforestation and reforestation activities (A/R) can generate some revenue streams associated with co-benefits (e.g., tourism or the sale of (non-timber) forest products. Biochar and enhanced weathering can generate returns by lowering fertilizer spending and increasing yields (Cornelissen et al., 2018; Kätterer et al., 2019; Ye et al., 2019). Marine CDR via ocean fertilization or alkalinization (with iron, phosphorus or limestone) could potentially result in fisheries yield increases, yet these are highly uncertain and their overall desirability is unclear (Cox et al., 2021). Some forms of carbon capture and use (CCU) may also result in revenue and in CDR: binding CO_2 permanently in long-lived materials (e.g.,

TABLE 1 | Cost-revenue projections and technology readiness based on Poralla et al., 2021.

CDR type	(Potential) non-carbon revenue streams[a]	Financial projection group	Technology readiness level (TRL)[b] Möllersten and Naqvi, 2020
Afforestation and reforestation	• Monetizable ecosystem services, e.g., through forest-related Payments for Ecosystem Services (PES) schemes • Flood risk reduction and regulation benefits • Ancillary tourism and leisure (if non-consumptive) • New income opportunities generated by forests-based ecotourism • Sale of non-timber forest products	Mostly II, some III	7–9
Bioenergy with carbon capture and storage (BECCS)	• Electricity sales • Heat sales (district heat) • Waste treatment (if biomass is sourced from waste)	II	BE: 6–9 CCS: 4–7
Biochar as soil additive	• Agricultural productivity enhancement • District heat sales • Electricity sales	Mostly III, some II	3–7
Direct air carbon capture and storage (DACCS)	• Uptake of power when priced negatively	I	3–6
Direct air carbon capture and durable materials production (construction materials)	• Sale of pure CO_2 as a feedstock for carbon-based materials	II	5–7
Wetland restoration	• Monetizable ecosystem services, e.g., through PES • Water supply services • Reduced risk of flooding and soil erosion • Ancillary tourism and leisure (if non-consumptive)	II	3–5
Enhanced weathering	• Sale as replacement of conventional sand or pebbles • Sale of formed carbonates to paper producers (replacement of lime) • Sale as replacement of fertilize	Mostly II, some III	4–7
Accelerated mineralization (in reactor)	• Heat production (at large scale) • Sale of substitute for clinker in blended cement	II	5–7
Soil carbon sequestration	• Soil quality improvement services • Enhanced agricultural productivity	II	2–5
Ocean fertilization	• Fisheries yield increase services	II	

[a] *Monetizable non-carbon revenue streams and co-benefits may need distinction. While both sometimes overlap, some revenue streams (e.g., revenue from selling power or heat) do not necessarily constitute a co-benefit in the classical sense (accruing broadly to society) and some co-benefits are not readily monetizable.*
[b] *Technology readiness levels defined in line with Horizon 2020 – Work Programme 2018–2020 (European Commission, 2019): TRL 1, basic principles observed; TRL 2, technology concept formulated; TRL 3, experimental proof of concept; TRL 4, technology validated in lab; TRL 5, technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies); TRL 6, technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies); TRL 7, system prototype demonstration in operational environment; TRL 8, system complete and qualified; TRL 9, actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).*

cement, steel or alternative materials), or if enhanced oil or gas recovery (EOR/EGR) were done in a way that maximizes CO_2 storage (resulting in a net-removal of CO_2, despite emissions associated with the production and later consumption of oil and gas) (Zakkour et al., 2020).

Technologies in group III are non-additional, which means that they could go ahead without any dedicated financial incentive. While some may be financially viable, they may be held back by other non-monetary barriers, which could render them additional nonetheless.

Overall, while transparently determining additionality will also be important for CDR project proposals overall, additionality of many CDR types will be obvious from the outset given their significant cost and their frequent lack of a business case (generation of revenues other than from the sale of carbon credits).

Costs – and in some cases revenue potentials – are evolving. With technology learning and scaling through an s-curve adoption, some CDR approaches may move from one group to another. While the actual pace of cost-reduction and revenue discovery is highly uncertain, it is very likely that to enable rapid learning and scaling, dedicated near-term interventions are a prerequisite. Therefore, policies are needed to pick a basket of "potential winners" including those activities with the best scaling and cost-reduction prospects.

Approaches involving underground storage such as DACCS and BECCS, as well as some others e.g., biochar applications may have ongoing costs associated with transportation and storage of CO_2 (Hughes, 2017) or operational energy requirements. Furthermore, costs also vary between different regions as storage, energy and biomass resource cost and revenue streams vary (as well as planning and construction costs).

Projections for long-term costs of DACCS operation vary greatly with a lower limit at around USD 40/tCO_2 and the upper limit at around USD 600/tCO_2 (Möllersten and Naqvi, 2020), or even between USD 20/tCO_2 and USD 1000/tCO_2 (overnmental Panel on Cli, 2018). DACCS technology providers envisage long-term operating costs to stabilize on the order of 100 USD/tCO_2.

Some cost differences may thus remain in place in the long-term and a price differentiation within or across funding instruments may be warranted also on a continuing basis. Certainly, where there are differences in the innate permanence of storage (e.g., between storage in biological systems vs. in mineralized form or underground) a difference in incentives would be warranted.

Differentiation of CDR Value-Chain Elements

CDR tend to result from a combination of various value-chain elements, each of which is may be executed by a different actor (or even industry) and with varying marginal cost-gaps. Also, some elements of the value chain may be undertaken in different countries, generating challenges regarding the accounting and incentivization of the removal. Taking a typical (already existing) BECCS process as an example, there are at least three distinct elements of the value-chain: (I) biomass production and harvesting (II) utilization of biomass for energy production with CO_2 capture at source, and (III) the transport and underground storage of CO_2. Only the first two elements without CO_2-capture presently holds a functioning business model in the absence of dedicated funding for CDR. Variants, in which individual pieces are altered, may access some monetizable revenue from co-benefits such as the combination of (solid- or liquid) waste-burning with CO_2 capture, transport, and underground storage, whereby such waste management already tends to be funded as a public service. Replacing underground storage with using CO_2 as a raw material for production of long-lived (construction) materials may offer another such possibility for co-benefits-based revenues, although in such cases the innate permanence is limited.

Given that the scalability (both pace and final potential) likely varies across these elements, and given the consequent need to mobilize a portfolio of approaches, disaggregation of value-chain elements is thus necessary such that policy instruments or voluntary measures may pick potential winners with large long-term potentials (and permanence) – even when they may not compete well in the short-term (e.g., for lack of revenues from co-benefits).

Differentiation According to Full Value-Chain Results

An important differentiation also needs to be made based on the full value-chain mitigation result: Most combinations may be pursued in a (relatively less costly) way that either results in a mere net-reduction of (positive) emissions, or only a small volume of negative-emission – well below the actual CDR potential, thus failing to fund the scale-up of key value-chain elements. An example for this is the somewhat controversial use of direct air capture technology for enhanced oil recovery (EOR) or for production of synfuels. Both approaches somewhat reduce net (positive) emissions. EOR could in theory also be done in an *a priori* uneconomical manner whereby CO_2 storage is maximized rather than oil output, thus potentially resulting in zero or perhaps even negative emissions i.e., CDR. However, policy instruments that do not differentiate according to the final result of the full value-chain, risk creating false incentives by side-lining CDR and instead funding non-transformational activities (such as nominally lower-CO_2 fossil fuels). The net result of such policies may be a fossil fuel subsidy and corresponding overall increase in emissions (Clean Air Task Force, 2020). This appeared to be the case for the US tax credit known as 45Q, which particularly at the outset almost exclusively incentivized use of atmospheric CO_2 for EOR: The differentiation offered in the 2018 update (35 USD/tCO_2 for EOR vs. 50 USD for CDR) would appear insufficient in light of present cost differentials (Larsen et al., 2019).

NECESSARY FUNCTIONS FOR GOAL-COHERENT CLIMATE CHANGE MITIGATION GOVERNANCE

CDR used to achieve net-zero emissions compatible with the Paris Agreement's long-term temperature goal may sometimes be viewed as a stop-gap measure [a temporary measure to mitigate immediate harm and buy time for a permanent solution; Buck et al. (2020)], but given that most governments are not expected to achieve full decarbonization within appropriate carbon budgets (if ever), CDR may need to be attributed a more permanent role (Morrow et al., 2020). The corresponding paradigm shift - requiring a novel understanding of climate change mitigation as the composite of both emissions reductions and removals - may require a reorientation and a strengthened political mandate for consequent public policy (Geden et al., 2019). Unfortunately, neither target-setting, individual research or pilot activities, nor public deliberation will achieve much on its own. Based on these observations regularly raised in the literature in this field, we identify six functions that CDR policy instrument mixes ought to jointly deliver in order to pursue the objectives that CDR may have to fulfill as part of long-term mitigation efforts that are compatible with the Paris Agreement objectives:

1. Provide clarity on the intended role of CDR for the mitigation of climate change (particularly regarding scale and fungibility) in a way that is compatible with the Paris Agreement's goals and countries' targets [particularly regarding cumulative carbon budgets; Fyson et al. (2020)].
2. Accelerate innovation, technology learning and associated cost reductions to unlock a sufficient range of affordable and reliable CDR options – appropriate to each country's circumstances (Morrow et al., 2020).
3. Ensure an appropriate public participation in decisions surrounding how CDR is to be implemented – in a way that is appropriate to each country's political context (Bellamy, 2018; Cox et al., 2018; Bellamy et al., 2021).

4. Transition from piloting to cost-efficient, effective, long-term, scaled operation of CDR that further drives down cost (within a timeframe that is compatible with the role identified in function 1.).
5. Ensure robust and comparable measuring, reporting, verification and accounting of results to track national, regional and global progress toward net-zero emissions (Brander et al., 2021).
6. Prevent adverse side-effects to sustainable development goals and maximize positive co-benefits (Honegger et al., 2020).

Policies that could target CDR can be grouped into different categories similar to GHG emissions reductions policies (Gupta et al., 2007). Some may offer a generic framework, while others provide specific support or regulation (Center for Carbon Removal 2017; Jeffery et al., 2020). Most will – individually – offer necessary, but not sufficient, contributions to fulfilling the above functions. Policy instrument mixes, therefore, ought to be designed to jointly fulfill the different functions needed to align with the Paris Agreement and its long-term objective.

Governmental Climate Change Mitigation Targets

The uppermost policy layer (after the Paris Agreement itself) is the definition of specific short- to medium-term mitigation targets (Nationally Determined Contributions, NDC) and the long-term (mid-century) mitigation strategies (Long-Term Low GHG Emission Development Strategies, LT-LEDS). Both often merely represent a generic framework, but should provide sufficient medium- to long-term orientation for various government departments and private sector actors to anticipate more specific steps. Increasingly, LT-LEDS and NDCs – particularly in industrialized countries – are expected to specify how net-zero or net-negative emissions will be achieved, thus potentially including specific targets for CDR as a category (McLaren et al., 2019) or even more specific (e.g., sectoral, see Kaya et al., 2019) CDR targets, thereby creating clarity on the intended role of CDR and opening up public participation in the setting and operationalization of CDR policy. Where targets become sufficiently concrete, private sector actors increasingly likely want to become active and front-run potentially emerging policies. Several multinational companies have already started, as discussed in section Voluntary Action – Challenges and Opportunities.

As of the end of 2020, 126 countries (accounting for over 50% of global GHG emissions) have announced or considered net-zero goals[1]. Yet, on aggregate, NDCs had not significantly decreased the projected 2030 mitigation gap (United Nations Environment Programme (UNEP), 2020) before the end of 2020 and the vast majority of NDCs and LT-LEDS do not specify a cumulative net emissions volume (i.e., carbon budget), nor do they detail the relative contribution expected from emissions reductions vs. CDR. Information needed to judge the contributions' adequacy is thus missing. The latest government announcements interpreted optimistically suggest a reduction in the median global projected temperature increase by 0.5°C (from 2.6 to 2.1°C), yet still comprising a 16% chance of exceeding 2.7°C (Climate Action Tracker, 2020). Even the optimistic median (50:50 chance) value of 2.1 would still be far from "well below 2°C" and 1.5°C. And even this (insufficient) level of ambition is at risk, given that the commitment to specific sets of mitigation policies that would be likely to deliver on these targets remains highly inadequate.

Further, the approach to planning remains unsystematic: LT-LEDS that mention CDR focus strongly on nature-based solutions including A/R, wetland restoration and various other soil carbon sequestration approaches without offering a strategy to dealing with the lack of innate permanence of these approaches. A dozen countries include plans for using CCS to achieve emissions reductions (but so far not toward mobilizing CDR to achieve net-negative emissions). Approximately 30 further Parties have made public announcements that they might be considering CCS in the future, often without specifying the expected respective contributions (Potsdam Institute for Climate Impact Research (PIK), 2017; Mills-Novoa and Liverman, 2019; Zakkour and Heidug, 2019; Global CCS Institute (GCCSI), 2020).

In light of the above, national commitments in NDCs and LT-LEDS to date largely fail to adequately advance all six necessary functions (regarding clarity, innovation, participation, transition to cost-effective long-term operation, monitoring and accounting, and side-effects).

Domestic Mitigation Policy Instruments

Policy instruments introduce a regulatory or financial alteration of market and behavioral dynamics targeting a specific range of actors, sectors, activities, products, or services. We identify five types of instruments that – by way of a policy mix – may allow mobilizing CDR activities: (a) R&D activity-oriented subsidies, (b) mitigation results-oriented subsidies, (c) regulatory mandates (d) fully-fledged carbon pricing, and (e) ancillary instruments.

a) *R&D activity-oriented subsidies* enable or accelerate CDR research, design, development, or demonstration (RDD&D). Given that this type of subsidy is to target technology advancements at various stages of development, funding volumes and envisaged results have to be adapted individually to allow each technology to progress to its respective next maturity level. Such funding is not constrained to considering near-term cost-effectiveness, but can take a long-view and attempt picking potential future winners, thus unlocking early-stage technology learning. The EU Innovation Fund is an example of such an approach. Activity-oriented subsidies are not intended (and suitable) for funding scaled operations beyond an initial piloting phase and therefore are necessary, but not sufficient to CDR scale-up. Past experience with such subsidies shows that governments need to be bold to prevent emergence of "bottomless pits" swallowing public money (Haapanen et al., 2014).

[1] While most countries with pledged neutrality targets refer to carbon neutrality, others go further by aiming for greenhouse gas- or even climate neutrality, i.e., not only focusing on CO_2 but also taking other GHG and aerosols into account as well. Other countries like Finland and Sweden move even further than that by announcing net-negativity targets, i.e., removing more CO_2 or other GHG and aerosols from the atmosphere than they emit.

b) *Mitigation results-oriented subsidies* for scaled implementation and initial operation may be provided as direct grants, tax credits, concessional loans or contracts for difference. Contrary to activity-oriented (R&D, piloting) subsidies these are allocated on the basis of expected or achieved tons of CO_2 removed. In order to be efficient, such subsidies could e.g., be allocated through reverse auction in order to ensure that the most cost-competitive CDR provider is funded (Olsson et al., 2020). Mitigation results-oriented subsidies can have a bridging-function for near-mature activities, which cannot yet access permanent instruments or themselves serve as longer-term instruments. Given that such subsidies can serve to enable larger-scale piloting they also offer crucial opportunities to test and explore possible environmental and social implications of scaled CDR activities in a particular geographical context. The US' tax break 45Q is an example of a mitigation-oriented subsidy, yet it has to date largely failed to meaningfully advance CDR, due to lack of focus (Larsen et al., 2019). Experience from renewable energy deployment evidence the importance of large-scale subsidy programs for achieving operation-scales that rapidly unlock further cost reductions.

c) *Regulatory mandates* could require specific actors (public or private) to pursue or fund CDR activities. If targeting particular sectors, regulations could e.g., require heavy emitters such as power, cement, or steel producers to satisfy an emissions intensity standard, which may be unattainable without CDR. Companies in such sectors could then either develop in-house CDR capacities, purchase CDR-assets (e.g., incorporate a CDR company as a subsidiary), or pool (net) emissions with other companies that overachieve requirements. In all cases, such regulatory mandates could be highly effective at upscaling CDR, but generate significant near-term uncertainty and costs for entities subjected to the mandate. If proposed, certain interest groups and lobbies will therefore try shaping or even preventing them; broader mitigation policy experience suggests that the resulting instruments may end up being limited in scope to already profitable technologies (Michaelowa et al., 2018). Various *carbon pricing instruments* such as cap-and-trade, baseline-and-credit systems or carbon taxes with or without a revolving fund for CDR may seek to enable the long-term continuous operation of efficient mitigation activities. Long-term reliability and explicit eligibility of CDR under such instruments needs to be ensured, given that long-term revenue security is a prerequisite for meaningful private sector investment. Ideally, carbon pricing can act to further incentivize technology learning (including for CDR), and lower overall cost while expanding efforts. If it achieves long-term increases in price levels, as part of a credible, long-term governmental commitment to ambitious climate policy on a path to e.g., net-zero or net-negative domestic emissions, carbon pricing can be suitable for mature CDR technologies. It is also a very useful mechanism to drive continued innovation and thereby bring down the costs of competing technologies. Even where industries or specific CDR activities are not directly covered by a carbon pricing system, they could be made eligible to create removal credits that could be sold into the system. A credible prospect for such possibility could offer a sufficient incentive to build-up CDR activities (if the carbon price in that system is sufficiently high and not overly volatile). Given that such eligibility would affect supply-and-demand it would have to be offered in such a way that the carbon pricing objectives (the overall resulting mitigation) are advanced rather than undermined: Caps may for example be adjusted downwards or credits may be retired into a market reserve in order to reflect for the greater ambition levels that CDR eligibility might unlock in the medium-term.

d) *Ancillary policy instruments* serve to enhance consistency and alignment with overarching objectives, by creating regulatory boundaries and operational guidance to key actors. For CDR this could entail establishing permanence requirements, a system of long-term storage guarantees or reserves, a harmonized framework for liability, as well as public engagement processes that feed into policy design and enable building broad-based support for CDR policy mixes. Ancillary policy instruments are critical to ensure that CDR can become a mature element of consistent national and international climate policy rather than being pursued haphazardly, limited to pilot projects and never actually fulfilling any meaningful role in climate change mitigation. Clearly establishing all relevant CDR value-chain elements within financial guidance and regulations – such as the EU sustainable finance taxonomy – would be another type of ancillary policy instrument, which could be essential for aligning public and private efforts toward a common goal.

Policy instruments can thus be differentiated by their objectives (to offer short-term support for R&D, piloting, bridging or a long-term framework). For credibly transitioning to cost-efficient, effective and long-term continuous operation, long-term instruments (regulatory mandates, tax- and subsidy-based incentives, or market-based incentives) need to be evaluated against challenges and opportunities that affect their feasibility, effectiveness, and long-term efficiency and stability. These often depend on country-specific political economies and thus require nationally rooted evaluation. For adopting nationally appropriate policy instruments, governments would do well to proactively identify in particular the factors that may challenge the long-term stability of instruments and resulting incentives (including in countries with frequently changing administrations) alongside their expected efficiency and effectiveness in their respective national contexts.

So far, purely regulatory mandates for inducing CDR activities do not appear to play an important role among (at least) OECD countries' deliberations on mitigation policies (Schenuit et al., 2021). Arguably US EPA emissions standards for the energy sector could be viewed as a template – including for other sectors – for a regulatory approach that might ultimately incentivize the use of CDR for reductions in company- or sector-wide net-emissions.

While there already are several domestic (market-based) policy instruments in place for A/R activities (New Zealand's ETS, Chinese provincial ETSs, California's ETS, Australia's domestic crediting scheme), other CDR approaches – notably those with higher innate permanence – have largely been neglected.

Parliaments, and administrative agencies in the US, the UK, Germany, Norway, Sweden, and Switzerland, as well as the European Commission, are taking note of the need to develop policy instruments suitable to advance high-permanence CDR[2] but in most cases specific policy instruments have not yet been implemented. Sweden is a notable exception: it has set a net-zero emissions target for 2045, with net-negative emissions thereafter, and publicly emphasized that various types of CDR, including BECCS, will be mobilized to contribute to this target. Furthermore, Sweden is developing concrete plans to include BECCS in its carbon tax scheme and – in committee and public debate – appears to be moving fast toward an additional policy instrument where the government (through the Swedish Energy Agency) purchases CDR services through a system of reverse auctions (Lund Christiansen, 2020, p. 20ff). While clearly not as far advanced, the UK may become a runner-up. The UK has set a carbon neutrality target for 2050, its revised NDC introduces an intermediary emission reduction target of 68% by 2030 (compared to 1990), and government communications consistently highlight the prominent role of CCS applications as well as nature-based removals. However, given that specific policy instruments appear to still be missing, it is not yet possible to judge the adequacy of their overall policy instrument mix (e.g., in dealing with permanence issues of nature-based removals) and by consequence the overall merits of the UK's approach.

Among the sub-national actors, California is a notable frontrunner: its low-carbon fuel standard (LCFS) – a baseline-and-credit instrument for mitigating transportation emissions – allows for external credits from DACCS activities. In 2020, LCFS credits reached a world-record high of USD 200/tCO_2 [California Air Resources Board (CARB), 2020; International Energy Agency (IEA), 2020].

International Policy Toolset

International carbon markets have existed for the last 20 years, first under the Kyoto Protocol [Clean Development Mechanism (CDM) and Joint Implementation (JI)] and now under the Paris Agreement (Article 6). As negotiations on international cooperation under the Paris Agreement are still ongoing to conclude the rulebook of Article 6 (at COP26), we look to the past for insights on how mitigation transfers might be designed in the future: The Kyoto Protocol's CDM, which has already been discussed in section Differentiating Cost-Revenue Projections (regarding the demonstration of additionality), in many ways has served as key reference for baseline-and-credit mechanisms for mitigation and offers several lessons for CDR. The CDM included A/R activities – of the over 7,800 registered CDM projects, 66 were A/R projects (UNEP DTU Partnership, 2021). The CDM offers several baseline and monitoring methodologies to quantify removals for this activity type. After a long process, CCS activities were made eligible under the CDM in 2010; the CCS rules under the CDM provide detailed terminology and clear regulatory guidance on the selection, characterization and development of geological storage sites, liabilities, risk and safety assessments as well as guidance on baseline methodology submission. So far, however, no approved CCS baseline or monitoring methodology exists given that credit prices have been too low and uncertain to mobilize CCS.

The role of international cooperation and transfer of mitigation outcomes is expected to change under the Paris Agreement – given its long-term objective of global net-zero (or even net-negative) emissions and requirement for all countries to set national mitigation targets. Over time, with the pace reflecting the countries' "common but differentiated responsibilities and respective capabilities," national mitigation targets will need to balance out any residual emissions through CDR. As global emissions approach zero, international market-based cooperation, based on the international transfer of mitigation outcomes under Article 6 of the Paris Agreement will by consequence increasingly shift focus from emissions reduction activities to mitigation outcomes from CDR activities. The CDM's lessons regarding additionality assessment need to be carefully considered when applying market-based cooperation to CDR, especially regarding the separation of Group II and III technologies, as discussed in section Differentiating Cost-Revenue Projections above.

VOLUNTARY ACTION–CHALLENGES AND OPPORTUNITIES

With governments slowly moving toward the operationalization of net-zero targets, some private sector actors have, somewhat unexpectedly, become first movers in mobilizing various types of CDR. There is, however, a strong divergence in the quality and ambition of these efforts (**Table 1**). While some attempt a quick-fix corporate social responsibility (CSR) strategy and pursue the lowest-hanging fruit without a credible long-term strategy (purchasing the lowest-cost carbon credits offered on the voluntary market or announcing tree-planting campaigns with questionable permanence and additionality), others have adopted a leadership approach by seeking to enable technology learning through investment in high-cost, high-permanence CDR approaches. Some of the most ambitious efforts include to date the plans of Microsoft, Shopify, Stripe, and SwissRe (see **Box 1**). It should, however, be noted that none of these approaches addresses the challenge of double-counting of removals at the company and national level. This means that the mitigation outcomes of widely advertised voluntary private sector mitigation activities automatically show up as lower emission levels in the national GHG inventory of the government where the activity takes place (thereby contributing to its claimed progress toward NDC achievement). The double-claiming of the same mitigation

[2]Some agencies have commissioned reports on CDR, e.g., the German Environment Agency, the US Government Accountability Office, the British Science and Technology Committee, the European Commission and the European Academies' Science Advisory Council. Switzerland has provided a mandate for developing a policy roadmap for mitigation through CDR.

BOX 1 | Private sector leadership in mobilizing CDR with a long-term view.

Microsoft aims to achieve "carbon negativity" by 2030 and to have removed all of the company's past CO_2 emissions by 2050. It has established the Climate Innovation Fund with a budget of USD 1 billion to support nature-based solutions, soil carbon sequestration as well as novel technological CDR technologies. Most recently, Microsoft has announced that its fund will make a substantial investment into the DACCS technology provider Climeworks.

Shopify has announced becoming carbon neutral and even net negative in the future and will spend at least USD 1 million/year for carbon sequestration projects. The pledge is especially noteworthy because Shopify announced that they will buy these credits at any price.

Stripe claims to have reached carbon neutrality in 2019 and has pledged to invest USD 1 million/year into forestation initiatives, soil management reforms, enhanced weathering, and DACCS technologies. In May 2020, it announced that Climeworks, Project Vesta, CarbonCure and Charm Industrial have been selected to receive funding. In addition to its own commitment, Stripe launched its app Stripe Climate, through which clients can direct a fraction of their revenue to support scaling up CDR.

Swiss Re aims to achieve net-zero emissions of its operations by 2030. To drive and finance mitigation, Swiss Re will increase its internal carbon levy from USD 100/tCO_2 in 2021 to USD 200/tCO_2 in 2030. This strategy allows the company to enter into long-term agreements with carbon removal service providers to boost the CDR markets.

outcome toward both the private sector actor's carbon neutrality target and the host country's NDC would effectively render the private sector actor's carbon neutrality claim untrue. This is because, in case of mitigation outcomes counted toward the host country's NDC, the private sector actor effectively subsidizes the achievement of mitigation levels that the country was committed to achieving anyway. Double-claiming can be avoided if the host country agrees to "uncount" such mitigation outcomes in its NDC-related reporting to the Paris Agreement.

What makes the voluntary efforts highlighted in textbox 1 stand out from other voluntary efforts is their willingness to tackle high up-front costs of some CDR types that potentially have high innate permanence, rather than simply purchase ready-made, often low-cost and sometimes low-permanence credits from voluntary carbon markets to claim carbon neutrality. Their efforts can thus help accelerate innovation and piloting of CDR activities and raise public interest. This development represents a noteworthy deviation from the experience under the CDM and JI as well as voluntary markets to date: In the past appetite for up-front investment for capital expenditures of novel projects was very limited, reflecting the buyers' interest in making immediate mitigation claims through credits that represent already achieved and verified mitigation outcomes (Michaelowa et al., 2019b). Furthermore, up-front investments face various risks and uncertainties as to whether these activities ever lead to the expected mitigation outcomes that investing companies can claim to count toward their pledges.

Conventional voluntary offsetting through the purchase and cancellation of credits in the voluntary carbon markets may promote those CDR activities that can already be competitively implemented with results-based funding. So far, A/R has been the dominant CDR activity type in voluntary carbon markets (Donofrio et al., 2020), with a roughly 400% growth in A/R credits between 2016 to 2018 (Donofrio et al., 2019), mostly stemming from projects in Latin America and Africa (Hamrick and Gallant, 2017).

Private standard-setting organizations such as Verra, Gold Standard Foundation, and Plan Vivo issue carbon credits against verified mitigation outcomes from eligible activities, including A/R, that meet their standards. There is no unified approach to managing non-permanence risk of eligible CDR activities: Verra's approach includes a risk assessment to determine a share of credits that may not be traded or claimed, but are instead deposited into a pooled buffer account. In case of unforeseen reversals (re-emission of carbon), a corresponding volume of credits will have to be canceled from the buffer account (Verra, 2018). The Gold Standard approach includes five elements: (i) specific requirements to assess the innate risk of each activity; (ii) frequent monitoring, reporting and verification (MRV) of outcomes; (iii) a compliance pathway adapted to each activity type with high permanence risks; (iv) attribution of liability for underperformance to project owners; and (v) an overarching buffer fed by 20% of all activities' issuances (Gold Standard, 2020).

New voluntary market platforms and service providers specifically focussed on CDR units have emerged in the past 2 years, including Puro.earth (Finland), Nori (US), MoorFutures (Germany), and max.moor (Switzerland). These also predominantly focus on CDR with storage in biological systems (with limited innate permanence) and they come with widely different approaches to addressing fundamental issues such as the additionality of activities as well as the permanence of removed carbon. Many lessons from past baseline-and-credit systems, most notably the CDM, appear to have been ignored in their design. MoorFutures and max.moor exclusively focus on wetland and peatland restoration projects (with credits priced around USD 78-92/tCO_2), Nori focusses on agricultural carbon removals (priced on the order of USD 15/tCO_2), and Puro.earth offers credits from biochar production as well as the use of wooden and carbonated building materials (prices ranging USD 23-180/tCO_2).

While the purchase of carbon credits through voluntary carbon markets can deliver near-term reduction in net emissions, it does not necessarily ensure long-term mitigation in line with net-zero global emissions. The introduction of NDCs by all countries under the Paris Agreement expands the challenge of double claiming for voluntary actions given that virtually all mitigation is now also counted toward a country's NDC achievements. Private actors can make Paris-aligned carbon neutrality claims only with mitigation outcomes that are not counted toward an NDC. It is important that private sector support for CDR is recognized as complementary to public CDR policy, rather than a substitute or justification for postponing public action.

REQUIREMENTS FOR ALIGNING POLICY INSTRUMENT MIXES AND PRIVATE SECTOR EFFORTS WITH THE PARIS AGREEMENT

In the following, we discuss how the different instruments may all be necessary but not sufficient for fulfilling the six functions for achieving alignment with the Paris Agreement laid out in section Necessary Functions for Goal-Coherent Climate Change Mitigation Governance.

National (medium-term) targets and (long-term) strategies are necessary to provide clarity on the intended role of CDR for the mitigation of climate change, to allocate public funding for innovation and research as well as for pilot-scale subsidies. As such, the definition and later operationalization of strategies and targets provides opportunities for public engagement and deliberation on the appropriate role and implementation of CDR as part of national mitigation efforts. Targets that are consistent with global pathways and national responsibilities and offer sufficient detail are thus a precondition to the development of domestic and international long-term carbon pricing and regulation instruments for mobilizing CDR alongside emissions reductions. At the same time, targets alone are not sufficient to fulfill the stated objectives as they have to rely on more specific and operational instruments for implementation.

Public innovation and research funding is another necessary (but not sufficient) element to achieve alignment with the stated objectives, given that a broad ensemble of approaches needs to be nurtured in order to prevent running out of options. Some approaches still have a long technology learning path ahead of themselves – particularly approaches involving geological storage or mineralization with high innate permanence. Activity-focused public funding is on its own not sufficient and as per its defined scope often does not entail funding longer-term operation of pilot plants in a results-based manner.

Therefore, to fund operating cost of pilot plants and initial projects at scale (e.g., in a period in which long-term instruments are not yet ready) mitigation-oriented temporary subsidies are needed to avoid a valley-of-death for actors that run out of innovation and research funding before they can access permanent carbon pricing instruments or benefit from regulation. Yet such funding may per its stated objective be limited in time and scale of activity and has thus to pave the way for inclusion of the funded activities in a pricing or regulatory regime that is intended to be operational indefinitely (or for as long as gross positive emissions make CDR necessary).

True long-term alignment with net-zero mitigation pathways ultimately requires carbon pricing or regulatory instruments that effectively ensure covering long-term marginal operating cost of a nationally appropriate set of CDR approaches that will remain in place indefinitely. This has to be the objective of any national or regional climate target that cannot with absolute certainty achieve 100% emissions-reductions based decarbonization (within the stated time-horizon). This arguably applies to virtually all Paris Agreement Parties, perhaps with the exception of countries such as Bhutan that presently already boast a negative emissions balance due to extensive and stable forest cover and very minor industrial activity.

Given the potential for significant side-effects – both harmful and positive – largely depending on CDR policy design (Honegger et al., 2020) and scale (Cox et al., 2018) as well as the importance of climate change mitigation for achieving long-term sustainable development (Nerini et al., 2019), it is essential that both domestic policy instruments and international (market and non-market) cooperation efforts are based on sound understandings of potential negative side-effects and positive co-benefits arising from every specific intervention. While the rulebook for Article 6 itself may require host countries to assess such effects on their sustainable development priorities, this minimal requirement may not be sufficiently stringent. It would seem advisable that – particularly early movers – put in place a far-reaching and transparent process through which to judge possible sustainable development implications that take all involved countries' SDG strategies into consideration. International certification (e.g., for biomass sourcing and biochar quality) could, furthermore, help create transparency and a trustworthy basis for broader efforts (Cox and Edwards, 2019).

While we observe some steps toward fulfilling individual functions (see **Table 2**), we find each to be falling short even taken on their own. Given that all six functions are necessary conditions, we submit that urgent action at multiple levels is needed in order to move toward comprehensive and overall sufficient policy mixes.

We notably observe the following shortfalls – even among what we consider to be the best-practice approaches and much more so in others' (see also **Table 2**): 1. lacking specificity on the role of CDR (even in the highly advanced plans of Sweden), 2. absence of a systematic approach to R&D and piloting activity-based support for CDR (even among the well-endowed EU-funded innovation support instruments), 3. lack of proactive invitations for public engagement and deliberation by public administrations developing policy mixes for CDR (including in countries with well-established deliberation processes on mitigation policy such as Germany, the UK, and France), 4. lack of clear steps to transition to a cost-efficient long-term CDR policy framework, 5. gaps regarding provisions on accounting of (trans-boundary) CDR and CDR-specific MRV under the Paris Agreement's transparency framework and Article 6 (a study on a European carbon removal crediting mechanism may offer an opening only by 2023), and 6. no systematic approach to anticipating and managing potential negative and/or positive side-effects of CDR applications.

The above list demonstrates that key functions lay in the domain of public policy. Voluntary efforts by private sector actors can contribute to some of the objectives (e.g., mobilizing removals including by funding research and development of high-cost CDR types), these efforts cannot on their own fulfill the functions that public policy mixes need to provide. Functions that in particular cannot count on private efforts include most notably: Functions 1 and 3 (gaining clarity on the societally desirable role of CDR through proactive public deliberation), function 4 (as costly voluntary efforts cannot be maintained indefinitely on competitive markets), and functions 5 and 6 (as

TABLE 2 | Examples of government steps toward specific policy functions (and how they fall short).

Function	Example
1. Clarity on role of CDR (aligned with Paris targets)	Sweden specifies an 85% domestic emissions reductions target and maximum permitted use of so-called supplementary measures, consisting of CDR (increased carbon sink in forests and land, BECCS and other technological measures for negative emissions) and international verified mitigation outcomes, to compensate for the remaining 15% of emissions to reach net zero by 2045 and to go beyond net zero thereafter. Sweden has also set intermediary goals for 2030 and 2040. In its strategy and action plan for achieving negative GHG emissions after 2045, Sweden specifies preliminary contributions of different categories of supplementary measures, and their planned evolution over time, e.g., gradually shifting the source of international verified mitigation outcomes from emission reductions to CDR.
2. Accelerate CDR innovation, technology learning and cost reductions	The EU funds research and development of CCS (including some CCS-reliant CDR) as well as (separately) agricultural soil carbon based CDR. These instruments do not systematically target CDR (lacking focus), but instead broader technology/sector categories.
3. Public engagement	France, the UK and Germany (as well as others) have created deliberation processes dedicated to inviting a public conversation on desirable climate change mitigation policy mixes Federal Ministry of the Environment. Nature Conservation and Nuclear Safety (BMU), 2020; Convention Citoyenne pour le Climat (CCC), 2021a,b; Federal Ministry for Economic Affairs and Energy (BMWi), 2021; United Kingdom's Climate Change Committee (CCC), 2021. All three countries have failed to give adequate space to considerations regarding the role of CDR and corresponding policy design for reaching long-term mitigation objectives.
4. Transition to a cost-efficient long-term CDR policy framework	The European Commission has signaled intent to develop a carbon removal crediting (CRC) mechanism. The mechanism is currently designed by consultants and will only enter political consideration from 2023 onwards.
5. Consistent MRV and accounting	CDM and IPCC guidance offer indications for the future accounting of CDR. Such guidance may be interpreted in different ways (e.g., in case of transboundary CDR value-chains) and due to the novelty of many CDR approaches application to date has been limited.
6. Identifying and managing side-effects	Voluntary carbon credit certifiers have offered relevant standards for assessing side-effects of mitigation activities (e.g., the Gold Standard) and under the Kyoto Protocol national governments were tasked with determining the overall desirability of proposed activities. To date, equivalent standards and procedures have not been developed – neither for voluntary efforts nor for governmental CDR policies.

global comparability is required). Furthermore, private actors can only partially contribute to (costly) innovation. In the best case, they can complement or build upon public mitigation efforts – if these represent a stringent framework. Where the public policy ensemble, however, is incomplete or inconsistent, the absence of comparable approaches to fundamental pillars of mitigation can lead to a "race to the bottom." This risk is particularly large where voluntary activities are wrongly perceived to replace public policy and thereby alleviate pressure on governments to take on their responsibilities.

ACTIONABLE RECOMMENDATIONS

Against the backdrop of six functions that each appear necessary – but on their own not sufficient – for pursuing CDR in alignment with the Paris Agreement, we find a need for governments to start pursuing a systematic approach to multi-layered public policy instrument deployment targeting CDR as part of their mitigation efforts at the international and domestic level and with the private sector.

Our recommendations target three types of actors: those shaping international climate policy, those shaping national level climate policy and private sector (including philanthropic) actors.

International Climate Policy

International climate policy may have to undergo a paradigm shift (Geden et al., 2019) in order to overcome the present chasm between the abstract notion of CDR as relevant for Paris-aligned net-zero emissions targets and the widespread lack of operationalization in policy. This includes actors shaping expectations regarding revised NDCs and the outstanding parts of the Paris Agreement rulebook relating to the guidance and rules for international transfers of mitigation outcomes under Article 6. In the Article 6 work programme, methodological work on baseline setting and MRV should consider also CDR-specific issues so as to safeguard the environmental integrity also of CDR-based transfers.

In light of fundamental and unresolved questions associated with varying levels of innate permanence across CDR approaches, pilot activities that specifically examine these issues conceptually while testing them in practice can play a crucial role in highlighting and – through appropriate design and application choices – demonstrating how environmental integrity can be ensured while mobilizing CDR. International institutions should therefore support methodological work on baseline and MRV methodologies for various CDR types and advance conceptual work on instruments to ensure permanence and prevent transfers of removal credits for activities with a high risk of non-permanence. Moreover, a stringent yet operational approach to additionality assessment needs to be developed. This type of work will be essential for ensuring proper accounting of CDR in line with the spirit and provisions of the Paris Agreement and relevant IPCC inventory guidelines and practices.

Many actors in international climate policy also play a key role in creating expectations for and judging the ambition levels in countries' mitigation contributions and strategies (NDCs and LT-LEDS) as well as implementation plans and policies. For coherent planning regarding CDR in particular and mitigation in general, it is crucial that these judgments take a long-term view (Morrow et al., 2020) and anticipate the need to include both short- and long-term action to promote CDR. This could include, for example, recognizing particular efforts toward advancing high-cost CDR options, which may not provide significant short-term results in tons of CO_2 mitigated, but may be upscaled in the long-term while costs could be reduced, and thus be crucial for reaching net-zero emissions. Actors in international climate politics increasingly ought to establish the expectation that long-term targets ought to specify not only a net-zero year, but include commitment to a cumulative net-emissions constraint as precondition for judging the adequacy of contributions and to later adequately track progress.

Also, technical questions have to be resolved at the international level, which affect the setting of national targets: The operationalisation of the Paris Agreement's Enhanced Transparency Framework should address CDR specific challenges and offer accounting rules that are suited to deal with all variants of CDR. This includes also the possibility of CDR activities with transboundary CDR value-chains, which risk causing issues of double counting if not addressed properly.

In the context of the upcoming global stocktake, the role of CDR in reaching the long-term goal of the Paris Agreement should become a focus area that promotes public attention and debate relating to the transparent elaboration of CDR roadmaps – i.e., policy mandates for a particular role of CDR within long-term mitigation efforts. In this context negotiators in the international process as well as Parties' domestic climate policy planners and NDC developers should examine the operational pros and cons of specifying both net-emissions reduction pathways and how these are decomposed into separate gross emissions and CDR pathways. Separate targets can have the advantage of creating greater transparency and offer an opportunity to critically examine the adequacy of plans, yet they may also complicate definitions of climate finance or the use of carbon markets for international cooperation.

National Level Climate Policy

While many issues necessitate international coordination thus requiring international and domestic actors work hand-in-hand (notably regarding the implications of specifying CDR targets, piloting international CDR mitigation cooperation under Article 6 and advancing a consistent approach to properly accounting for CDR in national inventories), actors focussing on national climate policy face several specific challenges associated with CDR.

Perhaps most notably, governments need to establish long-term commitments and policies that ensure the delivery of emissions reductions and CDR for reaching net-zero emissions within the constraints of a fair, Paris-aligned carbon budget. Furthermore, they – particularly in developed countries – need to implement short- to medium-term efforts to tackle the R&D costs as well as the capital and operating cost of CDR activities. Unspecific targets (e.g., a single-year target for achieving net-zero emissions, without a carbon budget constraint) are ambiguous and could, in extreme cases, entail no transformation at all. Thus, NDCs and LEDS, or at least the related policy documents, ought to increasingly specify intermediary, sector-specific objectives, including for CDR-related action and elaborate a quantitative carbon budget that represents a fair share of the collective effort.

Such commitments, communicated via NDCs and LT-LEDSs, need to promptly be backed with specific policy instruments that can effectively deliver the stated short- or long-term objectives: Short-term activity-focussed funding (focussed on R&D- or pilot activities to accelerate innovation and technology learning) as well as long-term mitigation-focussed results-based instruments (market mechanisms or service contracts awarded to the most cost-effective CDR provider) are both necessary as a basis for – and to achieve the necessary transition to – efficient, effective, and long-term operation. For this purpose, forward-looking domestic climate policy has to include proactively advancing best-practice CDR pilot activities as well as gradually developing roadmaps, guidance, and where needed regulation not only to advance domestic policy, but also to offer other countries project templates and learning opportunities. While rooted in domestic climate policy, some governments may also choose to fund CDR activities elsewhere – either as climate finance (whereby the host country counts the mitigation outcomes toward its NDC through its GHG inventory) or by acquiring CDR-based mitigation outcomes under Article 6 (whereby the host country would have to "uncount" any internationally transferred mitigation outcomes).

Given the large potential for double counting between voluntary market activities (often involving grandiose claims) and public climate policy, regulation may become necessary to address also voluntary market activities by private sector actors. At a minimum, further concerted international efforts are needed to enhance the comparability of private sector actors' claims associated with mitigation outcomes to avoid a race to the bottom in voluntary mitigation activities, including by ensuring that they are additional, robustly designed and implemented, that the associated mitigation outcomes are robustly MRV'd and accounted for, and that leakage and non-permanence are appropriately addressed.

Particularly for large-scale nature-based removals, policy-makers may want to advance stronger environmental and social safeguards, based on host countries' sustainable development strategies. Given the public calls for strong scrutiny of CDR activities, this may not only be warranted for the sake of preventing adverse impacts and enabling co-benefits, but also necessary for alleviating public concerns and preventing a negative public perception of such (costly) publicly funded mitigation efforts and thereby ensure long-term feasibility.

Private Sector and Philanthropic Actors

While public authorities are responsible for ensuring coherence with Paris Agreement objectives and – where deemed as such – ensuring that CDR is being offered as a public service, private sector actors can, and in some cases, have already become frontrunners, demonstrating possible approaches and creating expectations. Under most circumstances it will be private actors who deliver CDR – be it as is currently the case in anticipation of future policy measures, as part of ESG efforts, or simply in executing upon a functioning business case enabled by policy incentives or regulation. Continuous learning and exchange of ideas between public and private actors is therefore important to identify barriers as well as opportunities – particularly at this early stage where public roadmaps, strategies and policies are to be developed.

Given the risk of undermining mitigation through badly executed actions causing adverse side-effects, eroding public support or proving ineffective or not permanent, the current flurry of private initiatives needs to be scrutinized and strengthened to enable a "race to the top" in the quality of activities instead of a temporary rush that risks to tarnish all CDR efforts. This is true not only for companies' internal efforts but all the rapidly emerging markets for CDR credits. Past lessons and experiences must be utilized to the fullest.

The limited innate permanence of carbon storage in the biosphere (challenging nature-based approaches), the inherent risk of reversals in these removal activities, and the risk of other side-effects is reminiscent of failures and scandals associated with forestry projects in the early days of in the CDM and in voluntary markets (Michaelowa et al., 2019b). These experiences should be a warning sign and lead us to approach "nature-based solutions" with great care. Further efforts are needed to enhance the certification of high-quality nature-based removals, building on and engaging with the extensive existing efforts.

Finally, more progressive actors in the private and philanthropic sector should follow with a willingness to address CDR with a long-term perspective and contribute to exploring high permanence approaches in which CO_2 is stored underground and/or mineralized. Together, we can hope that these efforts will be met by governments stepping up and putting in place the necessary policy infrastructure to create sustained and reliable long-term public demand for CDR.

DISCUSSION

While CDR has a long-contested history in climate policy (Carton et al., 2020) and – at large-scale – subsumed under "geoengineering" in biodiversity and waste policy (Brent et al., 2018), it can no longer be sidelined in international and domestic climate policy, given that such neglect further undermines the already drastic underachievement of collective mitigation (Michaelowa et al., 2018).

We set out to contribute to the emerging CDR-policy literature, in particular by offering a structure that operationalizes conditions, concerns, and expectations already voiced in the academic literature and rooting this structure in the governance architecture afforded by the international climate change regime. We believe to have succeeded in our approach, particularly in offering six necessary functions that allowed us to identify governance gaps and deduce actionable recommendations. Upon further examination the six functions may prove not exhaustive or warrant refinement. We are however confident that they, indeed, are necessary.

Our examination of CDR governance and funding needs and ongoing efforts highlights the enormous amount of work that lies ahead in order to embed CDR into climate policy in a manner that accelerates, rather than undermines the pursuit of overarching climate (and sustainability) objectives.

Action is needed at all levels to 1. gain clarity on the intended role of CDR for limiting warming, 2. accelerate innovation, 3. ensure participation, 4. transition to long-term cost-effective operation, 5. robustly measure, report and verify results as well as account for them properly and 6. manage side-implications. We were surprised by the currents' policy mixes' near-universal failure to address all six policy functions, although Sweden emerged as a clear leader and possible exception. We see possibilities to "anchor," adapt and develop existing policy tools into comprehensive policy mixes addressing these functions. In our view, this will, however, have to build on strong and high-level public engagement. In our view, future work needs to properly address the normative nature of questions regarding the appropriate role of CDR in public policy and should not shy away from the apparent divergence of views on these matters. We see an important research need on the way to design deliberation processes and to build them on a science-based manner that utilizes the rich experience in mitigation policy overall and with CDR-related practices in particular. To move away from the current state of conceptual reliance of net-zero pledges on CDR without actual policy planning to mobilize CDR at scale, we need to see stronger transdisciplinary engagement (Dowell et al., 2020) and broader alliances across research, CDR practitioners and industry partners, as well as across public policy domains (Fuss et al., 2020). Such alliances should aim at generating a sound understanding of how innovation can be accelerated, costs can be brought down, and costly "dead-end streets" can be avoided in the particular political economy of each country or region. The sense of urgency for such collaborative effort is growing in light of the time-constraint afforded by "well-below 2°C" or 1.5°C compatible net-emissions budgets. Therefore, we call on the entire community of policy-oriented research to overcome disciplinary barriers and to embark on the necessary collaborative work without delay.

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

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REFERENCES

Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nat. Energy* 3, 532–534. doi: 10.1038/s41560-018-0156-6

Bellamy, R., Fridahl, M., Lezaun, J., Palmer, J., Rodriguez, E., Lefvert, A., et al. (2021). Incentivising bioenergy with carbon capture and storage (BECCS) responsibly: comparing stakeholder policy preferences in the United Kingdom and Sweden. *Environ. Sci. Policy* 116, 47–55. doi: 10.1016/j.envsci.2020.09.022

Brander, M., Ascui, F., Scott, V., and Tett, S. (2021). Carbon accounting for negative emissions technologies. *Clim. Policy* 21, 1–19. doi: 10.1080/14693062.2021.1878009

Brent, K., McGee, J., McDonald, J., and Rohling, E. J. (2018). International law poses problems for negative emissions research. *Nat. Clim. Change* 8, 451–453. doi: 10.1038/s41558-018-0181-2

Buck, H. J. (2020). Should carbon removal be treated as waste management? Lessons from the cultural history of waste. *Interface Focus* 10:20200010. doi: 10.1098/rsfs.2020.0010

Buck, H. J., Martin, L. J., Geden, O., Kareiva, P., Koslov, L., Krantz, W., et al. (2020). Evaluating the efficacy and equity of environmental stopgap measures. *Nat. Sustain.* 3, 499–504. doi: 10.1038/s41893-020-0497-6

California Air Resources Board (CARB) (2020). *Monthly LCFS Credit Transfer Activity Reports*. Available online at: https://ww3.arb.ca.gov/fuels/lcfs/credit/lrtmonthlycreditreports.htm (accessed December 09, 2020).

Cames, M., Harthan, R., Füssler, J., Lazarus, M., Lee, C., Erickson, P., et al. (2016). *How Additional is the Clean Development Mechanism?* Freiburg: OEKO-Institut.

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *Wiley Interdiscipl.Rev.* 11:e671. doi: 10.1002/wcc.671

Clean Air Task Force (2020). *Potential Carbon Capture Projects Database*. Available online at: https://docs.google.com/spreadsheets/d/115hsADg3ymy3lKBy4PBQRXz_MBknptqlRtlfuv79XV8/edit#gid=1540463113 (accessed April 02, 2021).

Climate Action Tracker (2020). *Paris Agreement Turning Point. Wave of Net Zero Targets Reduces Warming Estimate to 2.1 C in 2100*. Available online at: https://climateactiontracker.org/documents/829/CAT_2020-12-01_Briefing_GlobalUpdate_Paris5Years_Dec2020.pdf (accessed February 26, 2021).

Convention Citoyenne pour le Climat (CCC) (2021a). *Avis de le* Convention Citoyenne Pour *le* Climat *sur les* Réponses Apportées *par le* Gouvernement *à ses* Propositions. Available online at: https://www.conventioncitoyennepourleclimat.fr/wp-content/uploads/2021/03/CCC-rapport_Session8_GR-1.pdf (accessed April 08, 2021).

Convention Citoyenne pour le Climat (CCC) (2021b). *Les propositions de la Convention Citoyenne pour le Climat*. Available online at: https://propositions.conventioncitoyennepourleclimat.fr/pdf/ccc-rapport-final.pdf (accessed April 08, 2021).

Cornelissen, G., Jubaedah, N., Neneng, L., Hale, S. E., Martinsen, V., Silvani, L., et al. (2018). Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. *Sci. Total Environ.* 634, 561–568. doi: 10.1016/j.scitotenv.2018.03.380

Cox, E., Boettcher, M., Spence, E., and Bellamy, R. (2021). Casting a wider net on ocean NETs. *Front. Clim.* 3:576294. doi: 10.3389/fclim.2021.576294

Cox, E., and Edwards, N. R. (2019). Beyond carbon pricing: policy levers for negative emissions technologies. *Clim. Policy* 19, 1144–1156. doi: 10.1080/14693062.2019.1634509

Cox, E. M., Pidgeon, N., Spence, E., and Thomas, G. (2018). Blurred lines: the ethics and policy of greenhouse gas removal at scale. *Front. Environ. Sci.* 6:38. doi: 10.3389/fenvs.2018.00038

Donofrio, S., Maguire, P., Zwick, S., Merry, W., Wildish, J., and Myers, K. (2020). *The Only Constant is Change, State of the Voluntary Carbon Markets 2020*. Washington, DC: Forest Trends & Ecosystem Marketplace.

Donofrio, S., Maguire, P., Merry, W., and Zwick, S. (2019). *Financing Emissions Reductions for the Future. State of the Voluntary Carbon Markets 2019*. Washington, DC: Forest Trends and Ecosystem Marketplace.

Dowell, G., Niederdeppe, J., Vanucchi, J., Dogan, T., Donaghy, K., Jacobson, R., et al. (2020). Rooting carbon dioxide removal research in the social sciences. *Interface Focus* 10:20190138. doi: 10.1098/rsfs.2019.0138

Federal Ministry for Economic Affairs and Energy (BMWi) (2021). *Roadmap Energieeffizienz 2050*. Available online at: https://www.bmwi.de/Redaktion/DE/Dossier/Energieeffizienz/roadmap-energieeffizienz-2050.html (accessed April 02, 2021).

Federal Ministry of the Environment, Nature Conservation, Housing, and Reactor Safety (BMUB) (2017). *Expert pool: Questions and Answers to the CDM Additionality Study*. Available online at: https://www.carbon-mechanisms.de/fileadmin/media/dokumente/sonstige_downloads/Opinions_Expert_Pool.pdf (accessed April 03, 2021)

Federal Ministry of the Environment. Nature Conservation and Nuclear Safety (BMU) (2020). *Bundesregierung Beruft Expertenrat für Klimafragen*. Available online at: https://www.bmu.de/pressemitteilung/bundesregierung-beruft-expertenrat-fuer-klimafragen/ (accessed April 03, 2021)

Fridahl, M., Bellamy, R., Hansson, A., and Haikola, S. (2020). Mapping multi-level policy incentives for bioenergy with carbon capture and storage in Sweden. *Front. Clim.* 2:25. doi: 10.3389/fclim.2020.604787

Fuss, S., Canadell, J. G., Ciais, P., Jackson, R. B., Jones, C. D., Lyngfelt, A., et al. (2020). Moving toward net-zero emissions requires new alliances for carbon dioxide removal. *One Earth* 3, 145–149. doi: 10.1016/j.oneear.2020.08.002

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., et al. (2018). Negative emissions – Part 2: costs, potentials and side effects. *Environ. Res. Lett.* 13:063002. doi: 10.1088/1748-9326/aabf9f

Fyson, C. L., Baur, S., Gidden, M., and Schleussner, C. F. (2020). Fair-share carbon dioxide removal increases major emitter responsibility. *Nat. Clim. Change* 10, 836–841. doi: 10.1038/s41558-020-0857-2

Gattuso, J. P., Williamson, P., Duarte, C. M., and Magnan, A. K. (2021). The potential for ocean-based climate action: negative emissions technologies and beyond. *Front. Clim.* 2:37. doi: 10.3389/fclim.2020.575716

Geden, O., Peters, G. P., and Scott, V. (2019). Targeting carbon dioxide removal in the European Union. *Climate Policy*, 19, 487–494. doi: 10.1080/14693062.2018.1536600

Geden, O., and Schenuit, F. (2020). *Unconventional Mitigation: Carbon Dioxide Removal as a New Approach in EU Climate Policy*.

Global CCS Institute (GCCSI) (2020). *Global Status of CCS 2020*. Melbourne, VIC: GCCSI.

Gold Standard (2020). *How do You Ensure that Gold Standard Emission Reductions from sequestration (Land Use) Represent Permanent Carbon Reductions*. Available online at: http://www.goldstandard.org/resources/faqs (accessed January 15, 2021).

Gupta, S., Tirpak, D., Burger, N., Gupta, J., Höhne, N., Boncheva, A., et al. (2007). "Policies. Instruments and Co-operative Arrangements," in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds B. Metz, O. Davidson, P. Bosch, R. Dave, and L. Meyer (Cambridge: Cambridge University Press), 746–807.

Haapanen, M., Lenihan, H., and Mariani, M. (2014). Government policy failure in public support for research and development. *Policy Stud.* 35, 557–575, doi: 10.1080/01442872.2014.971728

Hamrick, K., and Gallant, M. (2017). *Fertile Ground, State of Forest Carbon Finance 2017*. Washington, DC: Forest Trends' Ecosystem Marketplace.

Honegger, M., Burns, W., and Morrow, D. (2021). *Is Carbon dioxide Removal 'Mitigation of Climate Change'? Review of European.* Comparative and International Environmental Law. doi: 10.1111/reel.12401

Honegger, M., Michaelowa, A., and Roy, J. (2020). Potential implications of carbon dioxide removal for the sustainable development goals. *Clim. Policy* 21, 1–21. doi: 10.1080/14693062.2020.1843388

Hughes, G. (2017). *The Bottomless Pit. The Economics of Carbon Capture and Storage, GWPF Report 24.* Global Warming Policy Foundation. Available online at: http://www.thegwpf.org/content/uploads/2017/06/CCS-Report.pdf (accessed February 26, 2021).

Olsson, O., Bang, C., Borchers, M., Hahn, A., Karjunen, H., Thrän, D., et al. (2020). *Deployment of BECCS/U Value Chains*. IEA Bioenergy Task 40. Available online at: https://www.ieabioenergy.com/wp-content/uploads/2020/06/Deployment-of-BECCS-Value-Chains-IEA-Bioenergy-Task-40.pdf (accessed November 13, 2020).

Intergovernmental Panel on Climate Change (IPCC) (2018). *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways,* *in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge: Cambridge University Press.

International Energy Agency (IEA) (2020). *California Low Carbon Fuel Standard*. Available online at: https://www.iea.org/policies/11671-california-low-carbon-fuel-standard (accessed November 23, 2020).

Jeffery, L., Höhne, N., Moisio, M., Day, T., and Lawless, B. (2020). *Options for Supporting Carbon Dioxide Removal*. Available online at: https://newclimate.org/wp-content/uploads/2020/07/Options-for-supporting-Carbon-Dioxide-Removal_July_2020.pdf (accessed September 16, 2020).

Kätterer, T., Roobroeck, D., Andrén, O., Kimutai, G., Karltun, E., Kirchmann, H., et al. (2019). Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. *Field Crops Res.* 235, 18–26. doi: 10.1016/j.fcr.2019.02.015

Kaya, Y., Yamaguchi, M., and Geden, O. (2019). Towards net zero CO_2 emissions without relying on massive carbon dioxide removal. *Sustain. Sci.* 14, 1739–1743. doi: 10.1007/s11625-019-00680-1

Keith, D. W., Ha-Duong, M., and Stolaroff, J. K. (2006). Climate strategy with CO 2 capture from the air. *Clim. Change* 74, 17–45. doi: 10.1007/s10584-005-9026-x

Kupfer, D., Karimanzira, R., et al. (1990). "Chapter 4 Agriculture. Forestry and other human activities," in *Climate Change – the IPCC Response Strategies, the IPCC First Assessment Report. Working Group 3*, ed IPCC (Geneva: World Meterological Organization), 73–127.

Larsen, J., Herndon, W., Grant, M., and Marsters, P. (2019). *Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology.* New York, NY: Rhodium Group. Available online at: https://rhg.com/wp-content/uploads/2019/05/Rhodium_CapturingLeadership_May2019-1.pdf (accessed April 02, 2021).

Lehtveer, M., and Emanuelsson, A. (2021). BECCS and DACCS as negative emission providers in an intermittent electricity system: why levelized cost of carbon may be a misleading measure for policy decisions. *Front. Clim.* 3:647276. doi: 10.3389/fclim.2021.647276

Lund Christiansen, K. (2020). *Governing the emerging sociotechnical imaginary of a climate-positive Sweden.* Master Thesis Series in Environmental Studies and Sustainability Science No 2020:032. Available online at: https://lup.lub.lu.se/luur/download?func=downloadFileandrecordOId=9012835andfileOId=9012836 (accessed December 09, 2020).

McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B., and Markusson, N. O. (2019). Beyond "net-zero": a case for separate targets for emissions reduction and negative emissions. *Front. Clim.* 1:4. doi: 10.3389/fclim.2019.00004

Michaelowa, A., Allen, M., and Sha, F. (2018). Policy instruments for limiting global temperature rise to 1.5° C–can humanity rise to the challenge? *Clim. Policy* 18, 275–286. doi: 10.1080/14693062.2018.1426977

Michaelowa, A., Hermwille, L., Obergassel, W., and Butzengeiger, S. (2019a). Additionality revisited: guarding the integrity of market mechanisms under the Paris agreement. *Clim. Policy* 19, 1211–1224. doi: 10.1080/14693062.2019.1628695

Michaelowa, A., Shishlov, I., and Brescia, D. (2019b). Evolution of international carbon markets: lessons for the Paris agreement. *WIREs Clim. Change* 10:e613. doi: 10.1002/wcc.613

Mills-Novoa, M., and Liverman, D. M. (2019). Nationally determined contributions: material climate commitments and discursive positioning in the NDCs. *Wiley Interdiscipl. Rev. Clim. Change* 10:e589. doi: 10.1002/wcc.589

Möllersten, K., Yan, J., and Moreira, J. R. (2003). Potential market niches for biomass energy with CO_2 capture and storage—opportunities for energy supply with negative CO_2 emissions. *Biomass Bioenergy* 25, 273–285. doi: 10.1016/S0961-9534(03)00013-8

Möllersten, K. Yan, J., and Naqvi, R. (2020). *Qualitative Assessment of Classes of Negative Emission Technologies (NETs).* Mälardalen: Mälardalen University.

Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., et al. (2020). Principles for thinking about carbon dioxide removal in just climate policy. *One Earth* 3, 150–153. doi: 10.1016/j.oneear.2020.07.015

Nerini, F. F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., Howells, M., et al. (2019). Connecting climate action with other sustainable development goals. *Nat. Sustain.* 2, 674–680. doi: 10.1038/s41893-019-0334-y

Poralla, M., Honegger, M., Ahonen, H., Michaelowa, A., and Weber, A. (2021). "Sewage Treatment for the Skies": mobilising carbon dioxide removal through public policies and private financing," in *NET-Rapido Consortium and Perspectives Climate Research* (London, UK and Freiburg i.B., Germany).

Potsdam Institute for Climate Impact Research (PIK) (2017). *Paris Reality Check*. Available online at: https://www.pik-potsdam.de/paris-reality-check/ (accessed February 21, 2021).

Pozo, C., Galán-Martín, Á., Reiner, D. M., et al. (2020). Equity in allocating carbon dioxide removal quotas. *Nature Climate Change* 10, 640–646. doi: 10.1038/s41558-020-0802-4

Preston Aragonès, M., Whiriskey, K., Neele, F., and Jordal, K. (2020). *Europe Needs a Definition of Carbon Dioxide Removal*. Report by the Zero Emissions Platform, Brussels. Available online at: zeroemissionsplatform.eu/wp-content/uploads/Europe-needs-a-definition-of-Carbon-Dioxide-Removal-July-2020.pdf (accessed November 03, 2020).

Ruseva, T., Hedrick, J., Marland, G., Tovar, H., Sabou, C., and Besombes, E. (2020). Rethinking standards of permanence for terrestrial and coastal carbon: implications for governance and sustainability. *Curr. Opin. Environ. Sustain.* 45, 69–77. doi: 10.1016/j.cosust.2020.09.009

Schenuit, F., Colvin, R., Fridahl, M., McMullin, B., Reisinger, A., Sanchez, D. L., et al. (2021). Carbon dioxide removal policy in the making: assessing developments in 9 OECD cases. *Front. Clim.* 3:638805. doi: 10.3389/fclim.2021.638805

UNEP DTU Partnership (2021). *UNEP DTU CDM/JI Pipeline Analysis and Database*. Available online at: https://cdmpipeline.org/ (accessed April 8, 2021).

United Kingdom's Climate Change Committee (CCC) (2021). *Latest Publications*. Available online at: https://www.theccc.org.uk/publications/ (accessed April 08, 2021)

United Nations Environment Programme (UNEP) (2020). *The Emissions Gap Report 2020*. Nairobi: UNEP.

United Nations Framework Convention on Climate Change (UNFCCC) (2015). *The Paris Agreement*. Available online at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed October 14, 2020).

Van Vuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al. (2011). The representative concentration pathways: an overview. *Clim. Change* 109, 5–31. doi: 10.1007/s10584-011-0148-z

Verra (2018). *Voluntary Carbon Standard Guidance for Agriculture, Forestry and Other Land Use Projects*. Washington, DC: Verra.

Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B., and Sabir, M. (2019). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use Manag.* 36, 2–18. doi: 10.1111/sum.12546

Zakkour, P., Heidug, W., Howard, A., Haszeldine, R. S., Allen, M. R.;, and Hone, D. (2020). Progressive supply-side policy under the Paris agreement to enhance geological carbon storage. *Clim. Policy* 21, 63–77. doi: 10.1080/14693062.2020.1803039

Zakkour, P., and Heidug, W. (2019). *A Mechanism for CCS in the Post-Paris Era: Piloting Results-Based Finance and Supply Side Policy Under Article 6*. Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC).

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Navigating Potential Hype and Opportunity in Governing Marine Carbon Removal

Miranda Boettcher[1,2]*, *Kerryn Brent*[3], *Holly Jean Buck*[4], *Sean Low*[1,2,5], *Duncan McLaren*[6] *and Nadine Mengis*[7]

[1] Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, Netherlands, [2] Institute for Advanced Sustainability Studies, Potsdam, Germany, [3] Adelaide Law School, Faculty of the Professions, University of Adelaide, Adelaide, SA, Australia, [4] Department of Environment and Sustainability, University at Buffalo, Buffalo, NY, United States, [5] Department of Business Development and Technology, Aarhus University, Aarhus, Denmark, [6] Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom, [7] GEOMAR Helmholtz Center for Ocean Research Kiel, Kiel, Germany

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James Palmer,
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University of California, Los Angeles,
United States

***Correspondence:**
Miranda Boettcher
miranda.boettcher@iass-potsdam.de

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As the technical and political challenges of land-based carbon dioxide removal (CDR) approaches become more apparent, the oceans may be the new "blue" frontier for carbon drawdown strategies in climate governance. Drawing on lessons learnt from the way terrestrial carbon dioxide removal emerged, we explore increasing overall attention to marine environments and mCDR projects, and how this could manifest in four entwined knowledge systems and governance sectors. We consider how developments within and between these "frontiers" could result in different futures—where hype and over-promising around marine carbon drawdown could enable continued time-buying for the carbon economy without providing significant removals, or where reforms to modeling practices, policy development, innovation funding, and legal governance could seek co-benefits between ocean protection, economy, and climate.

Keywords: marine governance, carbon dioxide removal, negative emissions, Net Zero, IPCC scenarios, climate policy, blue economy, marine law

IS BLUE THE NEW GREEN?

Marine environments are the blue frontier of a strategy for novel carbon sinks in post-Paris climate governance, from "nature-based" ecosystem management to industrial-scale technological interventions in the Earth system (**Figure 1**). *Marine carbon dioxide removal* (mCDR) approaches are diverse (Royal Society/Royal Academy of Engineering (RS/RAE), 2018; GESAMP, 2019)—although several resemble key terrestrial CDR (tCDR) proposals. Ocean alkalinisation (adding silicate mineral such as olivine to coastal seawater, to increase CO_2 uptake through chemical reactions) is enhanced weathering, "blue carbon" (enhancing natural biological CO_2 drawdown from coastal vegetation) is marine reforestation, and cultivation of marine biomass (i.e., seaweed) for coupling with consequent carbon capture and storage (CCS) is the marine variant of bioenergy and CCS (BECCS).

Wetlands, coasts, and the open ocean are being conceived of and developed as managed carbon removal-and-storage sites, with practices expanded from the use of soils and forests. In this article, we explore increasing overall attention to marine environments and mCDR projects,

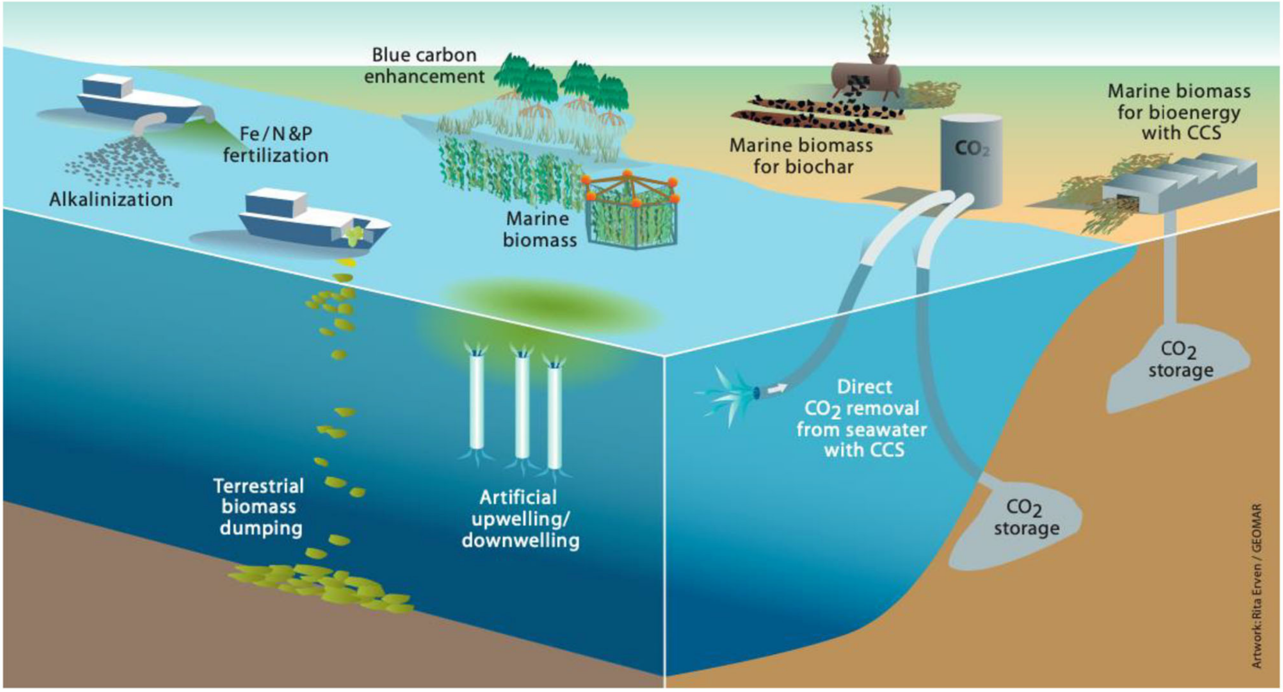

FIGURE 1 | An overview of proposed marine carbon dioxide removal (mCDR) options, artwork © Rita Erven/GEOMAR.

and how this could manifest in four entwined knowledge systems and governance sectors: modeling pathways (in Intergovernmental Panel on Climate Change reports), climate policy and politics (the Paris Agreement and Net Zero commitments), innovation, and international legal frameworks. We compare growing interest in mCDR with that surrounding BECCS—an imperfect proxy for tCDR—as a springboard for thinking about mCDR's knowledge and innovation economy, potentials, and governance of research and development.

Why does BECCS matter? BECCS, and through it, the prospect of large-scale tCDR, emerged at the confluence of key trends in climate assessment and governance: it is an immature technological system that allows ambitious temperature targets to be reached in IPCC mitigation pathways, while reflecting rationales for "buying time" in climate policy and industry (Low and Boettcher, 2020; McLaren and Markusson, 2020). These trends are escalating how terrestrial environments have been made thinkable and practicable as operating spaces for CDR, and reinforcing the legitimacy of CDR as a response to climate change. Throughout, we refer to the dangers of hype and over-promising—by which we intend both the everyday meaning of exaggerative promotion, as well as the processes by which speculative, evolving assessments implicitly or intentionally support novel technologies (e.g., Brown et al., 2000).

But the technical and political feasibility of BECCS has come under deep questioning. Furthermore, there are concerns that BECCS is politically useful precisely as an idea; permitting mitigation pathway modeling and policy rhetoric to expand the (near-term) carbon budget (Carton et al., 2020). Meanwhile, planning around eventual carbon removal could become yet another factor in delaying decarbonization. Hence, we maintain BECCS and tCDR as a guiding comparison–but our interest is on how mCDR could come to prominence, and what kind of governance would be needed to ensure that on balance, mCDR supports rather than undermines opportunities for decarbonisation and sustainable development.

MODELING PATHWAYS

BECCS features heavily in mitigation pathways of the IPCC's Fifth Assessment Report and Special Report on 1.5C–projected by cost-optimizing integrated assessment models (IAMs)–for both technical and political rationales (van Beek et al., 2020). Most CDR technologies consume energy, while in some configurations BECCS increases availability of energy. Moreover, because both bioenergy and CCS were already included in IAMs, it was an easier task for modelers to expand their applications–crucially, in a modified and optimistic form. In reality, applications are less effective, need more space, and are combined with enhanced oil recovery (EOR) (GCCS, 2017; Fuss et al., 2018). Politically, modeling BECCS helps achieve target carbon budgets more cheaply by delaying costly near-term emissions reduction and replacing it with CDR whose future costs are discounted (Rogelj et al., 2019; McLaren, 2020).

But significant limits to tCDR are already foreseen, especially in land competition for biomass production (Smith et al., 2019; Doelman et al., 2020). As carbon budgets deplete, IAM work could instead adopt mBECCS: biomass taken from marine sources (i.e., Hughes et al., 2012) would maintain BECCS' advantage as an energy gain. Alternatively, other mCDR options might suggest new co-benefits. Blue carbon–e.g., seagrass or mangrove restoration–could sequester carbon while extending underwater natural habitats and increasing biodiversity (Hejnowicz et al., 2015; Vierros, 2017). Ocean alkalinization potentially removes large amounts of carbon due to large available surface (e.g., Kheshgi, 1995; Hartmann et al., 2013; Keller et al., 2014; Ferrer-Gonzalez and Ilyina, 2015; Renforth and Henderson, 2017), while at the same time directly counteracting ocean acidification (Keller et al., 2018). Oceans suggest huge prospective scale and leverage in modeling approaches (Resplandy et al., 2019). Yet, the technical and social feasibility of using this potential is debatable (Bindoff et al., 2019; GESAMP, 2019).

Ideally, before mCDR approaches are considered in future IAM pathway development, insights from earth system modeling (ESM) should be incorporated. While IAMs have now been coupled with more comprehensive Land-Surface Models that (albeit partially) account for uncertainties surrounding tCDR measures, this was not the case when the modeling of BECCS at large scale began. Even now, most IAMs still only use highly simplistic models to account for ocean-based carbon and heat uptake (Nicholls et al., 2020), and do not account for ocean biogeochemistry at all. An IAM minimally requires only parameters for carbon uptake potential and cost. Additional system-level feedbacks from ESMs–like leakage of CO_2 from the ocean to the atmosphere–*can* be incorporated in IAMs using aggregate emulators, but the magnitude is still subject to large uncertainties (Keller et al., 2018). In summary, mCDR could be implementable in IAMs, but through highly simplified renderings.

Given these considerations, it is unclear whether IAMs might trigger similar hype over mCDR. Yet if mCDR was included in IAMs, the physical uncertainties involved would be sidelined by the IAM imperative toward producing cost-optimized mitigation pathways over time. And modeling could yet inflate an mCDR bubble initiated elsewhere.

CLIMATE POLICY AND POLITICS

The introduction of BECCS into modeled pathways was facilitated by a change in how climate targets were expressed: via "carbon budgets." tCDR—relying on novel anthropogenic removals as well as on enhancement of natural sinks—has gained disproportionate importance as an essential mechanism to stabilize atmospheric CO_2 at concentrations compatible with the 2°C target (McLaren and Markusson, 2020).

The Paris Agreement has since cemented two critical roles for CDR. First, the 1.5°C aspiration brought CDR-heavy pathways to the fore as a way to further stretch the near-term carbon budget: a *time-buying* (Low and Boettcher, 2020) or *stopgap* strategy (Buck et al., 2020a) to ease impacts for vulnerable industries and populations during low carbon transitions. Second, the commitment to achieve Net Zero from "a balance of sources and sinks" makes CDR essential for *capturing residual emissions* accumulating in the atmosphere from the (transitioning) carbon economy (Morrow et al., 2020). CDR arguably underpins a green transition at both ends: highly desirable to wean the economy off carbon dependence today, and essential to clean up what carbon is left in the atmosphere afterward (Buck, 2019).

Parallel to these developments, the role of the oceans has been becoming increasingly central to international climate policy discussions. At COP 21, 23 UNFCCC parties issued the "Because the Ocean" declaration, claiming the Paris Agreement was too land-centric (Because the Ocean, 2015). A second "Because the Ocean" declaration was signed at COP 22 in 2016 by 39 countries, and an agreement was reached to give greater attention to the ocean at subsequent COPs (Because the Ocean, 2016). Recent policy-focused analyses have highlighted opportunities for ocean-based climate action in Nationally Determined Contributions (NDCs) (Gallo et al., 2017) and emphasized "ocean solutions" (e.g., Gattuso et al., 2018, 2021) and an assessment of ocean-based climate strategies was included in in Chapter 5 of the 2019 IPCC Special Report on Ocean and Cryosphere in a Changing Climate (Bindoff et al., 2019).

Whether terrestrial or marine, CDR does not have to be delivered at scale in order to exert perverse effects in climate governance. Rather, CDR may already be powerful as a promise that ongoing emissions can be reversed (Geden, 2016). Rhetoric on scaling up carbon sinks bridges the gap in reality between slow progress and future aspirations for climate action. In this sense, it may prematurely promise a "technological fix"—a technological solution to an otherwise intractable political problem (Nightingale et al., 2019). Indeed, CDR has the potential—if not guarded against in research and governance—to follow in the tracks of Kyoto Protocol-era carbon trading and offset schemes, carbon capture and storage, biofuels, shale gas, and other sociotechnical options in climate governance in which rationales and avenues for delaying and disincentivizing deep emissions cuts have emerged (Carton et al., 2020; Low and Boettcher, 2020; McLaren and Markusson, 2020).

Nonetheless, CDR loses credibility if it becomes implausible within modeling or real-world constraints. There is precedent: buying time with CCS—which has yet to be implemented at a globally-meaningful scale despite a history of over-promising (Krüger, 2017; Røttereng, 2018)—has now had to be further supplemented by CDR and BECCS (McLaren and Markusson, 2020). And now, projections of the adverse impacts of BECCS at scale may be causing it to lose credibility in both models and in political discussions. Without a credible prospect of large-scale CDR, this mutually-reinforcing complex of targets and modeling (Geden, 2016) will come under stress to generate emergency action, or find a new technology or strategy to enable continued time-buying.

CDR advocates might also hope to escape the limits that sovereign territories impose on land-bound techniques. It might be tempting for global powers or big business, pursuing neoliberal politics, to treat the "high seas" as a new frontier for overuse and exploitation (Mansfield, 2004). Existing opportunities could entrench such geopolitical and commercial moves. Providing new sinks for integration into carbon markets, following established logics and instruments for carbon offsetting and trading, may be attractive both commercially and politically (Schneider et al., 2019). Opportunities surrounding still-immature "bridging" fuels, such as algae-for-oil and marine biofuels, may be influential (Maeda et al., 2018)—even though such deployments can undermine potential for long-term carbon storage (McLaren, 2020). And actors may seek to strategically position themselves for further exploitation of resources such as minerals and fisheries in the "blue economy."

INNOVATION AND INDUSTRY

The idea of the "blue economy" emerged from Rio+20 (Voyer et al., 2018), and mCDR arises in this context. The story of terrestrial limits being transcended through development of marine frontiers is already mapped out for aquaculture (the "blue revolution" to bring cultivation to oceanic space), biofuels, and mineral and resource extraction (deep-sea mining); it follows a "blue growth" logic, as the availability of land and land-based resources seems foreclosed. Discourses prevalent in the blue economy–oceans as natural capital, as good business, as integral to small island developing states, as small-scale fisheries (ibid.)–are all present in the umbrella concept of mCDR.

This connection with the blue economy implies different sorts of actor coalitions than feature in tCDR, and perhaps different rationales. Coalitions may include ocean conservation organizations concerned with the dire state of the oceans (e.g., Blue Carbon Initiative (BCI), 2012; World Wildlife Fund (WWF), 2021a,b), as well as firms developing ocean sensing and monitoring technologies (e.g., Solid Carbon, 2020; Ocean Networks Canada, 2021). In the US and Germany, key oceanic research institutes and networks are developing road maps citing "enormous potential" (Oceans Visions Alliance, 2021) and "sustainable utilization" of mCDR (Deutsche Allianz Meeresforschung (DAM), 2020), and some seek to explore the potentials of commercial viability. Insofar as the ocean is perceived as both "a new economic and epistemological frontier" (Ertör and Hadjimichael, 2020), new rationales for urgency and experimentation with mCDR may emerge.

However, the seas are not an empty frontier, but busy (Bennett, 2019), which will near-inevitably lead to ocean use conflicts. Marine spatial planning may be able to optimize interactions between carbon removal and other ocean uses (Boucquey et al., 2016). However, if local opposition to ocean exploitation on other fronts grows, this could be detrimental to the prospects of mCDR. Already there are concerns about displacement of coastal communities, "ocean grabbing," and privatization of seas and coastlines (Barbesgaard, 2018; Ertör and Hadjimichael, 2020).

Under a commercial orientation of research and development, mCDR is likely to be hyped, to attract venture capital. But venture capitalists have their own agenda, and the demands of investors for early profitability and "exit" (a trade sale or initial public offering allowing investors to recover their stakes) push green-tech down predictable paths (Buck, 2016 on tCDR specifically; Goldstein, 2018). Inventors are sidelined in favor of experienced financial and business managers, and long-term ambitions to transform society with disruptive technology are shelved in favor of configurations that can deliver profitable incremental gains in existing sectors. We should recall CCS and BECCS, where EOR dominates real-world applications, rather than long-term storage, despite optimistic scientific and commercial roadmaps (GCCS, 2017; Fuss et al., 2018).

While commercial interests may drive speculation and investment in mCDR, it is not likely to get very far without strong regulation and investment by the state, which can provide incentives and infrastructure. Carbon markets will matter in determining the fate of carbon captured in mCDR, but so will utilization opportunities and marketable "co-benefits." Endeavors such as the non-profit Project Vesta, for enhanced weathering in coastal environments (Project Vesta, 2021), or the philanthropically funded Ocean CDR knowledge hub (Ocean CDR, 2021), are founded by entrepreneurs or are designed to appeal to entrepreneurs, even though recognized market protocols for the forms of mCDR they explore have not fully emerged yet. Moreover, the entrepreneurial discourse tends to retain an amnesia about failed commercial attempts surrounding the introduction of ocean iron fertilization into voluntary markets (Strong et al., 2015). And large-scale offshore CCS projects (Southern States Energy Board (SSEB), 2021; Northern Lights, n.d.) seem likely to require expensive infrastructures dependent on state support and partnerships.

LAW AND GOVERNANCE

In contrast to state-regulated tCDR spaces, the ocean could be framed as comparatively free from regulation. Nevertheless, legally, the ocean is not an "open frontier." Coastal states' laws may regulate mCDR in their territorial sea (UNCLOS, art 2, 3) and exclusive economic zone (EEZ) where states have limited sovereign rights concerning natural resources, environmental protection and scientific research (ibid., art 56, 57). Numerous international regimes also provide rules regarding marine scientific research and environmental protection that are pertinent to mCDR in all marine jurisdictions. Key regimes include the Convention on the Law of the Sea (UNCLOS, Part XII, XIII) and the London Protocol for the Dumping of Waste at Sea (Brent et al., 2019).

There is, however, a significant governance gap regarding the utilization of the ocean as a carbon sink. The Paris Agreement adopted de facto limits for atmospheric CO_2 concentrations, but no such limits exist for ocean CO_2 uptake (Stephens, 2015). Preliminary attempts to govern mCDR through the 2013 amendment to the London Protocol (Brent et al., 2019) aim to prevent environmental harm rather than regulate common use of the ocean for carbon drawdown. The prospect of mCDR as part of the "blue economy" raises significant questions about governing the ocean as a carbon sink, not only regarding environmental protection but also equal access and benefit-sharing for developing states. Taken on its own, this governance

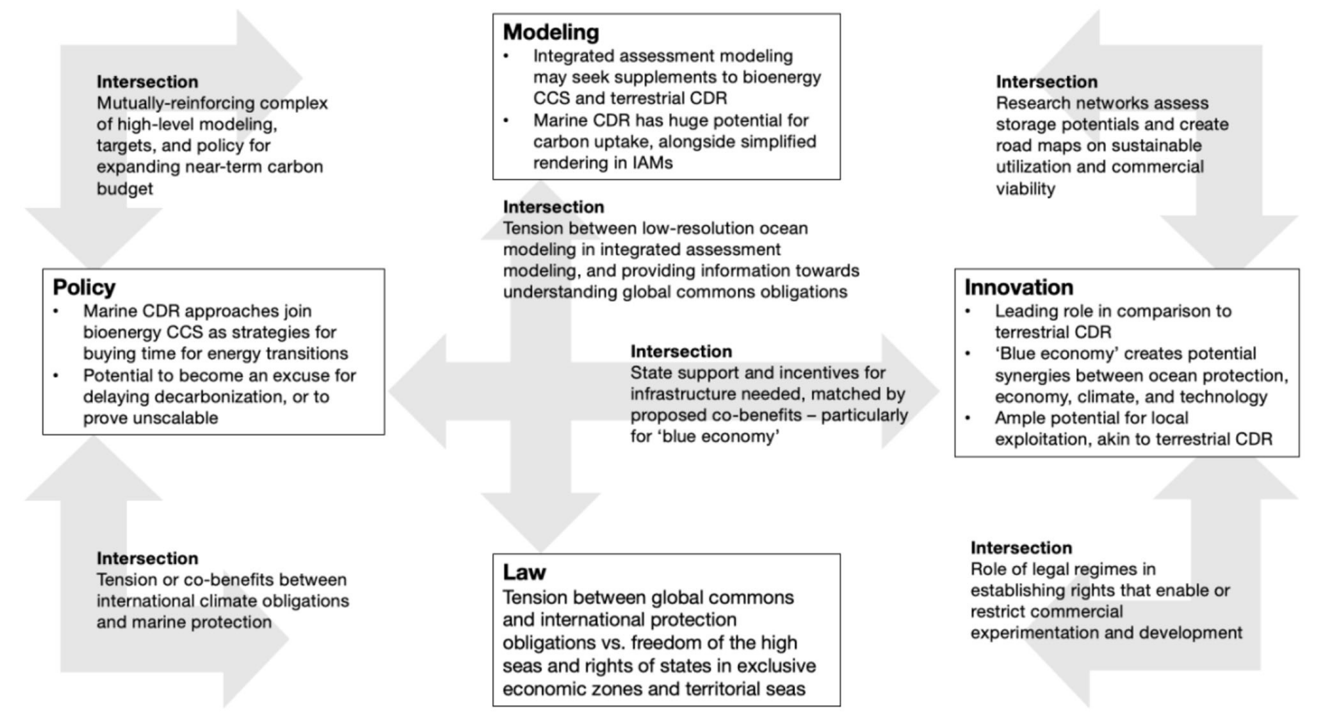

FIGURE 2 | Emerging frontiers for the governance of marine carbon dioxide removal (mCDR) options.

gap could suggest that this common resource is free to exploit. However, other rights and obligations in international ocean governance must still be considered—making different interpretations regarding mCDR possible.

For example, a state might conduct ocean alkalinization in territorial waters to minimize the effects of ocean acidification on coastal ecosystems, and associated tourism and shellfish industries (Renforth and Henderson, 2017). This activity would primarily be for the purpose of marine environmental protection, but could also result in CO_2 drawdown. Commercial interests and marketable co-benefits could play a role, especially if financial incentives were in place. The state responsible may claim the activity is consistent with international obligations to mitigate climate change *and* protect the marine environment (i.e., UNCLOS art 192), as well as their exclusive sovereign rights within their territorial sea (UNCLOS, art 2). However, other states could claim the OA activity is inconsistent with international law or require cooperation and coordination between states, especially if there is the risk of significant transboundary harm or impacts on the marine environment.

In addition to conflicting legal interpretations, this hypothetical example highlights broader tensions between different paradigms of ocean governance: the traditional focus on individual sovereign rights, vs. a more modern direction toward international cooperation and the safeguarding of the ocean as a common interest (Tanaka, 2019). Although still emerging, this second paradigm further weighs against any presumptions that states have unlimited sovereign rights in their own waters or absolute freedom in high seas areas to conduct mCDR. On balance, international oceans governance may discourage states, and by extension their citizens and corporations, from considering mCDR to be a convenient policy option.

CHARTING A COURSE

Tracking developments within and between these "frontiers" gives a more holistic picture of the contexts and activities through which marine environments are being imagined as enhanced carbon sinks, and the potentials and risks of mCDR are becoming understood (**Figure 2**). Unlike BECCS, mCDR is emerging less from a high-level modeling-policy complex (sections Modeling Pathways and Climate Policy and Politics), and more from innovation projects that pose co-benefits and conflicts between ocean protection, economy, and climate (section Innovation and Industry). Moreover, mCDR's "global commons" dimensions could serve as a springboard for more coordinated international governance (section Law and Governance). This mapping is double-edged: some possibilities are exploitative or delay decarbonization, while others present co-benefits underpinned by international legal obligations.

Let us consider the emergence of perverse logics in the research and governance of mCDR, and project a future to be avoided. In global modeling assessments, mCDR approaches bridge the growing gap between the Paris targets and mitigation efforts, as tCDR capacities run up against biophysical and techno-economic limits. Net Zero commitments spread further, with promised investments into patchworks of ecosystems management and industrial-scale approaches, and with an eye to integrating mCDR with carbon offsets and markets. These ambitions facilitate a spectrum of mCDR projects pushed in innovation circles under uneven regulation. The projects cite co-benefits between ocean protection and business, but create phantom commodities (ultimately proving unscalable) as investment sinks for governments and venture capitalists. Few removals are delivered, and many of those are deployed as offsets for continued emissions, or as stopgaps for carbon infrastructures. Meanwhile, international law produces contested implications for how to balance the right to use the oceanic commons as a carbon sink with the obligation of marine protection.

But we can imagine a different future, harnessing opportunities on these frontiers. Optimism for delivery of mCDR in line with climate and development goals demands careful steps to prevent hype and over-promising from these opportunities, including reforms in modeling practices, policy development, innovation funding and legal governance.

Parallels can be drawn directly with tCDR debates. To avoid unrealistic evaluation of future mCDR availabilities through limited treatments of techno-economic "feasibility" (Forster et al., 2020; Thoni et al., 2020), mitigation pathways and scientific roadmaps could be tempered with widespread, localized engagements on a range of mCDR projects, exploring the conditions that breed social resistance and commercial orientations that divert carbon away from long-term storage (Buck et al., 2020b; Low and Buck, 2020; Cox et al., 2021). Updates to Paris-mandated Nationally Determined Contributions must be wary of feeding mCDR into carbon offsetting and trading. Ongoing intergovernmental negotiations over Paris' Article 6 on potential market mechanisms could separate targets and processes for emissions reduced from decarbonization vs. those from CDR, forestalling double-counting (McLaren et al., 2019).

Governance can also harness conditions that differentiate marine from terrestrial spaces. Effective governance of the seas could be informed by existing transnational frameworks for governing aquaculture, marine food resources, and marine renewables, as well as from managing the seas for conservation. Cross-sectoral marine governance therefore offers opportunities: ocean conservation organizations could partner with research initiatives and innovation efforts. In the legal sphere, the right to use and the obligation to protect the ocean could be combined in novel co-benefits. States–working with research and environmental networks and commercial entities–could ensure that mCDR is in line with their international obligations to mitigate climate change and protect the oceans (e.g., from acidification), and their national right to use ocean resources as part of a "blue growth" strategy.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

All authors contributed equally to the conceptualizing, writing, and editing of this perspective.

REFERENCES

Barbesgaard, M. (2018). Blue growth: saviour or ocean grabbing. *J. Peasant Stud.* 45, 130–149. doi: 10.1080/03066150.2017.1377186

Because the Ocean (2015). First *Declaration*. Available online at: https://www.becausetheocean.org/first-because-the-ocean-declaration/ (accessed March 15, 2021).

Because the Ocean (2016). Second *Declaration*. Available online at: https://www.becausetheocean.org/second-because-the-ocean-declaration/ (accessed March 15, 2021).

Bennett, N. J. (2019). In political seas: engaging with political ecology in the ocean and coastal environment. *Coast. Manag.* 47, 67–87. doi: 10.1080/08920753.2019.1540905

Bindoff, N. L., W. W. L., Cheung, J. G., Kairo, J., Arístegui, V. A., Guinder, R., et al. (2019). *Chapter 5, p. 447-587 in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. WMO/UNEP.

Blue Carbon Initiative (BCI) (2012). Available online at: http://bluecarbonportal.org/wp-content/uploads/downloads/2012/09/Lawrence_WWF_Blue-Carbon_2012.pdf (accessed March 15, 2021).

Boucquey, N., Fairbanks, L., St. Martin, K., Campbell, L. M., and McCay, B. (2016). The ontological politics of marine spatial planning: assembling the ocean and shaping the capacities of "Community" and '"Environment." *Geoforum* 75, 1–11. doi: 10.1016/j.geoforum.2016.06.014

Brent, K., Burns, W., and McGee, J. (2019). *Governance of Marine Geoengineering*. Waterloo, ON: Centre for International Governance Innovation. Available online at: https://www.cigionline.org/sites/default/files/documents/MarineGov-web.pdf (accessed May 10, 2021).

Brown, N., Rappert, B., and Webster, A. (eds.). (2000). *Contested Futures: A Sociology of Prospective Techno-Science*. Aldershot: Ashgate.

Buck, H. J. (2016). Rapid scale up of negative emissions technologies: social barriers and social implications. *Clim. Change* 139, 155–167. doi: 10.1007/s10584-016-1770-6

Buck, H. J. (2019). *After Geoengineering: Climate Tragedy, Repair, and Restoration*. New York, NY: Verso.

Buck, H. J., Fuhrman, J., Morrow, D. R., Sanchez, D. L., and Wang, F. M. (2020b). Carbon removal and adaptation. One *Earth* 3. 425–435. doi: 10.1016/j.oneear.2020.09.008

Buck, H. J., Martin, L. J., Geden, O., Kareiva, P., Koslov, L., Krantz, W., et al. (2020a). Evaluating the efficacy and equity of environmental stopgap measures. *Nat. Sustain.* 3, 499–504. doi: 10.1038/s41893-020-0497-6

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *Wiley Interdiscip. Rev. Clim. Change* 11:e671. doi: 10.1002/wcc.671

Cox, E., Boettcher, M., Spence, E., and Bellamy, R. (2021). Casting a wider net on Ocean NETs. *Front. Clim.* 3:576294. doi: 10.3389/fclim.2021.576294

Deutsche Allianz Meeresforschung (DAM) (2020). *19 Leading German Marine Institutions in One Alliance*. Available online at: https://www.allianz-meeresforschung.de/en/ (accessed January 27, 2021).

Doelman, J. C., Stehfest, E., van Vuuren, D. P., Tabeau, A., Hof, A. F., Braakhekke, M. C., et al. (2020). Afforestation for climate change mitigation: potentials, risks, and trade-offs. *Glob. Change Biol.* 26, 1576–1591. doi: 10.1111/gcb.14887

Ertör, I., and Hadjimichael, M. (2020). Blue degrowth and the politics of the sea: rethinking the blue economy. *Sustain, Sci.* 15, 1–10. doi: 10.1007/s11625-019-00772-y

Ferrer-Gonzalez, M., and Ilyina, T. (2015). "Mitigation potential, risks, and side-effects of ocean alkalinity enhancement," in *Deglaciation Changes in Ocean Dynamics and Atmospheric* CO_2, eds M. Sarnthein and G. H. Haug (Halle: German Academy of Sciences Leopoldina-National Academy of Sciences), 275–278.

Forster, J., Vaughan, N. E., Gough, C., Lorenzoni, I., and Chilvers, J. (2020). Mapping feasibilities of greenhouse gas removal: key issues, gaps, and opening up assessments. *Glob. Environ. Change* 63:102073. doi: 10.1016/j.gloenvcha.2020.102073

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., et al. (2018). Negative emissions—Part 2: costs, potentials, and side effects. *Environ. Res. Lett.* 13:063002. doi: 10.1088/1748-9326/aabf9f

Gallo, N. D., Victor, D. G., and Levin, L. A. (2017). Ocean commitments under the Paris agreement. *Nat. Clim. Change* 7, 833–838. doi: 10.1038/nclimate3422

Gattuso, J.-P., Magnan, A. K., Bopp, L., Cheung, W. W. L., Duarte, C. M., Hinkel, J., et al. (2018). Ocean solutions to address climate change and its effects on marine ecosystems. *Front. Mar. Sci.* 5:337. doi: 10.3389/fmars.2018.00337

Gattuso, J.-P., Williamson, P., Duarte, C. M., and Magnan, A. K. (2021). The potential for ocean-based climate action: negative emission technologies and beyond. *Front. Clim.* 2:575716. doi: 10.3389/fclim.2020.575716

GCCS (2017). *The Global Status of CCS: 2017*. Canberra, ACT: Global CCS Institute.

Geden, O. (2016). The Paris Agreement and the inherent inconsistency of climate policymaking. *Wiley Interdiscip. Rev. Clim. Change* 7, 790–797. doi: 10.1002/wcc.427

GESAMP (2019). "High level review of a wide range of proposed marine geoengineering techniques," in *Rep. Stud. GESAMP No. 98, (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/ UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection)*, eds P. W. Boyd and C. M. G. Vivian (London: International Maritime Organization), 144p.

Goldstein, J. (2018). *Planetary Improvement: Cleantech Entrepreneurship and the Contradictions of Green Capitalism*. Cambridge, MA: The MIT Press.

Hartmann, J., West, A. J., Renforth, P., Köhler, P., De La Rocha, C. L., Wolf-Gladrow, D. A., et al. (2013). Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.* 51, 113–149. doi: 10.1002/rog.20004

Hejnowicz, A. P., Kennedy, H., Rudd, M. A., and Huxham, M. R. (2015). Harnessing the climate mitigation, conservation, and poverty alleviation potential of seagrasses: prospects for developing blue carbon initiatives and payment for ecosystem service programmes. *Front. Mar. Sci.* 2:32. doi: 10.3389/fmars.2015.00032

Hughes, A. D., Black, K. D., Campbell, I., Davidson, K., Kelly, M. S., and Stanley, M. S. (2012). Does seaweed offer a solution for bioenergy with biological carbon capture and storage? *Greenh. Gases* 2, 402–407. doi: 10.1002/ghg.1319

Keller, D. P., Feng, E. Y., and Oschlies, A. (2014). Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nat. Commun.* 5, 1–11. doi: 10.1038/ncomms4304

Keller, D. P., Lenton, A., Scott, V., Vaughan, N. E., Bauer, N., Ji, D., et al. (2018). The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6. *Geosci. Model Dev.* 11, 1133–1160. doi: 10.5194/gmd-11-1133-2018

Kheshgi, H. S. (1995). Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy* 20, 915–922. doi: 10.1016/0360-5442(95)00035-F

Krüger, T. (2017). Conflicts over carbon capture and storage in international climate governance. *Energy Policy* 100, 58–67. doi: 10.1016/j.enpol.2016.09.059

Low, S., and Boettcher, M. (2020). Delaying decarbonization: climate governmentalities and sociotechnical strategies from copenhagen to Paris. *Earth Syst. Gov.* 5:100073. doi: 10.1016/j.esg.2020.100073

Low, S., and Buck, H. J. (2020). The practice of responsible research and innovation in "climate engineering." *WIREs Clim. Change* 11:e644. doi: 10.1002/wcc.644

Maeda, Y., Yoshino, T., Matsunaga, T., Matsumoto, M., and Tanaka, T. (2018). Marine microalgae for production of biofuels and chemicals. *Curr. Opin. Biotechnol.* 50, 111–120. doi: 10.1016/j.copbio.2017.11.018

Mansfield, B. (2004). Neoliberalism in the oceans: "rationalization," property rights, and the commons question. *Geoforum* 35, 313–326. doi: 10.1016/j.geoforum.2003.05.002

McLaren, D. P. (2020). Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. *Clim. Change* 162, 2411–2428. doi: 10.1007/s10584-020-02732-3

McLaren, D. P., and Markusson, N. O. (2020). The co-evolution of technological promises, modelling, policies, and climate change targets. *Nat. Clim. Change* 10, 392–397. doi: 10.1038/s41558-020-0740-1

McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B., and Markusson, N. O. (2019). Beyond "Net-Zero": a case for separate targets for emissions reduction and negative emissions. *Front. Clim* 1:4. doi: 10.3389/fclim.2019.00004

Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., et al. (2020). Principles for thinking about carbon dioxide removal in just climate policy. One *Earth* 3, 150–153. doi: 10.1016/j.oneear.2020.07.015

Nicholls, Z. R. J., Meinshausen, M., Lewis, J., Gieseke, R., Dommenget, D., Dorheim, K., et al. (2020). Reduced complexity model intercomparison project phase 1: introduction and evaluation of global-mean temperature response. *Geosci. Model Dev.* 13, 5175–5190. doi: 10.5194/gmd-13-5175-2020

Nightingale, A. J., Eriksen, S., Taylor, M., Forsyth, T., Pelling, M., Newsham, A., et al. (2019). Beyond technical fixes: climate solutions and the great derangement. *Clim. Dev.* 12, 343–352. doi: 10.1080/17565529.2019.1624495

Northern Lights (n.d.). *About the Project*. Available online at: https://northernlightsccs.com/en/about (accessed January 27, 2021).

Ocean CDR (2021). *The leading knowledge Hub on Ocean-Based Carbon Dioxide Removal*. Available online at: https://oceancdr.net/ (accessed January 27, 2021).

Ocean Networks Canada (2021). *Discover the Ocean. Understand the Planet*. Available online at: https://www.oceannetworks.ca/innovation-centre/smart-ocean-systems (accessed January 27, 2021).

Oceans Visions Alliance (2021). *Transforming Science and Engineering Into Ocean Solutions*. Available online at: https://www.oceanvisions.org/ (accessed January 27, 2021).

Project Vesta (2021). *Could This Rock Reverse Climate Change?* Available online at: https://www.projectvesta.org/ (accessed January 27, 2021).

Renforth, P., and Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Rev. Geophys.* 55, 636–674. doi: 10.1002/2016RG000533

Resplandy, L., Keeling, R. F., Eddebbar, Y., Brooks, M., Wang, R., Bopp, L., et al. (2019). Quantification of ocean heat uptake from changes in atmospheric O2 and CO2 composition. *Sci. Rep.* 9:20244. doi: 10.1038/s41598-019-56490-z

Rogelj, J., Huppmann, D., Krey, V., Riahi, K., Clarke, L., Gidden, M., et al. (2019). A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* 573, 357–363. doi: 10.1038/s41586-019-1541-4

Røttereng, J.-K. S. (2018). The comparative politics of climate change mitigation measures: who promotes carbon sinks and why? *Glob. Environ. Polit.* 18, 52–75. doi: 10.1162/GLEP_a_00444

Royal Society/Royal Academy of Engineering (RS/RAE) (2018). *Greenhouse Gas Removal*. Available online at: https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf (accessed March 15, 2021).

Schneider, L., Duan, M., Stavins, R., Kizzier, K., Broekhoff, D., Jotzo, F., et al. (2019). Double counting and the Paris Agreement rulebook. *Science* 366, 180–183. doi: 10.1126/science.aay8750

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., et al. (2019). Impacts of land-based greenhouse gas removal options on ecosystem services and the United Nations sustainable development goals. *Annu. Rev. Environ. Resour.* 44, 255–286. doi: 10.1146/annurev-environ-101718-033129

Solid Carbon (2020). *Solid Carbon: A Negative Emissions Solution*. Available online at: https://www.solidcarbon.ca/ (accessed January 27, 2021).

Southern States Energy Board (SSEB) (2021). *SECARB Offshore*. Available online at: https://www.sseb.org/programs/offshore/ (accessed January 27, 2021).

Stephens, T. (2015). "Ocean acidification," in *Research Handbook on International Marine Environmental Law*, ed R. Rayfuse (Cheltenham: Edward Elgar Publishing). 431–450.

Strong, A. L., Cullen, J. J., and Chisholm,. S. W. (2015). Ocean fertilization: science, policy, and commerce. *Oceanography* 22, 236–261. doi: 10.5670/oceanog.2009.83

Tanaka, Y. (2019). *The International Law of the Sea, 3rd Edn*. Cambridge: Cambridge University Press.

Thoni, T., Beck, S., Borchers, M., Förster, J., Görl, K., Hahn, A., et al. (2020). Deployment of negative emissions technologies at the national level: a need for holistic feasibility assessments. *Front. Clim.* 2:590305. doi: 10.3389/fclim.2020.590305

van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D. P., and Cassen,. C. (2020). Anticipating futures through models: integrated assessment modeling in the climate science-policy interface since 1970. *Glob. Environ. Change* 65:102191. doi: 10.1016/j.gloenvcha.2020.102191

Vierros, M. (2017). Communities and blue carbon: the role of traditional management systems in providing benefits for carbon storage, biodiversity conservation and livelihoods. *Clim. Change* 140, 89–100. doi: 10.1007/s10584-013-0920-3

Voyer, M., Quirk, G., McIlgorm, A., and Azmi, K. (2018). Shades of blue: what do competing interpretations of the Blue Economy mean for oceans governance? *J. Environ. Policy Plan.* 20, 595–616. doi: 10.1080/1523908X.2018.1473153

World Wildlife Fund (WWF) (2021a). *World Wildlife Fund*. Available online at: https://www.worldwildlife.org/projects/incorporating-blue-carbon-in-kenya-s-national-green-house-gas-accounting (accessed March 15, 2021).

World Wildlife Fund (WWF) (2021b). Available online at: https://www.wwf.org.uk/ocean-heroes/uk-seas (accessed March 15, 2021).

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Carbon Removal as Carbon Revival? Bioenergy, Negative Emissions, and the Politics of Alternative Energy Futures

James Palmer[1]* *and Wim Carton*[2]

[1] School of Geographical Sciences, University of Bristol, Bristol, United Kingdom, [2] Lund University Center for Sustainability Studies, Lund, Sweden

Conscious of the need to limit climate warming to 1.5 degrees, many countries are pinning their hopes upon carbon dioxide (CO_2) removal through the industrial-scale combination of bioenergy with carbon capture and storage (BECCS). But it is not merely by storing captured CO_2 that BECCS enthusiasts hope to harness biomass combustion for climate repair. Increasingly, more productive and ostensibly profitable uses for captured CO_2 are also being identified. The concept of BECCS is evolving, in other words, into "BECCUS" —bioenergy with carbon capture, utilisation and storage. Against this backdrop, this Perspective sets out two main arguments. Firstly, regardless of the precise use to which captured CO_2 is put, efforts to predicate large-scale negative emissions upon biomass combustion should in our view be understood as attempts to reconfigure the fundamental relationship between climate change and energy use, turning the latter from a historical driver of climate warming into a remedial tool of climate repair. Secondly, the emergence of BECCUS cannot be understood solely as an attempt to make bioenergy-based negative emissions more economically viable. At stake, rather, are conflicting ideas about the role that intensive energy use should play in future global sustainable development pathways. This Perspective therefore calls for governance frameworks for carbon dioxide removal to adjudicate between conflicting approaches to achieving negative emissions not only on the basis of technical efficiency, or even "on-the-ground" social and environmental impacts, but also according to compatibility with socially legitimate visions and understandings of what energy—and more specifically energy use—should ultimately be for in the post-fossil fuel era.

Keywords: carbon dioxide removal, bioenergy, BECCS, energy consumption, negative emissions technologies, carbon utilisation and storage, social legitimacy

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Clare Heyward, Arctic University of Norway, Norway

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Jacopo Giuntoli, Independent Researcher, Montecatini Terme, Italy
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Correspondence:
James Palmer
james.palmer@bristol.ac.uk

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BIOENERGY WITH CARBON CAPTURE AND STORAGE: HARNESSING PLANT WORK FOR CLIMATE REPAIR?

As scenarios for avoiding dangerous climate warming increasingly come to hinge upon achieving massive quantities of negative greenhouse gas (GHG) emissions, many countries are pinning their hopes upon BECCS—the industrial-scale combination of bioenergy generation with carbon capture and storage technology—as a means of removing carbon dioxide from the atmosphere.

Not formally acknowledged by the Intergovernmental Panel on Climate Change (IPCC) until 2007, BECCS is now a linchpin of almost all IPCC emissions scenarios aiming to limit climate warming to no more than 1.5 degrees Celsius above preindustrial levels, and features in the majority of scenarios aiming to cap warming at 2 degrees as well (IPCC, 2014, 2018)[1]. On the surface, the core appeal of BECCS appears to reside in its reliance upon carbon sequestration processes already found in nature. Since vegetal lifeforms absorb carbon dioxide through photosynthesis as they grow, burning biomass fuels derived from trees and other plants theoretically adds less carbon dioxide to the atmosphere than burning fossil fuels instead. Research examining real-world bioenergy production, however, has raised significant concerns about the relative inefficiency of biomass burning when compared to coal, not to mention the long timescales often required for plant growth to cancel out combustion emissions in practice (Searchinger et al., 2018)[2]. Against this backdrop, the chief appeal of BECCS—we argue—lies not in its reliance upon the photosynthetic work of plants, but rather in its potential to help defuse controversy over the sometimes significant climate change impacts of "conventional" bioenergy production, by rendering biomass burning not just theoretically carbon neutral, but carbon negative.

Reports published by the Committee on Climate Change (2019) and the Royal Society and Royal Academy of Engineering (2018) suggest that BECCS could allow the UK to remove tens of millions of tonnes of carbon dioxide from the atmosphere annually over the coming decades. Theoretically at least, the UK already generates sufficient bioenergy for BECCS to be deployed on this scale—indeed, the country currently burns sufficient biomass fuel to emit more than 15 million tonnes of biogenic carbon dioxide annually (ONS, 2019). Yet to date, actual implementation of BECCS as a fully-fledged combination of biomass burning *and* carbon capture and storage technology has been modest. In early 2019, for example, Drax power station—the UK's largest piece of electricity-generating infrastructure—became the first such facility in the world to trial the capture of carbon dioxide emissions generated exclusively from the burning of biomass fuel. Only approximately one tonne of carbon dioxide per day was captured during this trial, however, and even then only temporarily (Drax Group plc, 2019a)[3]. In part, this discrepancy can be traced to the high existing costs of technologies designed to extract carbon dioxide from power station flue gases. But putting in place the necessary infrastructures to achieve the safe, long-term *storage* of captured CO_2, especially at scale, also remains a significant economic and policy challenge (see Scott et al., 2013; Durmaz, 2018). Viewing these issues together, the prospects for achieving genuinely large-scale BECCS, at least in the near future, seem somewhat bleak.

Despite these obstacles, powerful stakeholders in the UK energy sector continue to attach significant aspirations to biomass combustion as the basis for large-scale carbon dioxide removal. Moreover, it is not merely by storing captured carbon dioxide—for instance in former oil and gas fields—that these stakeholders hope to harness the work of plants as a large-scale basis for meaningful climate repair. Increasingly, a range of more *productive* and ostensibly profitable end uses for that CO_2–whether for enhancing horticultural yields, for producing synthetic feedstocks for fisheries and livestock, or even for manufacturing new forms of bioplastic (see for example Drax Group plc, 2018)—are also being identified. The concept of BECCS is hence evolving, at least in the hands of some energy actors, into "BECCUS" —bioenergy with carbon capture, *utilisation* and storage. In the context of these developments, this Perspective aims to set out two main arguments. Firstly, regardless of the precise use to which captured CO_2 is eventually put, efforts to predicate large-scale negative emissions upon biomass combustion should in our view be understood as attempts to reconfigure the fundamental relationship between climate change and energy use, turning the latter from a historical driver of climate warming into a remedial tool of climate repair. Secondly, and building on this first point, ongoing efforts on the part of some groups to advocate BECCUS (and not just BECCS) cannot be understood simply as a move intended to make bioenergy-based negative emissions more economically viable. At stake, rather, are fundamentally conflicting ideas about the role that intensive energy use—and indeed resource consumption more broadly—should play in shaping future global sustainable development pathways. As a result, we argue, it is vital that governance frameworks for carbon dioxide removal today devise means of adjudicating between conflicting approaches to achieving negative emissions not only on the basis of their technical efficiency, or even their "on-the-ground" social and environmental impacts, but also according to their compatibility with socially legitimate visions and understandings of what energy—and more specifically energy *use*—should ultimately be for in the post-fossil fuel era. While our argument mainly draws on examples from the UK, the concerns we identify should be of relevance to BECCS policy discussions in other contexts as well.

FANNING THE FLAMES: THE "FOSSIL INHERITANCE" OF BECCS

On its own terms, bioenergy's climate credentials hinge upon the vital capacities of trees and other plants to continually "remake themselves out of simple substances that are present in their surroundings" (Lenton and Latour, 2018, p. 1067). Unlike fossil fuels—derived from carbon dioxide absorbed by prehistoric plants (Sieferle, 2001)—biomass fuels are assembled through the photosynthesis of plants alive today, out of molecules which were already present in the atmosphere. For many protagonists of "natural climate solutions" such as afforestation

[1]According to Chatham House (2020, p. 5), more than 100 of 116 scenarios for limiting global warming to <2 degrees, as set out by the IPCC (2014) in its fifth assessment report, relied upon negative GHG emissions, with BECCS being responsible on average for c.12Gt of CO_2 removals annually by 2100. See also Smith and Porter (2018).

[2]In February 2021 more than 500 scientists signed a letter to five major world leaders calling for an end to subsidies for burning wood from forests (van Ypersele, 2021).

[3]More recently, Drax have partnered with Mitsubishi Heavy Industries to undertake a further 12 month trial, albeit aiming to capture just 300kg of CO_2 per day (Drax Group plc, 2020a).

or peatland restoration, these vital capacities of plants should be sufficient to achieve large-scale carbon dioxide removal by themselves. Yet, while the question of how best to expand the size of the earth's "natural" carbon sinks is the subject of fervent scientific and policy attention (Griscom et al., 2017; Moomaw et al., 2019; Cook-Patton et al., 2020) such sinks are not without weaknesses, including their susceptibility to environmental change and disruption (such as forest fires) and their potential to become saturated over time (Seidl et al., 2014; Hubau et al., 2020). Assessments of the potential benefits of combining bioenergy with man-made carbon capture and storage technology, accordingly, have long pointed to these innate limits to vegetal capacities to achieve long-term carbon *storage* (see e.g., Obersteiner et al., 2002), even as they depend critically upon plants and trees' ongoing carbon *absorption*.

Despite a commonplace view of bioenergy as "decarbonisation" tool[4], it is more accurate to describe the replacement of fossil fuels with biomass fuels as a means of *re*-carbonising incumbent energy systems. Relying on plants does not eradicate carbon from our energy systems, but simply alters the geographies and temporalities of carbon *metabolism* upon which those systems are based. To be sure, the practices through which biomass fuels are produced are radically different from the large-scale coal mining and other extractive activities associated with fossil fuels. In the space of a little over 10 years, for example, large-scale electricity generation facilities in the UK have become dependent upon the productivity of commercially-managed forests in places as disparate as the southern United States, Canada and Russia (USDA Foreign Agricultural Service, 2019; Palmer, 2021). Within the UK's road transport sector, meanwhile, hundreds of millions of litres of liquid biofuels are now blended into petrol and diesel each year, having started life initially as sugar cane growing in Brazil, corn cultivated in Ukraine, or even used cooking oil imported from China (UK DfT, 2020). Yet, despite the stark contrast with fossil fuel supply chains, such efforts to expand bioenergy use—whether coupled to carbon capture and storage facilities or not—inevitably act to perpetuate, rather than disrupt, the centuries-long practise of deriving energy from large-scale hydrocarbon combustion (Lohmann, 2021).

What *is* unique about BECCS specifically is its potential to turn this shared pyrogenic basis of fossil energy and bioenergy from a potential weakness—after all, GHG emissions are an inevitable consequence of both forms of combustion—into a strength. On this basis, efforts to couple large-scale bioenergy generation with carbon capture and storage facilities can be viewed as enrolling plants not only as a renewable, purportedly sustainable alternative to fossil fuels, but also as a means of reconfiguring the relationship between climate change and energy use itself. In promising to recalibrate large-scale hydrocarbon burning for energy around plants and to capture and safely store associated carbon dioxide emissions underground, the concept of BECCS raises the prospect—even if highly optimistic—that large scale energy consumption can be effectively transformed from a key historical driver of global climate warming into its polar opposite: a vital tool for climate repair. Viewed from such a favourable vantage point, a significant expansion of biomass burning could theoretically become a basis for decoupling energy generation from climate change *not* by making greater use of plants and trees as carbon sinks, but—somewhat paradoxically—by pressing plants and trees more intensively into service as bona fide *producers* of larger and larger quantities of carbon dioxide emissions.

As counterintuitive as this use of biomass burning as an environmental curative might seem, much of its appeal can be traced to its strong compatibility with deeply-ingrained, familiar understandings of the linkages between intensive energy consumption on the one hand, and economic development and growth (themselves understood colloquially as key markers of human progress) on the other. As critical energy scholar Daggett (2019) has recently shown, modern conceptions of energy are inextricably bound up with the laws of thermodynamics—a thoroughly nineteenth-century, north-west European science which served not only to optimise the use of fossil fuels and hence to kickstart the industrial revolution, but also to justify the increasingly efficient and productive use of those same fuels as a moral obligation, and means by which standards of living and economic development could—allegedly at least—be raised far beyond the bounds of north-west Europe itself. That energy consumption is commonly associated with development and progress today thus owes far less to the innate "nature" of energy itself, than it does to the specific political-economic context—one of fervent, fossil fuel-powered European industrial intensification and imperial expansion—within which thermodynamics was born. Moreover, and as we will argue in the next section, far from challenging these ideas, dominant visions of BECCS in the UK today serve to reinforce a view of large-scale hydrocarbon burning as both a key driver of economic growth and a moral obligation—albeit now an obligation centred not around the abstract imperative of human "progress" *per se*, but the rather more concrete objective of climate repair.

BECCUS: "TURNING POLLUTION INTO POSSIBILITIES"?[5]

Once enrolled within efforts to achieve large-scale BECCS, plants are relieved of the burden of keeping carbon dioxide permanently locked up in terrestrial landscapes, and required simply to perform the rapid, large-scale production of combustible hydrocarbon fuels. Indeed, by capturing and storing biomass combustion emissions underground, man-made technologies promise to augment the capacities of "natural" carbon sinks by keeping CO_2 out of the atmosphere for far longer periods of time than any perennial plant or tree, particularly one struggling to adapt to a changing climate, would be able to do. In the UK, the actual realisation of large-scale BECCS to date has been stymied by significant costs associated both with capturing CO_2 and with developing infrastructures capable of achieving its safe,

[4]For a notable example of the establishment of a strong link between biomass combustion and "decarbonization," see Drax Group plc (2020c).

[5]The phrase "turning pollution into possibilities" is derived from Drax Group plc (2018).

long-term storage. Recent research, moreover, has pointed to considerable expert "dissatisfaction" with a continuing tendency for BECCS to be presented as a viable carbon dioxide removal strategy at large scales (Hansson et al., 2021), as well as to divergent stakeholder interpretations of what it might mean to incentivise BECCS responsibly in practice (Bellamy et al., 2021). Nonetheless, for one influential contingent of UK-based industry organisations, scientific researchers and start-up firms, concerns about BECCS can be overcome by treating CO_2 not as a waste product *per se*, but as a valuable economic resource in its own right. This is the idea, in short, of bioenergy with carbon capture, *utilisation* and storage (BECCUS)—instead of waiting for long-term CO_2 storage to become more profitable on its own terms, why not turn emissions themselves into products and commodities for which there is already an established economic demand?

Efforts to make use of captured carbon dioxide as a raw material for other forms of commodity production are certainly in their infancy. For example, energy firm NRG's recent manufacture of footwear from captured CO_2 generated just five pairs of what it called the "shoe without a footprint" (Varinsky, 2016). Yet the ambitions which key energy stakeholders in the UK are attaching to BECCUS today are nonetheless soaring. Pointing to research which converted captured CO_2 into a sustainable alternative to conventional concrete, for example, Drax Group plc (2018)—the UK's largest producer of energy from biomass burning—recently suggested that "if the shoes people walk around on can be made from captured carbon, so can the cities they walk within" (see also Foulsham, 2016). No less far-reaching, meanwhile, are aspirations attached by Drax to its partnership with start-up firm Deep Branch Biotechnology, whose proposed use of captured CO_2 to produce synthetic fish and animal feed aims not only to reduce emissions from the global agricultural and fisheries sectors, but also to "help meet the anticipated increase in global demand for meat products" (Drax Group plc, 2019b). The full possibilities for BECCUS could even extend, at least in theory, to recycling captured biogenic carbon dioxide into synthetic alternatives to crude oil or gas (Jiang et al., 2010)—hypothetically enabling plants to serve not just as bioenergy resources, but also as the basis for producing man-made alternatives to fossil fuels as well, for use for example in the global aviation sector. The contrast between the scope of some of these future visions and the actual reach of BECCUS as a real-world technology today is stark—actual applications of CO_2 captured from biomass burning in the UK, for example, have to date been limited largely to boosting yields in the horticultural sector (Ecofys, 2017). Nonetheless, it is significant that active investment into research and development related to combining bioenergy with carbon capture and utilisation is being spearheaded by some of the country's most influential energy stakeholders, and indeed its largest current provider of biomass-based electricity.

One immediately obvious concern that can be raised about BECCUS, of course, is whether carbon dioxide emissions put to use as the basis for commodity production can really be said to be entering long-term *storage* at all. Certainly if incorporated into sustainable construction materials, captured CO_2 ought to remain locked up in the built environment for many decades at least, if not centuries. When used as a basis for producing synthetic animal feed or even synthetic fuels, however, the upshot of BECCUS is not strictly to keep captured CO_2 out of the atmosphere, so much as to replace existing uses of GHG emissions-generating resources in other economic sectors. In short, for the carbon accounting calculations to yield a negative bottom line, assumptions must inevitably be made about the degree to which products arising from BECCUS genuinely do substitute existing resource uses in other sectors (as opposed to merely adding to them), as well as about the lengths of time for which captured CO_2 remains out of atmospheric circulation. Far from seeing these assumptions as fatal flaws in the logic of BECCUS, however, we suggest that one of the key attractions of BECCUS for influential energy stakeholders in the UK today is precisely its ambiguity about the boundaries between achieving large-scale carbon dioxide removal on the one hand, and developing a truly sustainable, "circular" bioeconomy on the other. In other words, what these visions of BECCUS promise is not only—and perhaps not even—the achievement of negative GHG emissions *per se*. Instead, they promise a future in which the photosynthetic work of plants and trees is mobilised as the basis for establishing more synergistic, ostensibly "waste-less" interlinkages between large-scale energy generation and consumption on the one hand, and a diverse range of wider resource-intensive forms of industrial production on the other.

That the promise of BECCUS goes beyond the achievement of negative GHG emissions alone is already indicated, for example, by emergent efforts in the UK—led by Drax Group plc alongside a wider consortium of influential industrial actors—to create the "world's first net zero carbon industrial cluster by 2040" (Zero Carbon Humber, 2019, p. 4). For this consortium, investment in the necessary infrastructures to achieve BECCUS at Drax should exert a galvanising effect upon the wider economy of the Humber estuary region, not least by rendering investment in carbon capture, utilisation and storage technology in *other* industries—including notably in hydrogen fuel production—more economically viable. Decisive government investment in BECCUS is thus advocated by this group as an essential means of drastically reducing the GHG emissions associated with UK electricity generation, while simultaneously helping *other* energy-intensive industries (such as refining, petrochemicals, and steel manufacturing) to "grow in the Humber while helping to meet the UK's ambitious climate targets" (Zero Carbon Humber, 2019, p. 4). Against a backdrop formed by the economic shocks of the COVID-19 pandemic, the scenario envisaged by protagonists of this zero-carbon industrial cluster—involving tens of thousands of new jobs and the UK's transition "from a green recovery to a world-leading green industrial powerhouse" (Drax Group plc, 2020b)[6]—depends critically upon the switch from large-scale coal burning to large-scale biomass combustion. In other words, it is a scenario in which plants become the new prime movers of a mode of economic growth which is—for Drax Group plc. and their associates at least—truly "clean," having allegedly been

[6]For more detailed information see Vivid Economics (2020).

fully decoupled from the twin problems of resource depletion and climate change.

Of course, if BECCUS is ever to furnish developed economies like the UK not only with large volumes of renewable fuel, but also with large volumes of carbon dioxide from which to manufacture other commodities, the global energy sector will need to harness the photosynthetic work—or what might be termed the "vegetal labour" (Palmer, 2021)—of an unprecedented quantity of plants. Indeed, BECCUS scenarios like those being outlined by Drax and other industrial stakeholders in the UK today would arguably require the establishment, at the planetary scale, of an explicitly multi-species regime of "circular" carbon metabolism—a regime in which the vital capacities of vegetal lifeforms would not only be more extensively harnessed than ever before, but also deliberately augmented by human scientific, technological and engineering capabilities[7].

Whether or not BECCUS eventually does come to fruition at such a vast scale, visions of the technology being articulated by key industrial stakeholders are discursively powerful, we argue, in that they reinforce deeply-ingrained understandings—developed initially in the era of fossil fuels—of intensive energy consumption as a virtuous act (Daggett, 2019), in the process marginalising alternative visions that frame limits on, or absolute reductions in energy use, as desirable. In the nineteenth-century, of course, the supposedly universal economic and societal benefits associated with the industrial revolution were predicated ultimately on the increasingly efficient and productive use of fossil fuels. Depictions of BECCUS as desirable, by contrast, hinge on the idea that economic growth and climate repair can be reconciled—again, with purportedly universal benefits—by more intensively harnessing the theoretically inexhaustible energetic potential of plants.

GOVERNING CARBON DIOXIDE REMOVAL: BEYOND MERE NEGATIVE EMISSIONS

Simply by promising to achieve vast quantities of negative GHG emissions, carbon dioxide removal technologies of various kinds are already serving to postpone the point at which large-scale fossil fuel burning will become economically unviable. At least in part, enthusiasm for CDR can already be viewed as "the mobilisation of a specific vision of the future as a way to legitimise and reproduce the present" (Carton, 2019, p. 764). In this Perspective, we have sought to show how BECCS specifically risks "reproducing" the present in a still more fundamental sense, by perpetuating a thoroughly nineteenth-century, north-west European understanding of the purpose of energy itself, one in which the large-scale, centralised combustion of hydrocarbon-based fuels is sanctioned as a force for (purportedly) universal economic growth and wider societal benefit. In scrutinising the ongoing efforts of influential UK energy stakeholders to promote not just BECCS, but BECCUS, we have moreover argued that a potential turn to carbon utilisation would serve not just to render bioenergy-based negative GHG emissions more economically viable, but also to actively blur the boundaries between large-scale carbon dioxide removal on the one hand, and the realisation of a circular bioeconomy on the other. At the core of these prominent visions of BECCUS is not just the promise of decarbonisation, nor even of negative GHG emissions *per se*, but rather the promise of new regimes of carbon metabolism in which humans and plants work collectively to reconfigure large-scale energy generation and consumption, and indeed continued economic growth itself, into tools of climate repair. BECCUS can in this sense be viewed as the latest, optimised incarnation of longer-standing attempts to mobilise modern, large-scale bioenergy production as a "fix" for the socio-ecological contradictions not strictly of energy use, but rather of fossil fuel-based capitalism as a whole (Carton, 2019; Palmer, 2021).

Importantly, when BECCUS is viewed as global-scale project for reconfiguring the very flows of carbon upon which future, ostensibly "clean" economic growth can be predicated, many of the objections typically raised by the technology's opponents are effectively diffused and delegitimised *à priori*. Concerns relating for example to the impacts of increased biomass cultivation upon biodiversity, soil and water quality, food security, or even land rights (Schlesinger, 2018)—not to mention GHG emissions associated with land-use change—all appear from this perspective as products of *particular* but ultimately curable instances of ineffective implementation[8], rather than universal objections to the internal logic of BECCUS itself. Reckoning with what might be termed the "properly political" dimensions (Swyngedouw, 2009) of BECCUS will therefore require governance processes for CDR as a whole to go beyond assessments of the technical efficiency and "on-the-ground" impacts of diverse approaches to achieving negative emissions in practice—however ostensibly encouraging or discouraging those forms of assessment may be. Appraising BECCUS, and indeed adjudicating between other carbon dioxide removal technologies and systems, ultimately also needs to involve a societal discussion about the kind of energy futures that such technologies represent and the selective ideas of human progress implied within them.

Among the most fundamental questions to be deliberated here, perhaps, is what should be allowed to count as a desirable or useful form of energy consumption in the twenty-first-century. A satisfactory answer to this question is unlikely to emerge without also confronting the deeply uneven geographies of energy supply and consumption which are implied by the kind of visions of BECCUS being articulated by key industrial stakeholders in the UK today. Indeed, if carbon dioxide removal technologies are allowed to reinforce nineteenth-century ideas about the inevitably universal societal benefits of large-scale energy consumption, then they risk reinscribing, rather than

[7]Note that the appeal and possibility of "circular carbon" is not exclusive to BECCUS. It is present in visions of other proposed negative emission technologies as well, most notably Direct Air Capture (see Malm and Carton, 2021).

[8]The prodigious rise of sustainability certification schemes for biofuels and other bio-based commodities are an obvious product of this perspective—the problem is located at the level of particular supply chains, rather than with the internal logic of massive bioenergy expansion *per se*.

unpicking, a damaging set of interconnections forged between industrial production and imperialist plunder in the fossil fuel era. Partly replacing coal, oil and gas with biomass will inevitably reshape global energy geographies, but whether it will *restructure* them—in ways that prevent distant locales from being enrolled as the peripheral resource hinterlands for existing centres of global wealth and power—is another question altogether. In view of these uneven geographies, fully opening up the question of what energy consumption should be for in the coming decades will arguably require a reconfiguration of existing carbon dioxide removal governance processes, to facilitate greater dialogue and more even participation on the part of stakeholders and citizens in both high energy consuming and low energy consuming regions.

Amid the growing clamour to pursue large-scale negative emissions systems as a means of meeting net-zero GHG emissions targets in contexts like the UK, there is a danger associated with developing governance processes and institutions focused solely on comparing the technical "performance" and on-the-ground social and environmental consequences of various forms of carbon dioxide removal. It would be a missed opportunity to pursue carbon dioxide removal without explicit societal deliberation about the range of alternative energy futures that are possible in a post-fossil fuel era. A key role for CDR governance should be to enable these kinds of choices. In short, if ongoing CDR efforts are to be successful, they will need to achieve the removal of emissions of carbon dioxide in two senses—not only physically, from the global atmosphere, but also politically, from their position as principal (if not sole) indicators by which the wider desirability of societal development pathways is determined. Only by recognising large-scale carbon dioxide removal as a project concerned with far more than mere negative emissions—with more even than the issue of climate change itself—can relevant governance processes hope to cultivate genuinely post-fossil *ideas* about what "good" energy use might look like, and indeed about how else societal virtue might be defined, over the course of the remainder of the twenty-first century.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

JP wrote the first draft of the manuscript. JP and WC contributed to manuscript revision, read, and approved the submitted version. Both authors contributed to the article and approved the submitted version.

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REFERENCES

Bellamy, R., Fridahl, M., Lezaun, J., Palmer, J., Rodriguez, E., Lefvert, A., et al. (2021). Incentivising bioenergy with carbon capture and storage responsibly: comparing stakeholder responses in the United Kingdom and Sweden. *Environ. Sci. Policy* 116, 47–55. doi: 10.1016/j.envsci.2020.09.022

Carton, W. (2019). "Fixing" climate change by mortgaging the future: negative emissions, spatiotemporal fixes, and the political economy of delay. *Antipode* 51, 750–769. doi: 10.1111/anti.12532

Chatham House (2020). *Net Zero and Beyond: What Role for Bioenergy With Carbon Capture and Storage?*

Committee on Climate Change (2019). *Net Zero: The UK's Contribution to Stopping Global Warming*.

Cook-Patton, S. C., Leavitt, S. M., Gibbs, D., Harris, N. L., Lister, K., and Anderson-Teixeira, K. J., et al. (2020). Mapping carbon accumulation potential from global natural forest regrowth. *Nature* 585, 545–550. doi: 10.1038/s41586-020-2686-x

Daggett, C. (2019). *The Birth of Energy: Fossil Fuels, Thermodynamics, and the Politics of Work*. Durham, NC: Duke University Press.

Drax Group plc (2018). *What Can Be Made From Captured Carbon*?'. Available online at: https://www.drax.com/technology/can-made-captured-carbon/ (accessed May 28, 2021).

Drax Group plc (2019a). *Carbon Dioxide Now Being Captured in First of its Kind BECCS Pilot*. Available online at: https://www.drax.com/press_release/world-first-co2-beccs-ccus/ (accessed May 28, 2021).

Drax Group plc (2019b). *New Carbon Capture Technology Could Help Industry and Agricultural Sector Decarbonize*. Available online at: https://www.drax.com/press_release/new-carbon-capture-technology-help-industry-agricultural-sector-decarbonise/ (accessed May 28, 2021).

Drax Group plc (2020a). *Negative Emissions Pioneer Drax and Leading Global Carbon Capture Company – Mitsubishi Heavy Industries Group – Announce New BECCS Pilot*. Available online at: https://www.drax.com/press_release/negative-emissions-pioneer-drax-and-leading-global-carbon-capture-company-mitsubishi-heavy-industries-group-announce-new-beccs-pilot/ (accessed May 28, 2021).

Drax Group plc (2020b). *Jobs, Skills, Zero Emissions – The Economic Need for Carbon Capture at Drax*. Available online at: https://www.drax.com/energy-policy/jobs-skills-zero-emissions-the-economic-need-for-carbon-capture-by-drax/ (accessed May 28, 2021).

Drax Group plc (2020c). *UK Tops Global Decarbonization League Amid Renewable Revolution*. Available online at: https://www.drax.com/press_release/uk-tops-global-decarbonisation-league-amid-renewable-revolution/ (accessed May 28, 2021).

Durmaz, T. (2018). The economics of CCS: why have CCS technologies not had an international breakthrough?' *Renew. Sustain. Energy Rev.* 95, 328–340. doi: 10.1016/j.rser.2018.07.007

Ecofys (2017). *Assessing the Potential of CO_2 Utilisation in the UK*. London: Ecofys. Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/799293/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2__1_.pdf

Foulsham, G. (2016). UCLA researchers turn carbon dioxide into sustainable concrete. *UCLA Newsroom*, 14th March (2016). [https://newsroom.ucla.edu/releases/ucla-researchers-turn-carbon-dioxide-into-sustainable-concrete]

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., and Miteva, D. A., et al. (2017). Natural climate solutions. *Proc. Natl. Acad. Sci.* 114, 11645–11650. doi: 10.1073/pnas.1710465114

Hansson, A., Fridahl, M., Anshelm, J., and Haikola, S. (2021). Boundary work and interpretations in the IPCC review process of the role of bioenergy with carbon capture and storage (BECCS) in limiting global warming to 1.5°C. *Front. Clim.* 3:643224. doi: 10.3389/fclim.2021.643224

Hubau, W., Lewis, S., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., and Cuní-Sanchez, A., et al. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* 579, 80–87. doi: 10.1038/s41586-020-2035-0

IPCC (2014). *Climate Change 2014: Mitigation of Climate* Change.

IPCC (2018). *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas EMISSION pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*.

Jiang, Z., Xiao, T., Kuznetsov, V. L., and Edwards, P. P. (2010). Turning carbon dioxide into fuel. *Philos. Trans. R. Soc. A* 368, 3343–3364. doi: 10.1098/rsta.2010.0119

Lenton, T., and Latour, B. (2018). Gaia 2.0. *Science* 361, 1066–1068. doi: 10.1126/science.aau0427

Lohmann, L. (2021). "Bioenergy, thermodynamics and inequalities," in *Bioeconomy and Global Inequalities: Socio-Ecological Perspectives on Biomass Sourcing and Production*, eds M. Backhouse, R. Lehmann, K. Lorenzen, M. Lühmann, J. Puder, F. Rodríguez, and A. Tittor (London: Palgrave MacMillan), 85–103.

Malm, A., and Carton, W. (2021). Seize the means of carbon removal: the political economy of direct air capture. *Hist. Mater.* 29, 3–48. doi: 10.1163/1569206X-29012021

Moomaw, W. R., Masino, S. A., and Faison, E. K. (2019). Intact forests in the United States: proforestation mitigates climate change and serves the greatest good. *Front. Forests Glob. Change* 2, 1–10. doi: 10.3389/ffgc.2019.00027

Obersteiner, M., Azar, C., Möllersten, K., and Riahi, K. (2002). *Biomass Energy, Carbon Removal and Permanent Sequestration – A 'Real Option' for Managing Climate Risk*. International Institute for Applied Systems Analysis Interim Report IR-02–042.

ONS (2019). *A Burning Issue: Biomass is the Biggest Source of Renewable Energy Consumed in the UK*. Office for National Statistics. aVAilable online at: https://www.ons.gov.uk/economy/environmentalaccounts/articles/aburningissuebiomassisthebiggestsourceofrenewableenergyconsumedintheuk/2019-08-30 (accessed May 28, 2021).

Palmer, J. (2021). Putting forests to work? Enrolling vegetal labor in the socioecological fix of bioenergy resource-making. *Ann. Am. Assoc. Geogr.* 111, 141–156. doi: 10.1080/24694452.2020.1749022

Royal Society and Royal Academy of Engineering (2018). *Greenhouse Gas Removal.*

Schlesinger, W. (2018). Are wood pellets a green fuel?' *Science* 359, 1328–1329. doi: 10.1126/science.aat2305

Scott, V., Gilfillan, S., Markusson, N., Chalmers, H., and Haszeldine, R. S. (2013). Last chance for carbon capture and storage. *Nat. Clim. Change* 3, 105–111. doi: 10.1038/nclimate1695

Searchinger, T. D., Beringer, T., Holtsmark, B., Kammen, D. M., Lambin, E. F., Lucht, W., et al. (2018). Europe's renewable energy directive poised to harm global forests. *Nat. Commun.* 9:3741. doi: 10.1038/s41467-018-06175-4

Seidl, R., Schelhaas, M.-J., Rammer, W., and Verkerk, P. J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage. *Nat. Clim. Change* 4, 806–810. doi: 10.1038/nclimate2318

Sieferle, R. P. (2001). *The Subterranean Forest: Energy Systems and the Industrial Revolution*. Cambridge: White Horse Press.

Smith, P., and Porter, J. (2018). Bioenergy in the IPCC assessments. *GCB Bioenergy* 10, 428–431. doi: 10.1111/gcbb.12514

Swyngedouw, E. (2009). The antinomies of the postpolitical city: in search of a democratic politics of environmental production. *Int. J. Urban Reg. Res.* 33, 601–620. doi: 10.1111/j.1468-2427.2009.00859.x

UK DfT (2020). *Renewable Fuel Statistics 2019: Final Report*. UK Department for Transport, London. Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/932933/renewable-fuel-statistics-2019-final-report.pdf

USDA Foreign Agricultural Service (2019). *Global Agricultural Information Network Report: EU Biofuels Annual, 2019*. GAIN Report Number NL9022.

van Ypersele, J.–P. (2021). *It's Time to End Subsidies for Burning Wood From Forests*. Climate Home News. Available online at: https://www.climatechangenews.com/2021/02/11/time-end-subsidies-burning-wood-forests/ (accessed May 28, 2021).

Varinsky, D. (2016). *An Energy Company Just Debuted a Shoe Made From Power Plant Emissions*. Business Insider. Available online at: https://www.businessinsider.in/An-energy-company-just-debuted-a-shoe-made-from-power-plant-emissions/articleshow/54368673.cms (accessed May 28, 2021).

Vivid Economics (2020). *Capturing Carbon at Drax: Delivering Jobs, Clean Growth and Levelling Up the Humber*. Vivid Economics, London. Available online at: https://www.vivideconomics.com/wp-content/uploads/2020/11/Capturing-Carbon-at-Drax-Delivering-Jobs-Clean-Growth-and-Levelling-Up-the-Humber.pdf

Zero Carbon Humber (2019). *Capture for Growth—A Roadmap for the World's First Zero Carbon Industrial Cluster*. Available online at: https://www.drax.com/wp-content/uploads/2019/11/Capture-for-Growth-Zero-Carbon-Humber-V4.9-Digital.pdf (accessed May 28, 2021).

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Integrating Carbon Dioxide Removal Into European Emissions Trading

Wilfried Rickels[1], Alexander Proelß[2], Oliver Geden[3], Julian Burhenne[2] and Mathias Fridahl[4]*

[1] Research Center Global Commons and Climate Policy, Kiel Institute for the World Economy, Kiel, Germany, [2] Chair of International Law of the Sea and International Environmental Law, Public International Law and Public Law, University of Hamburg, Hamburg, Germany, [3] Research Division: EU/Europe, German Institute for International and Security Affairs, Berlin, Germany, [4] Unit of Environmental Change, Department of Thematic Studies, Centre for Climate Science and Policy Research, Linköping University, Linköping, Sweden

In one of the central scenarios for meeting an European Union-wide net zero greenhouse gas (GHG) emissions target by 2050, the emissions cap in the European Union Emissions Trading System (EU ETS) becomes net negative. Despite this ambition, no mechanism allows for the inclusion of CO_2 removal credits (CRCs) in the EU ETS to date. Amending the EU ETS legislation is required to create enabling conditions for a net negative cap. Here, we conceptually discuss various economic, legal, and political challenges surrounding the integration of CRCs into the EU ETS. To analyze cap-and-trade systems encompassing negative emissions, we introduce the effective (elastic) cap resulting from the integration of CRCs in addition to the regulatory (inelastic) cap, the latter now being binding for the net emissions only. Given current cost estimates for BECCS and DACCS, minimum quantities for the use of removals, as opposed to ceilings as currently discussed, would be required to promote the near-term integration of such technologies. Instead of direct interaction between the companies involved in emissions trading and the providers of CRCs, the regulatory authority could also transitionally act as an intermediary by buying CRCs and supplying them in turn conditional upon observed allowances prices, for example, by supporting a (soft) price collar. Contrary to a price collar without dedicated support from CRCs, in this case (net) compliance with the overall cap is maintained. EU legislation already provides safeguards for physical carbon leakage concerning CCS, making Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture and Storage prioritized for inclusion in the EU ETS. Furthermore, a special opportunity might apply for the inclusion of BECCS installations. Repealing the provision that installations exclusively using biomass are not covered by the ETS Directive, combined with freely allocated allowances to these installations, would allow operators of biomass installations to sell allowances made available through the use of BECCS. Achieving GHG neutrality in the EU by 2050 requires designing suitable incentive systems for CO_2 removal, which includes the option to open up EU emissions trading to CRCs.

Keywords: carbon dioxide removal, emissions trading, negative emissions credit, EU climate policy, bioenergy with carbon capture and sequestration, direct air capture

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Beat Hintermann,
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****Correspondence:***
Wilfried Rickels
wilfried.rickels@ifw-kiel.de

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INTRODUCTION

Currently, about 17% of global greenhouse gas (GHG) emissions are covered by emissions trading systems which have either already been implemented or are scheduled for implementation (World Bank, 2020). The EU Emissions Trading System (EU ETS) is one of the largest of its kind worldwide, covering roughly 40% of the EU27's GHG emissions and is considered to be the EU's most important climate policy instrument [EC (European Commission), 2020]. Due to an annual linear reduction factor (LRF) on the number of EU allowances issued (i.e., permits to emit 1 ton (t) of carbon dioxide (CO_2) or an equivalent amount of other greenhouse gases, GHGs), no new allowances will enter the market after a particular point in time. The rules for the 4^{th} trading period agreed upon in 2018 foresaw a LRF of 2.2% p.a. from 2021 onwards [EC (European Commission), 2020], which would result in reaching the zero line sometime after 2057. Recent decisions to strengthen the EU-wide GHG mitigation targets have set a net-zero GHG emissions target for 2050 with a net reduction of 55% between 1990 and 2030. Emissions covered by the ETS are expected to reach net zero by 2045, with substantial net negative levels achieved by 2050 [EC (European Commission), 2018a,b]. The EU Parliament is currently pushing for the inclusion of provisions specifically addressing the need to achieve net negative emissions after 2050, in the context of the EU Climate Law negotiations (European Parliament, 2020, amendment 94). Such scenarios are also part of the European Commission's vision for a climate neutral EU [EC (European Commission), 2018a, p. 7]. Accordingly, the EU faces the 2-fold challenge of organizing its ETS without issuing new allowances, while establishing new rules to guide and integrate CO_2 removal activities, i.e., anthropogenic activities to remove CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products (IPCC, 2018).

There is increasing awareness that CO_2 removal is an essential element for reaching the ambitious long-term temperature goal set out in the Paris Agreement (IPCC, 2018). But there is still little consensus on how measures for removing carbon could be organized and incentivized within climate policy (Torvanger, 2019). Cox and Edwards (2019), Hepburn et al. (2019), and Bellamy and Geden (2019) point out that for various NETs, policies are already in place that provide support because of the co-benefits resulting from their deployment, however, at the same it is also true that interaction with other regulations creates barriers with respect to their deployment. Honegger and Reiner (2018) consider the market mechanism referred to in Article 6.4 of the Paris Agreement as a possible cornerstone in incentivizing the deployment of NETs. However, it is still unclear how the market mechanism in Article 6.4 will be implemented and whether emissions trading involving non-governmental actors will be part of it.

Related to the question of the creation of incentives for deployment, Haszeldine (2016) and Haszeldine et al. (2018) suggest for the case of carbon capture and storage (CCS) from flue gases (i) the introduction of new CO_2 storage credits and (ii) that firms be required to surrender an increasing share of these credits as emissions allowances to provide incentives for commercial CCS by creating a prescribed demand. However, point-source flue-gas CO_2 removal should not be confused with atmospheric CO_2 removal, not least because market incentives for (flue-gas) CCS deployment are already in place, since Article 12(3a) of the ETS Directive of the ETS Directive lifts any obligation to surrender allowances for emissions that are verified as having been captured and transferred to an authorized installation for permanent, geological storage. However, no incentives are provided for the deployment of atmospheric removal and storage of CO_2 (Fridahl et al., 2020).

Since the EU ETS is one of the most important emissions trading systems in the world, any regulatory adjustments to integrate CO_2 removal will significantly influence global emissions trading and policies aimed at a net-zero (or even net negative) emissions future.

COSTS AND PERMANENCE OF NEGATIVE EMISSIONS TECHNOLOGIES

CO_2 removal is achievable through various NETs, which vary considerably in potential and costs, and in the duration and verifiability of storage. **Table 1** provides an overview of commonly discussed NETs [based in particular on Hepburn et al. (2019)], listing estimates about respective annual removal potentials and costs, and an assessment of the duration of storage. Unlike other studies, Hepburn et al. (2019) include the various non-CO_2-revenues, arising for example from electricity generation by BECCS, in their literature review.

Note that **Table 1** only lists the removal pathways discussed in Hepburn et al. (2019) which involve atmospheric CO_2 removal and subsequent storage and neglects for example removal pathways which involve carbon utilization. Furthermore, **Table 1** does not list measures such as ocean iron fertilization or artificial upwelling or a detailed overview about the various options for ocean alkalinity enhancement (see for example Renforth and Henderson, 2018).

Comparing these cost estimates with current EUA allowance prices in the EU ETS which reached about 50 EUR/tCO_2 in May 2021 for the first time, land management, biochar, and forestry techniques would be already competitive, while BECCS and DACCS are not and would require additional remuneration to participate in the market. Yet, while rather engineering-orientated estimates for NETs such as exemplified in **Table 1** are informative, they do not capture price effects which are expected to limit in particular the application of land-based methods nor learning or scale effects of methods. Accordingly, the contribution of different methods to the future mitigation portfolio remains difficult to estimate (Rickels et al., 2019) and is probably ideally discovered in a market-based approach.

The issuance of CRCs in a market-based approach requires that an equivalent amount of carbon has been removed and stored for a sufficient amount of time. As listed in **Table 1**, geological storage can be measurably verified and considered to be stored rather permanently (Alcalde et al., 2018; Hepburn et al., 2019). In contrast, carbon capture relying on biological processes like afforestation or ocean iron fertilization, requires

TABLE 1 | Overview of potential, breakeven cost, duration of storage, and likelihood of release for selected NETs.

Type	Techniques	Removal ($GtCO_2$/yr)	Cost (USD/tCO_2)	Storage	Storage permanence
Biological-based	Forestry techniques	0.5–3.6	−40 to 10	Standing forests and long-lived wood products (decades to centuries)	Low
	Land management	2.3–5.3	−90 to −20	Soil organic carbon (years to decades)	Low
	Biochar[1]	0.3–2.0	−70 to −60	Black carbon (decades to centuries)[a]	Medium[a]
	BECCS	0.5–5.0	60–160	Geological sequestration (millennia)	High
Chemical-based	Enhanced Weathering[2]	2.0–4.0	<200	Aqueous carbonate (centuries)	High
	DACCS[a]	0.5–5.0	200–600[b] 100[c]	Geological sequestration (millennia)	High

[1]*Biochar is manufactured by thermal decomposition in the absence of oxygen (i.e., pyrolysis) of biomass like wood, harvest remnants, green waste, cattle dung, slurry, sewage sludge and biological waste. Biochar is a chemically inert solid which can be used as a soil additive with many potential benefits including storage of biomass carbon in soils (Royal Society and Royal Academy of Engineering, 2018).*

[2]*Enhanced weathering aims at accelerating the breakdown of silicate rocks (e.g., basalt) to chemically remove CO_2 from the atmosphere (Royal Society and Royal Academy of Engineering, 2018).*

Table entries are based on Hepburn et al. (2019), providing information on CO_2 removal in the year 2050 and the breakeven cost in 2015 USD, with (a) based on Royal Society (2018), where current costs (b) are differentiated from (projected) long-term cost (c) (Table 2, p. 67). The assessment of the BECCS storage option from Hepburn et al. has been used also for DACCS. For both BECCS and DACCS, using mineral carbonation would even increase storage and reduce likelihood of leakage.

model-based assessment to determine the amount of carbon removed (Güssow et al., 2010). Furthermore, the carbon storage is in parts only temporary, prone to leakage. Leakage can arise from the emissions of other greenhouse gases (GHG leakage), reduced uptake outside the enhancement area (spatial leakage[1]) and non-permanence (arising from slow temporal physical leakage or oxidization) and also from unintended release due to disturbances like fires, droughts or hurricanes (Royal Society, 2001; Murray et al., 2004; Oschlies et al., 2010; Grassi et al., 2018). Different accounting methods are available to deal with the different characteristics of carbon storage reservoirs, distinguishing for example between permanent and temporary credits whereby the latter need to be replaced at some point in time with "regular" allowances and are therefore in particular suitable for temporary carbon storage (Rickels et al., 2010; Brandão et al., 2019). However, potential limitations regarding the liability with respect to unintended carbon release and model-based determination of actual CO_2 removal amplify the decentralized, and therefore also uncoordinated implementation of certain CO_2 removal methods. Thus, an additional intermediary verification processes or different incentives frameworks would be required[2].

Current proposals and underlying scenarios regarding the integration of NETs into the EU ETS focus in particular on methods with geological carbon storage, i.e. BECCS and DACCS [EC (European Commission), 2018b; Capros et al., 2019], where verification and accounting of permanent carbon storage appears realistic. In addition, and although CCS deployment did not emerge during the second and third EU ETS trading phases (Scott and Geden, 2018), EU regulation is already set up for dealing with physical leakage from geological storage of CO_2 captured at installations covered by the EU ETS.

The CCS Directive (EU, 2009a) prescribes permit procedures, monitoring requirements, and storage closure and post-closure obligations that must be respected by storage operators as well as EU Member States. According to Article 12(3a) of the ETS Directive, CO_2 captured at installations covered by the EU ETS and stored geologically should be considered not emitted. Even though the ETS Directive does not expressly state so, in cases where physical leakage of CO_2 is detected at a storage site, the leakage must be compensated for by surrendering a corresponding amount of EU ETS allowances[3]. This results from the fact that the obligation to surrender allowances under the ETS Directive is waived only in situations where emissions are verified as captured and transported for permanent storage to a facility for which a permit is in force under the CCS Directive[4]. Since the CCS Directive does not differentiate biogenic CO_2 from fossil CO_2, no amendments are required for the CCS Directive to appropriately deal with physical leakages from BECCS or DACCS, were these technologies to be included in the scope of the EU ETS and allowed to generate CRCs.

[1]This should not be confused with international carbon leakage which also involves spatial carbon leakage but describes a situation where carbon emissions increase outside a carbon pricing regime (like the EU ETS) in nonparticipating countries through, for example, the relocation of CO_2-intensive production (e.g., Eichner and Pethig, 2011).

[2]For example, regional ecosystem-based CO_2 removal projects could be awarded via tender calls where minimum requirements are listed to achieve a certain amount of allowances.

[3]See also Recital 30 of the CCS Directive, stating that "liability for climate damage as a result of leakages is covered by the inclusion of storage sites in Directive 2003/87/EC, which requires surrender of emissions trading allowances for any leaked emissions." See also Articles 11(4) and 17(4) of the CCS Directive.

[4]In case an operator does not surrender the required amount of EU ETS allowances, liability for the payment of an excess emissions penalty under Article 16 of the ETS Directive applies.

Thus, considering that the carbon storage of BECCS and DACCS is rather permanent, and because EU legislation already provides safeguards in case of physical leakage, the initial analysis of these technologies' potential for negative emissions trading in the EU ETS appears appropriate. Further developments regarding the accounting of carbon storage in building materials or long-lived chemicals accompanied with a corresponding extension of the CCS Directive to also include non-injected but permanent carbon storage warrant the investigation of further CO_2 removal methods[5]. In response to the European Commission's proposal for a European Climate Law, several EU Member States, Denmark, Sweden, and the Netherlands, supported by Norway, have expressed an openness toward including BECCS and DACCS in the EU ETS (KEF, 2020). In addition, as further elaborated upon in section "Legal Considerations on the Inclusion of Negative Emissions into the EU ETS", the land use, land use change and forestry (LULUCF) regulation (EU, 2018b) explicitly exempts any activity falling within the scope of the LULUCF Regulation from the EU ETS and only allows direct flexibility between the LULUCF and the non-trading sector, not between the LULUCF and the ETS (Böttcher et al., 2019).

This is reflected in the scenarios underlying the new long-term EU climate strategy on how to achieve net zero GHG emissions by the mid-century [*1.5LIFE* and *1.5TECH*, see EC (European Commission), 2018a,b]. These scenarios do not only include CCS applied to point-source emissions of fossil CO_2 in industry but also options to remove CO_2 from the atmosphere, mainly afforestation, BECCS and DACCS. CCS, BECCS and DACCS are modeled to capture 281–606 $MtCO_2$ of which 80–298 $MtCO_2$ is stored underground and 201–307 $MtCO_2$ is used in production of synthetic fuels and materials [EC (European Commission), 2018b, Figures 89 and 90]. These measures are designed to: (i) compensate for residual emissions that are very costly to be completely eliminated, such as in agriculture, the steel and cement industry, and aviation [EC (European Commission), 2018b; IPCC, 2018; Luderer et al., 2018; Capros et al., 2019], and (ii) achieve net negative emissions. The *1.5TECH* scenario foresees the entire EU ETS becoming net negative (−50 $MtCO_2$ in 2050), i.e., generating more CRCs than can be used for offsetting positive emissions [EC (European Commission), 2018b, Table 9, p. 198].

ECONOMIC CONSIDERATIONS FOR NEGATIVE EMISSIONS IN CAP-AND-TRADE SYSTEMS

From an economic point of view, we can distinguish between the cap (i.e., the total amount of allowances) defined by the regulatory authority and the effective cap resulting from the CRC supply curve, the latter being described by the NETs marginal cost curve. The regulatory (inelastic) cap applies to the net emissions, the effective (elastic) cap applies to the gross emissions. This is illustrated in **Figure 1** for a stylized, deterministic, and static cost minimization problem with a regulatory cap on (net) emissions, with a quadratic aggregated abatement cost curve to realize emissions reductions and a linear-quadratic aggregated NETs cost curve to realize CO_2 removals (both implying linear marginal cost curves, albeit with a positive intercept in the latter), assuming that market participants are price takers[6].

In case the marginal abatement cost curve intersects with the CRC supply curve (**Figure 1A**), the amount of gross emissions increases compared to the situation with no supply of CRCs. Naturally, in case NETs are not competitive with emissions reductions via abatement, gross emissions remain unchanged (**Figure 1B**). In both cases, the regulatory cap applying to net emissions remains unchanged. However, it is possible to adjust the regulatory cap by reducing allowance supply in accordance with CRC supply. With complete adjustment, the amount of gross emissions remains unchanged compared to the situation with no CRCs integration. The amount of net emissions and the cap decreases in parallel, to the extent that CRC supply via NETs becomes competitive (**Figure 1C**). Integrating competitive CRC supply without adjusting the regulatory cap (**Figure 1A**) implies that the reduction target, i.e., the cap, is achieved at a lower cost. CRC integration combined with a proportionate adjustment of the regulatory cap (**Figure 1C**) implies that a more ambitious emissions reduction target (lower cap) is achieved with an unchanged allowance price. Such CRC integration and cap adjustment leads to higher ambition but also overall higher cost. However, overall costs are lower than if the lower cap had to be reached through emissions reductions only[7]. Naturally, if the emissions trading system is supposed to comply with a negative regulatory cap, integration of CRC is required since gross emissions can only be reduced to zero. Still, not only with a negative but also with a zero-emissions cap, the CRC supply curve needs to intersect with the marginal abatement cost curve in the positive domain of the x-axes (i.e., at a point with positive gross emissions), otherwise sustaining an emissions trading system would be impossible. In addition, a negative

[5]Note that European Commission assesses biochar, ocean fertilization, enhanced weathering and ocean alkalinisation to be still rather uncertain regarding their effectiveness and scalability of their CO_2 absorption and storage potential and points out that with respect to these technologies "[f]urther research and large-scale field testing is needed to increase the understanding of the overall effects on CO_2 storage, the associated costs and other environmental impacts." (EC (European Commission), 2018b, p. 190).

[6]It should be noted that depending on the slope of the NETs cost curve, the implication of technological innovations for emissions abatement become more similar to the situation with a carbon emissions tax. In the case of a linear NETs cost curve (and constant marginal cost curve), an innovation in abatement technologies would result in a substitution of negative emissions without any price reaction (as long as the new equilibrium point still intersects with the horizontal part of the effective cap in the positive domain of the x-axes, i.e. for a net-zero or positive cap). Compare with Requate and Unold (2003) with respect to innovation adoption under taxes versus emissions trading for the situation without NETs.

[7]In a cap-and-trade system (i.e., a cost-effectiveness framework), integrating CRC supply to achieve a lower cap would only be considered beneficial if the cap has previously been set non-optimally. However, in actual implemented cap-and-trade systems, like the EU ETS, the determined caps are the outcome of a political bargaining process—lower compliance cost are likely to be considered in favor of setting a more ambitious cap to have lower damage costs (Meckling, 2015; Markard and Rosenbloom, 2020).

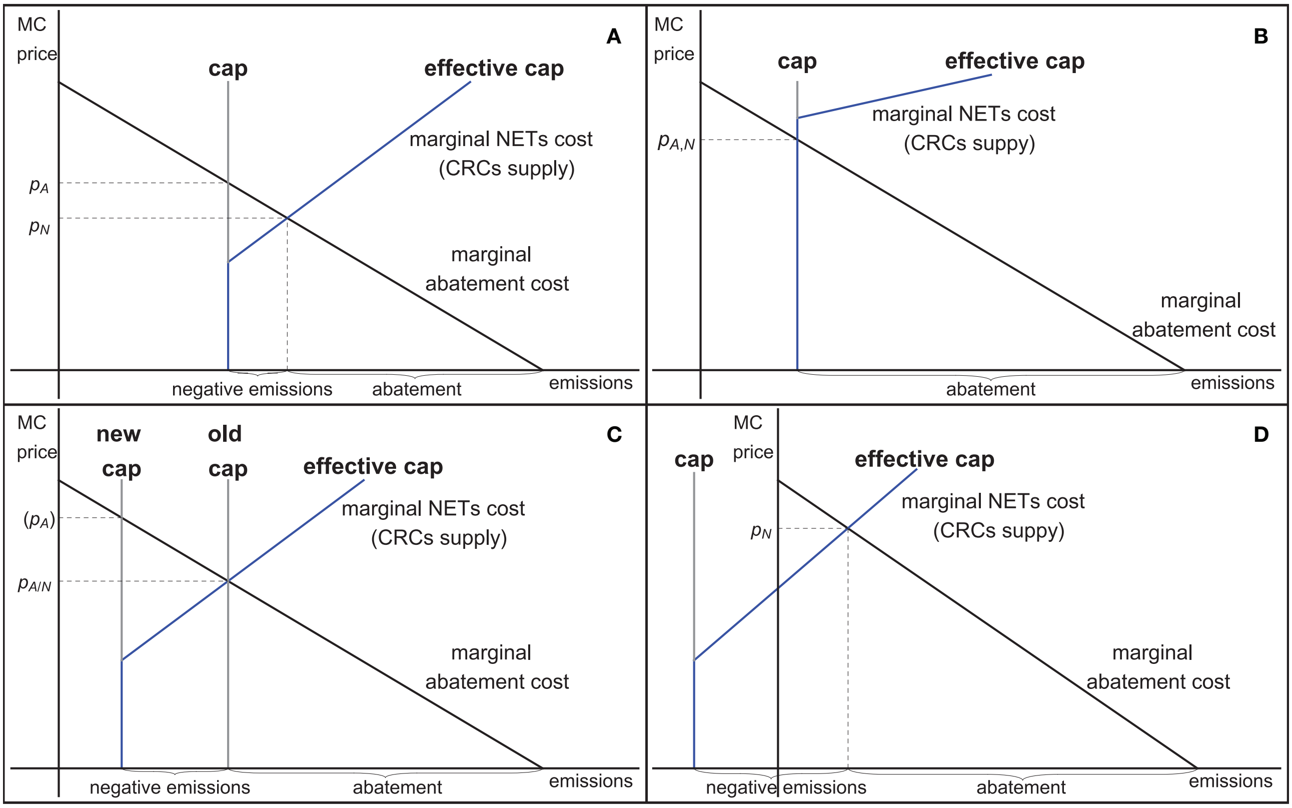

FIGURE 1 | Integration of CO_2 removal credits from Negative Emissions Technologies. Panel **(A)** shows the integration of competitive NETs without adjusting the regulatory cap and p_A and p_N indicate the prices observed with emissions reductions via abatement only and with negative emissions integrated, respectively, **(B)** shows the integration of non-competitive NETs, **(C)** shows the integration of competitive NETs with adjusting the regulatory cap such that the allowance price remains unchanged, and **(D)** shows the integration of NETs for a negative cap.

regulatory cap requires that CRCs are demanded in excess of gross emissions, implying that either there is additional demand by the regulatory authority or a fewer than one exchange rate between CRCs and allowances (**Figure 1D**). Note that these considerations also apply to the case of integrating international offsets which are generated in exchange for verified emissions reductions abroad—except that in the situation of a negative cap in the domestic ETS global emissions are required to be net positive.

Proposals calling for the progressive integration of NETs through the instauration of a minimum target for emissions reduction (or equivalently a maximum target for CRCs) have entered the discussion about the long-term EU climate policy strategy (Geden et al., 2019; McLaren et al., 2019; Geden and Schenuit, 2020). In the context of carbon pricing via emissions trading, imposing quantity constraints implies that only coincidentally marginal costs would be equated, so that efficiency is lost in comparison with a situation where full integration occurs. The introduction of ceilings for CRC supply is primarily motivated by the political feasibility of addressing the concern that full integration could lead to extensive substitution of conventional emissions reductions, which is also considered to negatively affect public acceptance of NETs deployment (Cox et al., 2020). Such a situation could arise under full integration of CRCs from afforestation or land and forest management, where Hepburn et al. (2019) estimate low or even negative break-even costs (see **Table 1**). As exposed in section "Costs and Permanence of Negative Emissions Technologies", there are strong grounds for focusing on BECCS and DACCS in discussions on integrating NETs for direct trading into the EU ETS. When comparing the current and projected EUA allowances prices with the estimated costs of BECCS and DACCS "section Cost and Permanence of Negative Emissions Technologies" (see **Table 1**), it seems more likely that a situation as displayed in Figure 2b would prevail, at least until the end of the 4th trading period in 2030 for DACCS. Consequently, there would be no utilization of DACCS or BECCS and thus no substitution of conventional emissions reductions under the current cap. This entails that minimum quantities, as opposed to ceilings, would be required for CRC demand in case the integration of NETs should be supported. In such a scenario, market participants would bear the additional costs of integration and thus of technology development. Alternatively, additional instruments would be required to cover the price difference between CRCs and traditional allowances, until the former becomes competitive. The existence of positive R&D externalities resulting from technology spillovers, or capital market restrictions with respect to new technologies, could warrant covering the price difference (or providing lump-sum market entry support) (Jaffe et al., 2005; Antoniou and Strausz, 2017; Kempa and Moslener, 2017).

Instead of covering the difference between the allowance market price and the price for CRCs from NETs, the regulatory authority could also act as an intermediary by buying CRCs from NETs suppliers for example via a technology-specific tender system. In turn the regulatory authority could sell them on the allowance markets in dependence on observed prices or traded volumes, either rule-based to support an allowance price collar or discretionary to support an allowance price target (Pizer, 2002). In contrast to a price target or price collar without support from CRCs via NETs, compliance with the overall cap would be achieved, and the net emissions do not change for the situation where the maximum price becomes binding. Such an approach is appealing because both uncertainties about abatement and damage costs, favor an endogenous emissions cap and a combination of price- and quantity control: adjusting the emissions caps allows aiming at the more ambitious target in the case of abatement cost being lower than expected, without fully passing uncertainty about abatement costs to consumers and companies (Hoel and Karp, 2002; Newell and Pizer, 2003). Such a situation might arise in the EU ETS in response to a further shortage of allowances resulting from a reduction of the cap in line with the new 2030 mitigation targets, reducing at the same time the requirement for CRC subsidies as allowance prices would increase. Up-front procurement of CRCs by the regulatory authority to not only realize economics of scale effects in NETs but to support some kind of maximum price mechanism would allow that net emissions comply with the reduction target. The involved budgetary risk is rather low since the linear marginal abatement cost curves in **Figure 1** serves for illustration purposes only and a more realistic description would probably show an asymptotic approach toward the y-axes. The latter implies that the maximum price to be stabilized by selling CRCs could be set such that up-front procurement costs are covered. Furthermore, with a public intermediary, the requirements for permanence and liability of storage would be lower if CRCs are kept in stock to respond to such situations of non-permanence, allowing to consider a broader set of possible NETs.

While the organization of the integration of CRC supply from NETs into the EU ETS is still an open question, current and past regulations in the EU ETS provide some guidance for further analysis. As mentioned above, guidance can be obtained from the integration of credits from the flexible mechanisms of the Kyoto Protocol, which could be used until the end of Phase III (2013–2020) (Hintermann and Gronwald, 2019). Such an eventuality is particularly interesting in the light of an international market for CO_2 removals analogous to the market for Kyoto offsets. A CRC market could develop in the course of increasing numbers of announcements of national net-zero or even net negative emissions targets, e.g., by the US, China, Japan or South Korea. The use of international credits from the flexible mechanism of the Kyoto Protocol was restricted through quantitative and qualitative constraints, implying that only a maximum of such credits could be used by market participants. Credits arising from afforestation and reforestation projects (LULUCF) were not permitted. Quantity limitations could be combined with a sectoral limitation on the use of CRCs. One possibility would be to restrict the use or allocation of (limited) CRCs for internationally competing sectors or for activities associated with high residual emissions. A similar one-way connection system already exists in the EU ETS for aviation. Flight operators can use both special (European Union Aviation Allowances, EUAAs) and conventional allowances, while other sectors are not allowed to use EUAAs. A comparable construction is conceivable for companies under international competition, currently still receiving (increasingly restricted) allowances free of charge. The corresponding distributional effects would depend on how the allocation of these allowances is organized and how the market price reacts (Hintermann and Gronwald, 2019). With respect to a rule-based quantity control (endogenous cap), experiences with the Market Stability Reserve provide guidance (e.g., Fell, 2016; Perino, 2018). CRCs from NETs could be used to feed a credit reserve (similar to the current Market Stability Reserve) releasing additional credits into the market in line with observed prices or volumes. However, these conceptual considerations provide a first collection of issues to be discussed in the context of negative emissions trading. Further research is required to analyze the various design options in more detail and in a dynamic setting, accounting for uncertainty in abatement and removal cost.

LEGAL CONSIDERATIONS ON THE INCLUSION OF NEGATIVE EMISSIONS INTO THE EU ETS

As far as European legal requirements are concerned, biological-based CO_2 removal approaches are presently excluded from the EU ETS if they fall within the scope of the LULUCF Regulation (EU, 2018b). This applies to forestry techniques and land management in the LULUCF sector. Based on the assumption that CO_2 removal and storage is here reversible and subject to greater fluctuations and inaccuracies (see **Table 1**), these sectors were designated by the European legislator as an independent pillar of European climate change mitigation policy. That said, the sectors covered by the LULUCF Regulation may, to a limited extent, be included into the scope of another legislative act of the EU, namely the Effort Sharing Regulation (EU, 2018c). This Regulation sets binding annual emissions targets for Member States for the periods 2013–2020 and 2021–2030 for sectors that are not covered by the ETS Directive. Under the conditions specified in Article 7 (1), the Effort Sharing Regulation allows Member States to account for net withdrawals from LULUCF when calculating the achievement of their individual emissions targets, but only to a maximum total (i.e., EU-wide) extent of 280 $MtCO_{2equiv}$ [cf. Article 7 and Article 9 (2) of the current Effort Sharing Regulation].

Insofar as NETs are not covered by the LULUCF Regulation, only installations which provide for the capture and transport of CO_2 for subsequent storage are presently included in the EU ETS. This inclusion only applies, however, with regard to the obligation to hold allowances for CO_2 emissions and to surrender them accordingly. In other words, there is no obligation to surrender allowances for emissions which have been captured and transferred to an authorized installation for permanent storage. This explicitly follows from Article 12(3a) of the ETS Directive (EU, 2003, 2018a). In contrast, the ETS Directive in its present form does not provide for the generation of *additional* allowances through the removal of CO_2. This would be contrary to the basic concept of the ETS Directive expressed in its Article 2(1), according to which the applicability of the EU ETS requires the existence of "positive" emissions. The current EU ETS thus only provides an incentive that CO_2 does not enter the atmosphere since it does not have to be offset by corresponding allowances. It is based on the coupling of emitting installations with mitigation and avoidance strategies but does not permit for the additional or separate integration of installations that remove CO_2 from the atmosphere.

Against this background, the question arises whether the current regime of the ETS Directive contains clauses on the basis of which NETs could be included into the EU ETS in the future. At first sight, relying on Article 24 of the ETS Directive, which entitles the Member States to extend trading in emissions allowances from 2008 onwards to activities *not* listed in Annex I of the ETS Directive (note again, though, that CCS is already listed), could seem obvious. On closer examination, however, it becomes apparent that Article 24 of the ETS Directive does not allow for deviating from the general regime of the ETS Directive and, in particular, the direct nexus between emitting activities on the one hand and the use of emissions-reducing technologies on the other on which it is based.

While BECCS activities are indeed characterized by the existence of the necessary link between emissions, capture and storage, they can equally not be taken into account in the context of the EU ETS in its present form due to the fact that according to No. 1 of Annex I of the ETS Directive, installations using exclusively biomass are not covered by the ETS Directive. Strictly speaking, BECCS installations are *not* "not listed in Annex I" in terms of Article 24(1) of the ETS Directive, but rather expressly excluded from the scope of the Directive. Thus, if that provision were to be repealed, the installations concerned would in principle fall within the scope of the ETS Directive, without the need to make use of the option provided for in Article 24 of the ETS Directive.

Prima facie, an alternative way to establish that CRCs could be issued for BECCS installations (without including it into the EU ETS, though) would be to rely on Article 24a, which was included into the ETS Directive in 2009 (EU, 2009b). This provision authorizes the European Commission to "adopt measures for issuing allowances or credits in respect of projects administered by Member States that reduce greenhouse gas emissions not covered by the EU ETS." In light of the general approach on which the ETS Directive is based, the competence of the European Commission only concerns projects aiming for a reduction of existing emissions, i.e., activities which emit CO_2 themselves. The fact that No. 1 of Annex I of the ETS Directive excludes installations using biomass exclusively from the scope of the ETS Directive does not render Article 24a ETS Directive inapplicable vis-à-vis BECCS, as this provision is, according to its wording, applicable to "projects administered by Member States that reduce greenhouse gas emissions *not covered by the EU ETS*." The phrase "not covered by the EU ETS" should be interpreted substantively (i.e., referring to the activities themselves) and not spatially (meaning that Article 24a of the ETS Directive would only cover projects that are conducted on the territory of non-EU Member States). This results from the fact that Article 24a of the ETS Directive only applies to domestic (i.e., intra-EU) activities.

Even if this can only be inferred indirectly from the wording of this provision, it must be born in mind, however, that Article 24a of the ETS Directive does not address the possibility to integrate the mentioned activities into the EU ETS, but rather provides the legislative basis for establishing an *autonomous offsetting mechanism* under EU law (Joosten et al., 2016, p. 82). On the one hand, Article 24a of the ETS Directive is only applicable, according to its wording, "in addition to the inclusions provided for in Article 24," and the measures concerned "shall only be adopted where inclusion is not possible in accordance with Article 24," the latter provision—in contrast to Article 24a of the ETS Directive—rendering possible the inclusion of activities and to greenhouse gases not listed in Annex I *specifically into the EU ETS*. On the other hand, Article 24a of the ETS Directive refers to "measures for issuing allowances or credits" instead of "emissions allowance trading" used in the context of the EU ETS—a fact that further demonstrates that the object and purpose of Article 24a of the ETS Directive is to make possible the establishment of a separate offsetting regime outside of (even though based on) the regime of the ETS Directive. In all that, it should be noted that the decision power under Article 24a of the ETS Directive has not yet been activated, i.e., no separate offsetting regime has yet been created. Taking further into account that such activation can only be envisaged "where inclusion is not possible in accordance with Article 24," the relevance of Article 24a of the ETS Directive for BECSS remains highly questionable.

Thus, the ETS Directive in its present form does not contain any opening clauses on the basis of which independent allowances could be generated under the EU ETS by removing CO_2 from the atmosphere and offered for sale. Any integration of NETs into the EU ETS regime would require a fundamental amendment of the ETS Directive, which would waive the mandatory link between emitting activities on the one hand and the use of emissions-reducing technologies on the other. Still, a special situation is given for BECCS since the operation of installations exclusively using biomass involves an emitting activity that can be combined with CCS to prevent the emissions from entering the atmosphere. In case reference to biomass installations in No. 1 of Annex I to the ETS Directive would be repealed, implying in turn that operators are required to surrender allowances for their biogenic CO_2 emissions, it would be possible to consider biomass installations in the free allocation of allowances (to the extent that they use biomass accounted for in the EU LULUFC sector, i.e., implying that emissions from imported biomass would not qualify as basis for freely allocated allowances). If allowances were freely allocated to biomass installations, these allowances could be sold by using BECCS instead of surrendered for emissions. As such, biomass installations would implicitly receive allowances for the removal of CO_2 from the atmosphere. Note that there would be less removal allowances (being implicit equivalent to CRCs) than freely allocated allowances to BECCS operators since CCS currently does not operate at capture rates of 100 percent (Rosa et al., 2021). If No. 1 of Annex I of the ETS Directive were to be repealed [and Arts. 38 and 39 of Regulation 2018/2066 (EU, 2018d) be adjusted correspondingly] in order to make it possible to incentivize BECCS through the ETS, the LULUCF Regulation should be amended by including a clarification such that emissions associated with biomass transferred to facilities covered by the ETS should not be accounted for in the LULUCF sector as emissions. These emissions would now instead be accounted for within the scope of the EU ETS. In order to keep the overall emissions target (across all sectors) unchanged, allowances allocated to the operators of biomass installations would need to be additional to the allowance stock under the given cap. However, as explained in the section "Economic Considerations for Negative Emissions in Cap-and-Trade Systems", introducing CRCs could go along with reducing the cap in the EU ETS, which would imply that allowance allocation to biomass installations would be realized by allowances from the current allowance stock (i.e., so far unused allowances).

THE WAY FORWARD

The integration of CRC supply into the EU ETS provides the option of achieving more ambitious net emissions reduction targets. First, repurposing so far unused allowances from the overall allowance pool to assign CRCs (or adjusting the unused allowance pool correspondingly) would imply that cumulative net emissions would be reduced. Second, the integration of CRCs indexed to the observed prices and quantities, allows for achieving a reduction in cumulative emissions in the case where the emissions reduction cost reveals to be lower than expected. Up-front procurement of CRCs by the regulatory authority would not only realize economics of scale effects in NETs but could also serve to support some kind of maximum price mechanism while ensuring that net emissions comply with the reduction target. Such a constellation might be relevant for the expected further reduction of the emissions cap in the EU ETS in line with the new 2030 mitigation target.

The European Commission, national emissions trading authorities that implement the supranational requirements, or a European agency that is yet to be established could take on the role of a regulatory authority, in charge of assessing the various options for integrating CRCs. From the point of view of subsidiarity and for the sake of coherence with the existing emissions trading system, the inclusion of the national emissions trading authorities would be preferable. However, any integration of CO_2 removal into the EU ETS regime requires a fundamental amendment of the ETS Directive, which would waive the mandatory link between emitting activities on the one hand and the use of emissions-reducing technologies on the other.

A special situation might arise in the context of BECCS installations. Repealing the provision that installations using biomass exclusively are not covered by the ETS Directive would imply, if combined with freely allocated allowances to these operators, that these operators could sell allowances made available through the use of CCS. This would mean that BECCS operators would receive implicit allowances for the removal of CO_2 from the atmosphere. Obviously, this requires that biomass harvest for bioenergy use is no longer accounted for as a debit in the LULUCF sector. However, with respect to the long-term target of achieving a net-zero and then net-negative EU ETS it seems advisable to adjust the EU ETS Directive more generally such that other CO_2 removal methods like DACCS without the link to emissions activity can be included as well.

It appears obvious to focus initially on BECCS and DACCS as potential candidates for decentralized provision of CRCs to be included in the EU ETS (i.e., for direct trade between market participants without a public intermediary). These technologies allow for the verification of removal, provide permanent storage and the current EU legislation provides already safeguards in case of physical leakage. However, developments regarding the accounting of carbon storage in building materials or long-lived chemicals warrant the investigation of further CO_2 removal methods for inclusion in the EU ETS.

So far, there is no clear timetable for any adaptation or modification of the existing EU ETS that would allow the integration of CO_2 removal. In view of the complexity of including CRCs into the EU ETS, with the large number of possible regulatory approaches available, the first preparatory steps need to be taken promptly. Still, decisions about the integration of CRCs will be embedded in the overall revisions of the EU ETS and relate to issues surrounding the adjustment of the cap, the reduction of free allocation of allowances, the possible introduction of a CO_2-border tax adjustment, and possible new coalitions of countries and regions (climate clubs) with linked emissions trading systems. The latter might involve import of CRCs from other trading systems, depending on the international development with respect to the inclusion of CO_2 removals into climate policy. The first global stocktake, to be carried out under the Paris Agreement in 2023, is expected to clarify the insufficiency of taken and proposed actions in meeting the Paris temperature targets so far, increasing the political momentum to rise ambition in terms of net emissions reductions.

At the same time, the revision of the EU ETS cap to comply with the new 2030 target will further increase the allowance price levels—increasing in turn incentives for (industrial) CCS deployment. This will be accompanied by learning and economies of scale effects in CCS which in combination with the development of a CO_2-transport infrastructure will increase the competitiveness of BECCS and DACCS. Initial inclusion of CRCs from these technologies could take place during a pilot phase in the second half of Phase IV, allowing to achieve an even more ambitious 2030 cap in terms of net emissions. An example for an emerging coalition of national governments is the call by Denmark, Sweden, Norway and the Netherlands to develop EU policy incentives for the promotion of BECCS and DACCS (KEF, 2020). An example of industry cooperation is provided by the memorandums of understanding on CCS signed between Equinor and several companies in northern and western Europe (Equinor, 2020).

Irrespective of these considerations, it is hardly foreseeable how the individual NETs will develop in terms of technology and costs, and it is currently impossible to predict how and at what speed the transition to a targeted CO_2 removal policy will take place. However, there is no doubt that in order to achieve the EU goal of greenhouse gas neutrality by 2050, and net negative emissions thereafter, it will be essential to design suitable incentive systems for CO_2 removal and to open up the most important climate policy instrument—EU emissions trading—to NETs from a regulatory perspective.

AUTHOR CONTRIBUTIONS

WR, OG, and AP had the initial idea for the study and developed the concept together. WR provided the economic analysis. OG and MF provided the policy analysis. AP and JB provided the legal analysis. WR, AP, OG, and MF wrote the manuscript, lead by WR. All authors discussed the results and provided input to the manuscript.

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REFERENCES

Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E., et al. (2018). Estimating geological CO2 storage security to deliver on climate mitigation. *Nat. Commun.* 9:2201. doi: 10.1038/s41467-018-04423-1

Antoniou, F., and Strausz, R. (2017). Feed-in subsidies, taxation, inefficient entry. *Environ. Res. Econ.* 67, 925–940. doi: 10.1007/s10640-016-0012-8

Bellamy, R., and Geden, O. (2019). Govern CO2 removal from the ground up. *Nat. Geosci.* 12, 874–876. doi: 10.1038/s41561-019-0475-7

Böttcher, H., Zell-Zieger, C., Herold, A., and Siemons, A. (2019). *EU LULUCF Regulation Explained: Summary of Core Provisions and Expected Effects.* Berlin: Öko-Institut e.V.

Brandão, M., Kirschbaum, M. U. F., Cowie, A. L., and Hjuler, S. V. (2019), Quantifying the climate change effects of bioenergy systems: Comparison of 15 impact assessment methods. *GCB Bioenergy* 11, 727–743. doi: 10.1111/gcbb.12593

Capros, P., Zazias, G., Evangelopoulou, S., Kannavou, M., Fotiou, T., Siskos, P., et al. (2019). Energy-system modelling of the EU strategy towards climate-neutrality. *Energy Policy* 134:110960. doi: 10.1016/j.enpol.2019.110960

Cox, E., and Edwards, N. R. (2019). Beyond carbon pricing: Policy levers for negative emissions technologies. *Clim. Policy* 19, 1144–1156. doi: 10.1080/14693062.2019.1634509

Cox, E., Spence, E., and Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nat. Clim. Change* 10, 744–749. doi: 10.1038/s41558-020-0823-z

EC (European Commission) (2018a). *A Clean Planet for All: A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*. Brussels: Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, the Committee of the Regions, and the European Investment Bank.

EC (European Commission) (2018b). *In-Depth Analysis in Support of the Commission Communication COM(2018) 773: A Clean Planet for All: A European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and climate Neutral Economy*. Brussels.

EC (European Commission) (2020). *Report From the Commission to the European Parliament and the Council, Report on the functioning of the European Carbon Market.* Brussels.

Eichner, T., and Pethig, R. (2011). Carbon leakage, the green paradox and perfect future markets. *Int. Econ. Rev.* 52, 767–805. doi: 10.1111/j.1468-2354.2011.00649.x

Equinor (2020). *Equinor Collaborates With Microsoft on Northern Lights Carbon Capture and Storage Value Chain*. Available online at: www.equinor.com/en/news/20201014-northern-lights-microsoft.html (accessed January 12, 2020).

EU (2003). *Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading Within the Community and amending Council Directive* (Luxembourg).

EU (2009a). *Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the Geological Storage of Carbon Dioxide and Amending Council Directive 85/337/EEC.* Luxembourg: European Parliament and Council Directives.

EU (2009b). *Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 Amending Directive 2003/87/EC so as to Improve and Extend the Greenhouse Gas Emission Allowance Trading Scheme of the Community* (Luxembourg).

EU (2018a). *Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 Amending Directive 2003/87/EC to Enhance Cost-Effective Emission Reductions and Low-Carbon Investments, and Decision* (Luxembourg).

EU (2018b). *Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the Inclusion of Greenhouse Gas Emissions and Removals From Land Use, Land Use Change and Forestry in the 2030 Climate and Energy Framework, and Amending Regulation* (Luxembourg).

EU (2018c). *Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on Binding Annual Greenhouse Gas Emission Reductions by Member States From 2021 to 2030 Contributing to Climate Action to Meet Commitments Under the Paris Agreement and amending Regulation* (Luxembourg).

EU (2018d). *Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018 on the Monitoring and Reporting of Greenhouse Gas Emissions Pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation* (Luxembourg).

European Parliament (2020). *Amendments adopted by the European Parliament on 8 October 2020 on the proposal for a regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU)* (Brussels: European Climate Law).

Fell, H. (2016). Comparing policies to confront permit over-allocation. *J. Environ. Econ. Manag.* 80, 53–68. doi: 10.1016/j.jeem.2016.01.001

Fridahl, M., Bellamy, R., Hansson, A., and Haikola, S. (2020). Mapping multi-level policy incentives for bioenergy with carbon capture and storage in Sweden. *Front. Clim.* 2, 604787. doi: 10.3389/fclim.2020.604787

Geden, O., Peters, G. P., and Scott, V. (2019). Targeting carbon dioxide removal in the European Union. *Clim. Policy* 19, 487–494. doi: 10.1080/14693062.2018.1536600

Geden, O., and Schenuit, F. (2020). *Unconventional Mitigation: Carbon Dioxide Removal as a New Approach in EU Climate Policy, SWP Research Paper*. Berlin.

Grassi, G., House, J., and Kurz, W. A. (2018). Reconciling global-model estimates and country reporting of anthropogenic forest CO2 sinks. *Nat. Clim. Change* 8, 914–920. doi: 10.1038/s41558-018-0283-x

Güssow, K., Proelß A., Oschlies, A., Rehdanz, K., and Rickels, W. (2010). Ocean iron fertilization. Why further research is necessary. *Marine Policy* 34, 91–1918. doi: 10.1016/j.marpol.2010.01.015

Haszeldine, R. S. (2016). Can CCS and NET enable the continued use of fossil carbon fuels after CoP21? *Oxford Rev. Econ. Policy* 32, 304–322. doi: 10.1093/oxrep/grw013

Haszeldine, R. S., Flude, S., Johnson, G., and Scott, V. (2018). Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. *Philos. Transact. R. Soc. A: Mathe. Phys. Eng. Sci.* 376:20160447. doi: 10.1098/rsta.2016.0447

Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., et al. (2019). The technological and economic prospects for CO_2 utilization and removal. *Nature* 575: 87–97. doi: 10.1038/s41586-019-1681-6

Hintermann, B., and Gronwald, M. (2019). Linking with uncertainty: the relationship between EU ETS pollution permits and Kyoto offsets. *Environ. Res. Econ.* 74, 761–784. doi: 10.1007/s10640-019-00346-7

Hoel, M., and Karp, L. (2002). Taxes versus quotas for a stock pollutant. *Res. Energy Econ.* 24, 367–384. doi: 10.1016/S0928-7655(02)00014-3

Honegger, M., and Reiner, D. (2018). The political economy of negative emissions technologies: Consequences for international policy design. *Clim. Policy* 18, 306–321. doi: 10.1080/14693062.2017.1413322

IPCC (2018). "Global Warming of 1.5°C," in *An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, eds V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla (Geneva).

Jaffe, A. B., Newell, R. G., and Stavins, R. N. (2005). A tale of two market failures: technology and environmental policy. *Ecol. Econ.* 54, 164–174. doi: 10.1016/j.ecolecon.2004.12.027

Joosten, H., Couwenberg, J., von Unger, M., and Emmer, I. (2016). *Peatlands, Forests and the Climate Architecture: Setting Incentives through Markets and Enhanced Accounting, German Environment Agency, Climate Change* (Dessau-Roßlau).

KEF (2020). *Non-Paper on Carbon Capture and Storage (CCS) by the Netherlands.* Norway, Denmark and Sweden, Copenhagen.

Kempa, K., and Moslener, U. (2017). Climate policy with the chequebook - an economic analysis of climate investment support. *Econ. Energy Environ. Policy* 6, 111–129. doi: 10.5547/2160-5890.6.1.kkem

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O. Y., Pietzcker, R. C., Rogelj, J., et al. (2018). Residual fossil CO_2 emissions in 1.5–2°C pathways. *Nat. Clim. Change* 8, 626–633. doi: 10.1038/s41558-018-0198-6

Markard, J., and Rosenbloom, D. (2020). Political conflict and climate policy: the European emissions trading system as a Trojan Horse for the low-carbon transition? *Clim. Policy* 20, 1092–1111. doi: 10.1080/14693062.2020.1763901

McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B., and Markusson, N. O. (2019). Beyond net-zero: a case for separate targets for emissions reduction and negative emissions. *Front. Clim.* 1, 1–5. doi: 10.3389/fclim.2019.00004

Meckling, J. (2015). Oppose, support, or hedge? Distributional effects, regulatory pressure, and business strategy in environmental politics. *Glob. Environ. Polit.* 15, 19–37. doi: 10.1162/GLEP_a_00296

Murray, B. C., McCarl, B. A., and Lee, H. (2004). Estimating leakage from forest carbon sequestration programs. *Land Econ.* 80, 109–124. doi: 10.2307/3147147

Newell, R. G., and Pizer, W. A. (2003). Regulating stock externalities under uncertainty. *J. Environ. Econ. Manage.* 45, 416–432. doi: 10.1016/S0095-0696(02)00016-5

Oschlies, A., Koeve, W., Rickels, W., and Rehdanz, K. (2010). Side effects and accounting aspects of hypothetical large-scale Southern Ocean iron fertilization. *Biogeosciences* 7, 4017–4035. doi: 10.5194/bg-7-4017-2010

Perino, G. (2018). New EU ETS Phase 4 rules temporarily puncture waterbed. *Nat. Clim. Change* 8, 262–264. doi: 10.1038/s41558-018-0120-2

Pizer, W. A. (2002). Combining price and quantity controls to mitigate global climate change. *J. Publ. Econ.* 85, 409–434. doi: 10.1016/S0047-2727(01)00118-9

Renforth, P., and Henderson, G. (2018). Assessing ocean alkalinity for carbon sequestration. *Rev. Geophys.* 55, 636–674. doi: 10.1002/2016RG000533

Requate, T., and Unold, W. (2003). Environmental policy incentives to adopt advanced abatement technology: Will the true ranking please stand up? *Eur. Econ. Rev.* 47, 125–146. doi: 10.1016/S0014-2921(02)00188-5

Rickels, W., Merk, C., Reith, F., Keller, D.P., and Oschlies, A. (2019). (Mis)conceptions about modeling of negative emissions technologies. *Environ. Res. Lett*. 14:104004.

Rickels, W., Rehdanz, K., and Oschlies, A. (2010). Methods for greenhouse gas offset accounting: A case study of ocean iron fertilization. *Ecol. Econ.* 69, 2495–2509. doi: 10.1016/j.ecolecon.2010.07.026

Rosa, L., Sanchez, D. L., and Mazzotti, M. (2021). Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. *Energy Environ. Sci.* 14, 3086-3097. doi: 10.1039/D1EE00642H

Royal Society (2001). *The Role of Land Carbon Sinks in Mitigating Global Climate Change.* London: Royal Society.

Royal Society (2018). *Greenhouse Gas Removal*. London: Royal Society.

Royal Society and Royal Academy of Engineering (2018). *Greenhouse Gas Removal*. London.

Scott, V., and Geden, O. (2018). The challenge of carbon dioxide removal for EU policy-making. *Nat. Energy* 3, 350–352. doi: 10.1038/s41560-018-0124-1

Torvanger, A. (2019). Governance of bioenergy with carbon capture and storage (BECCS): Accounting, rewarding, and the Paris agreement. *Clim. Policy* 19, 329–341. doi: 10.1080/14693062.2018.1509044

World Bank (2020). *State and Trends of Carbon Pricing 2020*. Washington, DC: World Bank.

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Cancel (Out) Emissions? The Envisaged Role of Carbon Dioxide Removal Technologies in Long-Term National Climate Strategies

Alexandra Buylova[1], Mathias Fridahl[2], Naghmeh Nasiritousi[1,3] and Gunilla Reischl[3]*

[1] Department of Political Science, Faculty of Social Sciences, Stockholm University, Stockholm, Sweden, [2] Department of Thematic Studies, Environmental Change, Centre for Climate Science and Policy Research (CSPR), Linköping University, Linköping, Sweden, [3] The Swedish Institute of International Affairs, Stockholm, Sweden

Carbon dioxide removal (CDR) increasingly features in climate scenarios that hold global warming well below 2°C by 2100. Given the continuous gap between climate mitigation pledges and the emission pathways that are aligned with achieving the temperature goals of the Paris Agreement, we would expect countries to promote CDR in their long-term planning to achieve mid-century targets. Yet, countries may not consider it their responsibility to contribute to the global response to climate change using CDR. Thus, a study of the respective country's long-term climate plans is both timely and vital. Such a study could reveal the pledged collective ambition, the contribution of CDR to the pledged ambition, and how the envisaged role of CDR is described by the different countries. This paper explores the long-term low emission development strategies (LT-LEDS) of countries in order to map the role of CDR in addressing climate change. We also supplement our examination of strategies with the opinions of climate experts. Based on an inductive coding of the material and a literature review, the analytical focus of the analysis includes CDR targets and planning, types of CDR, barriers and opportunities to CDR implementation, as well as international cooperation. Our study of 25 national LT-LEDS submitted to the UN or to the EU, as well as 23 interviews with climate experts, shows that national plans for CDR vary substantially across countries and are generally lacking in detail. The findings also demonstrate that CDR is perceived to be necessary and desirable for achieving mid-century climate goals, but also reveal variation in the intended role of CDR. We use an interpretive approach to outline three possible visions of CDR in climate action: as a panacea, as a necessary fallback and as a chimera. We conclude by discussing what our findings of the envisaged roles of CDR in addressing climate change mean for climate governance. This research thereby contributes to the literature on governing CDR with new comprehensive insights into the long-term climate strategies of countries.

Keywords: negative emission technologies, carbon dioxide removal, UN Framework Convention on Climate Change, long-term strategies, carbon removal

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*Miranda Boettcher,
Institute for Advanced Sustainability Studies (IASS), Germany
Alina Brad,
University of Vienna, Austria*

***Correspondence:**
*Alexandra Buylova
alexandra.buylova@statsvet.su.se*

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INTRODUCTION

While the adoption of the Paris Agreement has provided a basis for collective climate action, the world is far from being on track to hold global warming well below 2°C. Current levels of climate ambitions claimed in the Nationally Determined Contributions (NDCs) of countries fall short of the goals of the Paris Agreement (Mace et al., 2021). Collectively, even fully implemented NDCs are projected to increase global emissions from 2015 to 2030 (United Nations Environment Programme, 2020), contrary to the requirements for decarbonization provided by the rapidly shrinking carbon budget (IPCC, 2018). The vast majority of climate scenarios, in which the Paris Agreement temperature target is successfully achieved (even the scenarios assuming global emission reductions by 2030), deploy carbon dioxide removal (CDR) technologies to sequester greenhouse gases from the atmosphere on a massive scale (Anderson, 2015; Fridahl, 2017; IPCC, 2018; Minx et al., 2018; Workman et al., 2020). The scenarios that avoid overshooting the Paris Agreement temperature objective (limiting global warming to below 2°C), and which do not rely on future large-scale deployment of CDR, require global CO_2 emissions to start declining well before 2030 (IPCC, 2018; Kartha et al., 2020). For a more stringent carbon budget associated with a 1.5°C warming, zero emissions would be required by around the end of the 2020s (IPCC, 2018). Thus, there is a growing understanding that the introduction of CDR will be necessary in the future in order to maintain net-zero emissions, as we will otherwise fail to achieve carbon neutrality, whether for technological, economic or political reasons (Geden and Schenuit, 2020).

Assuming that by ratifying the Paris Agreement, countries implicitly agree to follow the IPCC carbon budget for achieving the temperature objective, we would expect countries to promote CDR in their long-term climate strategies, either on par with current greenhouse gas (GHG) mitigation measures or as a forward-looking approach to achieving net-negative emissions. Yet, countries may not consider it their responsibility to contribute to the global response to climate change using CDR technologies and approaches. Given the differences in domestic geographic, economic, and political conditions, it can be expected that countries have various views on the role of CDR in their national contexts.

This article explores the envisaged role of CDR technologies in addressing climate change as described in the long-term climate strategies of countries and by gauging the perceptions of policymakers and experts. Specifically, in order to develop a synthesized view of the envisioned implementation of CDR, we examine the specifications of CDR in the long-term low-emission development strategies (LT-LEDS) submitted to the United Nations Framework Convention on Climate Change (UNFCCC) and in the long-term strategies (LTS) submitted to the European Commission (EU), as well as in interviews with climate experts. LT-LEDS and LTS are intended to highlight national mid-century climate pledges and pathways to their achievement. As a source they reveal insights into collective long-term climate ambitions. Focusing on documents with a long-term perspective is useful as many CDR technologies are still nascent and are therefore quite scarce in shorter term policy documents, such as nationally determined contributions (NDCs) to the Paris Agreement (Thoni et al., 2020; Mace et al., 2021). Thus, it would be expected that CDR would feature more prominently in LT-LEDS and LTS, alongside emission reduction measures. While we expect to find references to CDR in LT-LEDS and LTS, the high-level planning nature of the documents arguably means that we do not expect to find lengthy debates on the potentials and barriers to CDR implementation. Thus, we complement our material with policymaker and expert interviews in order to contextualize our findings and provide a broader view of the role of CDR as perceived by climate experts.

This research focuses on carbon removal methods, including more mature and tried-and-tested nature-based solutions such as the sequestration of carbon in forest biomass and soils, and currently less economically viable and more technologically sophisticated, or technologically-based CDR, such as bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), ocean fertilization, enhanced weathering, biochar, and others (Minx et al., 2018; Fridahl et al., 2020a; Morrow et al., 2020). For the purposes of this research, we rely on "nature-based" and "technologically-based" as a commonly used heuristic to distinguish between CDR approaches (Schenuit et al., 2021). However, we acknowledge the important debates around the analytical clarity of these concepts and the impact of framing them as such. The distinction between what is natural and what is technological is often arbitrary and highly political. While, for example, forestation may be erroneously understood as low tech, modern forestry practice is actually highly technological, from the development of plant species through to harvest. This means that "nature-based" CDR should not necessarily be regarded as a less risky approach. To continue using forestation as an example, large-scale monoculture forestry is likely to have adverse effects on biodiversity and may increase water shortage and reduce food security (McLaren et al., 2019; Bellamy and Osaka, 2020; Carton et al., 2020; Woroniecki et al., 2020). Finally, we expect the main focus on CDR in the strategies and interviews to be on approaches that are not strictly considered to be climate engineering (CE) approaches (e.g., managing the Earth's radiation uptake). While CE methods have entered academic and popular science debates (Caldeira, 2009; Huttunen and Hildén, 2014; Himmelsbach, 2018; Lefale and Anderson, 2018; Low and Schäfer, 2019), alongside or interchangeably with CDR (Bellamy, 2013; Sapinski et al., 2020), and have been in focus in multilateral negotiations broadly aimed at limiting deployment (Bodansky, 2013; Möller, 2020; McLaren and Corry, 2021), solar radiation management is not yet a significant part of domestic policy debates (Reynolds, 2019).

We are only aware of a few studies that have examined CDR in long-term national climate strategies. In a report on CDR governance, Mace et al. (2021) briefly acknowledged the presence of CDR in LT-LEDS. In their effort to align long-term climate plans with NDCs, Falduto and Rocha (2020) conducted an overview of a few LT-LEDS, yet did not go into details about CDR specifications. Jaber et al. (2020) compared the LT-LEDS of France, Germany and the UK using criteria of political commitment, policy coordination, planning, policy effects and monitoring, without reference to CDR. Lastly, Thoni et al. (2020) focused on the CDR feasibility debate in LT-LEDS, finding more frequent manifestations of the technical and biophysical feasibility aspects compared to the socio-cultural dimensions, thereby suggesting a need for more holistic and comprehensive feasibility assessments in the future. They also concluded that CDR appears in most of the strategies analyzed, nature-based carbon sinks being the most popular carbon removal approach. We believe that our work complements their study and expands on it in order to particularly examine the role that CDR is envisaged to play in achieving mid-century climate targets.

This work is also timely as a growing number of countries are committing to more ambitious mid-century climate targets. However, a significant part of how the higher ambition will be accomplished remains unclear and unspecified. LT-LEDS offer enhanced focus to the transparency of climate targets and reveal insights into the global collective long-term climate ambition and plans for its implementation.

Our research is guided by the following questions: (1) What role does CDR play in national plans for achieving mid-century climate targets? (2) What do policymakers and experts think about the potentials and challenges of implementing CDR? While the first question focuses on what countries have communicated to a global audience about their long-term plans for achieving the goals of the Paris Agreement, the second question examines how policymakers and experts more broadly perceive the potentials and challenges of CDR implementation. Together, these two questions provide us with an initial assessment of the envisaged role of CDR in the long-term climate planning of countries and the potentials and challenges relating to CDR implementation.

MATERIALS

The Paris Agreement stipulates that its parties should "strive to formulate and communicate long-term low greenhouse gas emission development strategies [LT-LEDS]" (UNFCCC, 2016: Article 4.19). The Conference of the Parties to the UNFCCC has further encouraged countries to communicate their LT-LEDS to the UNFCCC Secretariat by 2020 to be published on the UNFCCC website (UNFCCC, 2016: Decision 1/CP.16, Section 36). Some countries acted early on this invitation and had already submitted LT-LEDS by 2016, including the USA, Canada and Mexico. Other countries, such as South Africa, Finland and the Republic of Korea, waited until 2020. By the end of 2020, 25 countries had submitted LT-LEDS to the UNFCCC and LTS to the EU in English. As some EU countries produced long-term strategies, but only submitted them to the EU and not to the UNFCCC, we also include these as they are considered to be the EU equivalent to the LT-LEDS submitted to the UNFCCC (Kulovesi and Oberthür, 2020). Countries that submitted strategies both to the UNFCCC and to the EU uploaded identical documents to both organizations. Thus, it was not necessary for us to prioritize. Only English language submissions were considered, which excluded the UNFCCC LT-LEDS submitted by Benin, Spain and Belgium and several EU LTS submissions, such as those from Greece, Hungary and Lithuania. Given our criteria, the only LTS that was submitted to the EU and not to the UNFCCC that we have included was submitted by Estonia. While the low number of submissions means that many high-emitting countries are missing from the analysis, the empirical material still provides an initial and extensive indication of how CDR is envisaged by a range of countries. Notably, six out of seven G7 countries have submitted their strategies and all global regions are covered. The online repositories for all the studied LT-LEDS and the Estonian LTS are listed in the data availability statement.

The different submission dates of the LT-LEDS should be understood in light of the fact that the debate and policy on mid-century climate objectives have progressed rapidly over the last couple of years. Thus, some older LT-LEDS may seem outdated as some countries have subsequently developed new net-zero targets. For example, the UK has issued an amendment to the national Climate Change Act 2008, legislating for a net-zero target by 2050. France has also enshrined a carbon-neutrality goal in national law (Felix, 2019). Other countries, such as Japan, have announced a pledge to achieve carbon neutrality by 2050 (Patel, 2020). It could be that other countries analyzed here have also updated their mid-century targets or discussions are currently underway on a national level. However, the legal status of these potentially renewed commitments is uncertain.

Despite the dynamic climate policy landscape, there are at least two reasons for looking favorably at using LT-LEDS for analyzing how CDR is envisaged in plans for mid-century climate action. First, there is nothing to prevent countries from submitting updated LT-LEDS to the UNFCCC in order to capture policy developments. The UNFCCC website for LT-LEDS continues to be a relevant and highly visible public platform for countries to communicate their mid-century plans to a global audience. In the midst of continuous debates and uncertain policy processes, LT-LEDS may be viewed as the basis of what countries regard as being sufficiently mature plans to be officially communicated. Second, LT-LEDS provide the most comprehensive source of comparable information across countries. As the focus of our analysis is not on the exact details of how CDR will be deployed, but on how CDR is represented in a country's decarbonization strategies, LT-LEDS yield useful empirical material for understanding how the role of CDR is communicated to a global audience.

The LT-LEDS are high-level policy documents and we assume that the envisaged role of CDR in these documents captures the views of national governments on the issue. While we acknowledge that these documents have been drafted by different policy actors such as government agencies and departments, and in consultation with various stakeholders, we view the discussions in the documents as a reflection of the positions of the respective national governments.

In order to gain a broader understanding of the potentials and barriers of CDR implementation, we also conducted interviews with 23 climate experts (academics, policymakers and climate diplomats working at national and international levels on addressing climate change) on their views about CDR. The semi-structured interviews were carried out via Zoom between

April and July 2020. They were recorded, transcribed and anonymized. The interviewees were chosen based on their expertise in climate change policy with the aim of identifying a diversity of backgrounds. Rather than targeting CDR experts from the countries that had submitted LT-LEDS, we aimed to gain extensive insight into how CDR might be perceived by the wider climate policy community as some forms of CDR implementation may depend on international cooperation and agreement. We therefore chose to broaden our search of respondents to also capture the views of climate professionals who might not work directly with CDR issues in order to gain a more inclusive understanding of the perceptions of policy experts in the climate field. Thus, a plurality of perspectives was sought, and while most respondents are from European countries, there is broad representation as the respondents are from across the globe (Australia, Canada, Costa Rica, Denmark, Estonia, Finland, Iceland, India, Ireland, Latvia, The Netherlands, Nigeria, Poland, Seychelles, Sweden, the UK, United Arab Emirates and the USA). Thus, the interview transcripts complement the document analyses by providing insights into how CDR is perceived by climate experts, as the respondents could speak freely and in depth about issues that might not be covered in the LT-LEDS. The interviewees were asked about their views on climate action in general, and the role of CDR in particular. The aim of the interviews was not to generate generalizable results, but rather to contextualize the document analysis and provide an examination of the perceptions of CDR planning and implementation amongst academics, policymakers and climate diplomats.

METHODOLOGY

The objective of this article is to take a synthesizing view on the role of CDR in achieving mid-century climate targets. In order to achieve this, using the joint development of analytical categories via an inductive coding of LT-LEDS and by deducing codes from previous literature on CDR, our study assesses the CDR specifications in LT-LEDS and in the interview material using four elements. In the second stage of our analysis, we try to systematize the discourse and formulate three visions of the role of CDR in climate action that highlight the similarities and differences across the analytical elements (Schenuit et al., 2021).

Inductive Coding

The initial reading of LT-LEDS generated a broad range of categories describing CDR. We took account of the context first, i.e., strategy names, when they were submitted and their purpose as broadly defined in the texts themselves. We recorded information on overall climate targets, separate emission reduction and CDR targets, base year and target year. Several strategies present pathways or scenarios for achieving their climate ambitions, resulting in a range of emission reduction and carbon removal targets or potentials. The LT-LEDS' narratives also include types of CDR methods, their role and purpose, time frame, barriers and opportunities, as well as requirements for implementation. It is important to note the great degree of variation regarding the form and frequency of this information in and across strategies. We then tried to make sense of the level of specificity in planning or committing to CDR implementation. Our original coding included a finely granulated set of categories subsequently aggregated into broader themes such as "target specification and planning." We also attempted to code for CDR policy instruments, e.g., demand-pull and supply-push measures. Unfortunately, the language used to describe policy instruments was too general to arrive at a meaningful distinction between policies related to other technologies or innovations and CDR specifically. We opted to exclude analysis of choice of policy instruments from this study. Overall, the way in which CDR is described in LT-LEDS varies significantly across strategies in terms of language and number of references, while generally lacking analytical clarity. In an attempt to systematize this information, we decided to focus on categories that appeared to be more uniformly and analytically distinct across strategies. These included types of CDR, target specification and planning, barriers and opportunities to implementation and international cooperation. While studying the literature relating to the induced codes, it was used to deduce more refined codes. The process was repeated iteratively, going back and forth between the empirics and previous research, until "code saturation" (Hennink et al., 2017) was achieved. The next section describes how these dimensions appear in the literature, providing additional motivation for their use in understanding the role of CDR in climate action.

Previous Literature: Key Dimensions of CDR in Long-Term Planning

The first key aspect for understanding the envisaged role of CDR in climate action is the type of CDR that policymakers plan to implement for target achievement. Different *types of CDR* have different pros and cons, not least in terms of, for example, potentials, socio-economic, environmental and biophysical impacts, storage stability and maintenance requirements, which involve various uncertainties and risks (Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018; Fridahl et al., 2020a). There is significant variation in the way in which each CDR performs across the dimensions of potentials, impacts, risks, and uncertainties and the performances of CDR also depend on the scale and location of deployment. Thus, it is difficult to precisely state whether betting on a future delivery of each type of CDR would increase the risk of a failure to reach climate targets if CDR is not realized in the future. However, research shows that in terms of technological and market readiness for immediate deployment, methods of forestation and carbon sequestration in soils are more readily available for widespread implementation today than technologically-based CDR. For example, DACCS and BECCS have a larger overall potential for carbon sequestration but are currently still costly (Minx et al., 2018).

In coding for types of CDR, we used concepts from the literature (Fawzy et al., 2020; Geden and Schenuit, 2020) and our own judgment based on descriptions in LT-LEDS. For example, afforestation and reforestation to increase carbon sequestration in standing forests are widely accepted CDR methods. Yet, we also code bioplastics as CDR, motivated by it being described as such in one LT-LEDS. However, the potential for carbon removal via bioplastics is more questionable than via forest biomass. An initial search for CDR in LT-LEDS was based on various search queries using multiple versions of the terms (net) carbon sink, carbon sequestration, carbon removal, carbon capture and storage, negative emissions, carbon stock, absorb, capture and conserve carbon. We did not record carbon capture and storage (CCS) and carbon capture and utilization (CCU) technologies as CDR, unless they were mentioned in conjunction with bioenergy.

The importance of the second category of *target specification and planning* is enhanced when connected to issues of timing. A strategy centered on offsets may involve immediate offsets or offsetting not only in space but also in time. Meadowcroft (2013) argues that "immediate emissions reductions could be delayed" (p. 141) through achieving larger reductions in the future using CDR. According to Anderson and Peters (2016), such strategies represent a moral hazard by speculating on the realization of future CDR, which may or may not be delivered (see e.g., Fuss et al., 2014). Planning to offset contemporary emissions using large volumes of future CDR, instead of prioritizing near-term emission reductions, also heightens the risk of temperature overshoot that may activate tipping points and trigger irreversible climate change (Geden and Löschel, 2017). To avoid mitigation deterrence based on speculating on future CDR, McLaren et al. (2019) argue that policymakers should adopt separate targets for emission reductions and removals. This would serve to maintain pressure on emission-reducing activities, but also make the envisaged scale of CDR explicit. Specifying the scale of the required emission reduction *and* CDR would pave the way for discussions on the necessary policy to be put in place in order to deliver on both types of targets. Current examples of CDR integration into national climate policies reflect these issues (Schenuit et al., 2021). For example, in Australia, New Zealand and the UK, nature-based carbon removal is regarded as the equivalent to emission reduction measures, with no cap on the permissible amount of CDR to reach the overall targets. In contrast, Sweden has set two separate emission reduction and CDR targets on the road to its goal of net-zero emissions by 2040.

The third dimension represents *barriers and opportunities* to CDR implementation. While CDR has the potential to cancel out future emissions, currently much CDR faces a number of uncertainties related to technological developments, economic considerations and public acceptance, meaning they are not a particularly attractive policy choice (Smith et al., 2015; Williamson, 2016; Bui et al., 2018; Fridahl and Lehtveer, 2018; Gough et al., 2018; Bellamy and Geden, 2019; Fridahl et al., 2020b). The moral hazard debate highlights the potential tradeoffs and the positive synergies between CDR and emission reductions, different CDR methods (Levihn et al., 2019; Fridahl et al., 2020b) and between CDR and the sustainable development goals, SDGs (IPCC, 2018, 2019; Honegger et al., 2020). Understanding the nature and likelihood of such tradeoffs or synergies is important when examining the conditions for CDR deployment. For example, the issue of scale needs to be addressed. The IPCC (2019) has concluded that deployment of small-scale, best-practice CDR may contribute to SDG 13 (climate action), while it is unlikely to impact the achievement of other SDGs. However, there is a high risk that large-scale deployment will generate negative synergies. While there are many barriers to and opportunities for CDR implementation that could originate in various sectors of society and be implied by the presence or absence of other factors directly unrelated to CDR, our analysis focuses on barriers and opportunities as explicitly described and related to CDR by the countries themselves, as well as through interviews with climate experts.

Finally, the need for *international cooperation* in order to promote CDR implementation has been raised by several researchers. The Sustainable Development Mechanism (SDM) under Article 6.4 of the Paris Agreement (Honegger and Reiner, 2018) and natural resource and carbon credit sharing between countries (Fajardy and Mac Dowell, 2020) are highlighted as channels for multilateral work in CDR proliferation. The international cooperation category did not appear prominently in the initial, inductive coding of the LT-LEDS. Yet, given the transboundary nature of the climate change issue and the importance of international ties in climate policy efforts, we decided to investigate how this aspect, or lack thereof, is presented in the strategies in relation to CDR.

Thus, based on our literature review, we scrutinized the respective country's long-term climate strategies and interview transcripts by examining how they described types of CDR, target specification and planning, barriers and opportunities to CDR implementation, as well as international cooperation. We used these dimensions to finally map CDR as presented in LT-LEDS and as analytical themes for the interview analysis. We present the results of the content analysis of LT-LEDS and interviews separately in order to answer our two respective research questions. The results of the document and interview analyses were used to identify and discuss what our material reveals about the different understandings of the envisaged role of CDR in addressing climate change. We propose three visions of CDR based on our material: a panacea, a necessary fallback and a chimera, and debate the implications of these envisioned roles of CDR in the discussion and conclusion section.

RESULTS

Mapping of the CDR Specification in LT-LEDS

Targets and Planning

Many countries have pledged to achieve net-zero, carbon (climate) neutrality or close to net-zero emission reduction goals. Technically speaking, carbon neutrality implies net-zero emissions, while climate neutrality implies a broader focus on factors such as changes in albedo (Butler et al., 2015; Fridahl et al., 2020a). Despite their different implications, in practice these terms are often used interchangeably in strict reference to emissions. As with the interpretative flexibility surrounding the phrase "net-zero emissions," there is no definitive agreement on how these targets are put into practice. The content of two net-zero commitments can be dramatically different, aiming for different timelines, covering different kinds of GHG emissions and removals and relying on offsets to varying extents. **Table 1**

TABLE 1 | Overall target and target specification, as described in the most recent LT-LEDS submitted to the UNFCCC and to the EU.

Country	Target	Target year (base year)	Allows CDR to meet the target	Specified separate long-term emission reductions target	Compilation of information on underpinning scenarios for emission reduction, as described in LT-LEDS (excluding CDR, to the extent possible)	Net-negative post-target goal
Austria	Climate neutrality	2050 (1990)	Yes	No	−72 to −84%	No
Canada	−80%	2050 (2005)	Yes	No	−65 to −80%	Yes
Costa Rica	Net-zero	2050 (2012)	Yes	No	Approx. −59%[a]	No
Czech Republic	At least −80%	2050 (1990)	Yes	Unclear	No economy-wide quantifications	No
Denmark	Climate neutrality	2050 (1990)	Yes	No	No economy-wide quantifications	No
Estonia	−80%	2050 (1990)	Yes	No	No economy-wide quantifications	No
Finland	Carbon neutral	2035 (1990)	Yes	Yes (−90% by 2050)	−67 to −81% (incl. BECCS)	Yes
Fiji	Net-zero	2050 (2013–2016)[b]	Yes	No	4.54 to −0.78 $MtCO_2eq$ (incl. LULUCF)[c]	No
France	−75%	2050 (1990)	Yes	No	No economy-wide quantifications	No
Germany	−80 to −95%, aspiring to GHG neutrality	2050 (1990)	No (yes for the GHG neutrality aspiration)	Yes (no CDR)	−80 to −95%	No
Japan	−80%	2050 (2013)	Yes	No	No economy-wide quantifications	No
Latvia	Climate neutrality ±5%	2050 (1990)	Yes	No	−68%	No
Marshall Islands	Net-zero	2050 (2010)	Yes	No	−56 to −87%	No
Mexico	−50%	2050 (2000)	Yes	Unclear[d]	−50%, two pathways	No
The Netherlands	−95%	2050 (1990)	Yes	No	No economy-wide quantifications	No
Norway	−80 to −95%	2050 (1990)	Yes	No	No economy-wide quantifications	No
Portugal	Carbon neutral	2050 (2005)	Yes	No	−85 to −90%	No
Republic of Korea	Carbon neutral	2050 (2017)	Yes	No	No economy-wide quantifications	No
Singapore	33 $MtCO_2$, net-zero thereafter	2050	Yes	No	No economy-wide quantifications	No
Slovakia	Climate neutral	2050 (1990)	Yes	Yes (−90%)	Scenarios will be updated to reflect the −90% by 2050 emission reduction target	No
Sweden	Net-zero	2045 (1990)	Yes	Yes (at least −85%)	−85%	Yes
Ukraine	Qualitative objectives (decarbonization and enhanced sinks)	2050 (1990)	Yes	No	−47 to −69% (energy and industrial processes only)	No
UK	At least −80%	2050 (1990)	Yes	No	−80 to −77% (incl. LULUCF)[e]	No

(Continued)

TABLE 1 | Continued

Country	Target	Target year (base year)	Allows CDR to meet the target	Specified separate long-term emission reductions target	Compilation of information on underpinning scenarios for emission reduction, as described in LT-LEDS (excluding CDR, to the extent possible)	Net-negative post-target goal
USA	At least −80%	2050 (2005)	Yes	No	−70 to −74%[f]	No
South Africa (ZA)	Just transition toward carbon neutrality	2050	Yes	No	212 to 428 $MtCO_2eq$ (unclear if incl. LULUCF)[g]	No

This table has been compiled by the authors based on the information in the LT-LEDS.

[a]*Own calculation based on information in the LT-LEDS: Base year (2011) emissions excl. forest sink: 13.29 MtCO2eq. The so-called "1.5°C scenario" (consistent with the Costa Rican 2050 net-zero target) emissions excl. the forest sink: 5.50 MtCO2eq (p. 25).*

[b]*Fiji uses a range of base years that depends on the availability of reliable data.*

[c]*Percentage reduction from base year emissions unavailable due to the use of a range of base years for different sectors and activities.*

[d]*Mexico's modeling exercise, underpinning the mitigation objective, appears to exclude LULUCF sinks from the −50% by 2050 compared to 2000 target. Whether this should be interpreted to mean that Mexico has excluded LULUCF sinks from its 2050 mitigation objective is unclear.*

[e]*Base year emissions of 803 $MtCO_2eq$, target year emissions of 165 $MtCO_2eq$. Three pathways are explored that deliver on the target. Pathway 1 relies on no negative emissions, i.e., emission reductions of −80%. Pathway 3 relies on negative emission technologies in the power sector resulting in net-negative emissions from this sector (−22 $MtCO_2eq$). Excluding these net-negative emissions, this results in a −77% emission reductions (see pp. 151). It is likely that pathway 3 also includes some positive emissions in the power sector that are offset through BECCS, resulting in net-negative emissions. This means that the deployment of negative emission technologies in the power sector in Pathway 3 exceeds 22 $MtCO_2eq$, an addition which has not been excluded from the estimated lower range of the modeled emission reductions, i.e., not deducted from the −77%.*

[f]*Own calculation based on information in the LT-LEDS: The 2050 target, expressed in absolute terms, equals 1,329 $MtCO_2eq$ (20% of base year, 2005, emissions of 6,644 $MtCO_2eq$). The range of removals then amounts to 399–664 $MtCO_2eq$, resulting in absolute emission reductions (excluding CDR) in the range of 1,728–1,994 $MtCO_2eq$.*

[g]*Percentage reduction from base year emissions unavailable due to lack of a base year. The scenarios can be compared to 2000 and 2015 emission levels: "South Africa's total gross GHG emissions (excluding forestry and other land use) increased by 23% from 439 Mt CO_2-eq in 2000 to 541 Mt CO_2-eq in 2015 […]. Forestry and land use are a CO_2 sink and reduced gross emissions by 5% in 2015. South Africa's net GHG emissions are 512Mt CO_2-eq." (South Africa, p. 12).*

gives a detailed overview of overall targets, emission reduction pledges and CDR presence in climate strategies by country.

The first three columns of **Table 1** summarize how each country has specified its long-term target, including target and base year. The targets are described in several ways, from emission reduction targets relative to a base year, via net-zero targets, to carbon or climate neutrality targets. Targets as well as base years vary dramatically, with the target years ranging from 2035 to 2050. The most commonly applied base year is 1990, but this also varies from 1990 to 2017. Two countries, Singapore and South Africa, do not specify base years since they describe their targets in terms of absolute emissions (Singapore) or as a qualitative development goal (South Africa). Some countries use different base years for different sectors. Already by this stage, before attempting to disentangle which types of CDR will be able to meet the targets, comparability generally becomes lost in the differences between the underlying assumptions.

We found that all strategies are open to using CDR to compensate for residual emissions in order to achieve mid-century targets, be they net-positive emission reductions targets or net-zero (neutrality) targets, and sometimes also when aiming to move toward net-negative emissions in the more distant future. However, the envisaged role of CDR varies considerably across countries. None of the documents explicitly specify separate CDR targets.

Some countries present targets and planning for CDR in non-specific generic terms as a potential or a possibility to be explored in the future, or make statements about the importance of CDR in the process of decarbonization and climate action. This category includes countries such as Czech Republic, Denmark, Estonia, France, Japan, The Netherlands, Norway, Republic of Korea, and Singapore. Examples of qualitative statements from LT-LEDS include the following: "The Government will promote carbon storage in cropland soil [… and] realize innovation to further expand wood use in high-rise buildings in urban area[s] as well" (Japan, p. 64–65); "Carbon sequestration ability will be increased through productive and sustainable forest management, and the carbon stock of forests will be maintained in the longer perspective" (Estonia, p. 4); "Coastal and marine environments are also effective ecosystems in carbon storage and sequestration. Carbon stocks in mangrove ecosystems can be three times or more that of terrestrial forests. In this regard, mangrove restoration projects are being implemented at key conservation sites such as Sungei Buloh Wetland Reserve" (Singapore, p. 78). Regarding technologically-based CDR, Denmark's strategy refers to the carbon storage capacity of the country's subsoil as being up to 500 times the current total annual Danish CO_2 emissions, and estimates that from 2030, 0.9 $MtCO_2$ per year can be sequestered through carbon capture and storage, including BECCS.

The commitment of countries to CDR can also be assumed in more concrete terms from a quantified potential or projection of the amount of emission reduction and removal, either in the form of percentages or in absolute amounts of CO_2e. However, this is often referred to as a potential option rather than a target. Countries in this category include Austria, Canada, Costa Rica, Fiji, Latvia, Marshall Islands, Mexico, Portugal, Ukraine, UK, USA and South Africa (see **Table 1**, column 6). Examples of statements from countries in this category regarding nature-based CDR include the following: "Other land uses, including forests, can significantly increase current sequestration levels to around 11–13 million tons of CO_2" (Portugal, p. 19). "With early and sustained effort, maintaining and enhancing the land carbon sink beyond today's levels could offset up to 45 percent of economy-wide emissions in 2050, with US forests playing a central role." (USA, p. 10). Regarding technologically-based CDR, the UK demonstrates a scenario in which carbon removal via BECCS would account for around 20 $MtCO_2$ in meeting the 2050 target.

Finally, in some cases, the intention to use CDR for overall target achievement is implied in terms of net-zero targets or *net* emission reduction targets. CDR commitments could then be estimated from overall targets when countries also specify a separate emission reduction target. Examples of countries for which an implicit CDR target could be calculated include Finland, Germany (for carbon neutrality aspiration), Slovakia and Sweden (see **Table 1**, column 5). However, determining explicit CDR targets is not possible since countries are also open to complying with targets by using international offsets. The relative importance of using CDR as opposed to international offsets is not discussed in quantitative terms.

CDR Types

Carbon sequestration in forests, soils, water biomass and harvested wood products (HWP) dominate LT-LEDS narratives in terms of the frequency in which they are referred to as a potential source of carbon removal today and in projections to 2050, resonating with the findings of Thoni et al. (2020). **Table 2** describes the types of nature-based CDR and measures to maintain and/or increase their carbon capture and storage capacity as they appear in the strategies.

Table 3 presents definitions and examples of technologically-based CDR. These carbon removal solutions include bioenergy with carbon capture (utilization) and storage [BECC(U)S], direct air carbon capture (utilization) and storage [DACC(U)S], enhanced weathering, ocean liming and bioplastics. We also found some ambivalences in the definitions and classifications. For example, the French strategy refers to bioenergy and CO_2 capture separately, leaving scope for interpretation as to whether these two approaches are planned to be used jointly.

A summary of all CDR in **Table 4** demonstrates that all strategies, except for one (Marshall Islands), refer to forests and soils as sources of carbon removal. Blue carbon is more frequently discussed by coastal states (e.g., Fiji, Japan, Republic of Korea and Singapore). In this table, biochar is placed in a separate category from the soil sink category because of the additional stages

TABLE 2 | Examples of nature-based carbon sinks and measures for their maintenance or enhancement as described in the strategies.

Forest carbon sink	Soil carbon sink	Blue carbon sink	HWP
Forest conservation Nature reserves/parks Green (urban) spaces Agroforestry Reducing deforestation Re- (a)forestation Sustainable forest management (e.g., changing tree species, forest fire management, improving forest productivity) Restoring degraded forestland	Sustainable land management (e.g., reduce cultivation of peat soil, restoration of peatlands, precision agriculture) Conservation agriculture (capturing CO_2 in farmland, pastures, cropland, grazing land, rangeland, grasslands) Conservation of wetlands and buffer zones soil enhancement with biochar	Seagrass meadows Mangrove restoration and protection Conservation and restoration of algae beds Ocean fertilization to fixate carbon in phytoplankton and useful aquatic plants	Wood products for carbon retention in buildings Substitution of wood-based materials for more emission-intensive materials Carbon storage in wood and wood-based products Expansion of the application of materials derived from woody biomass

Claims made in the climate strategies sometimes likely overstate the potential of CDR by including activities whose status as a removal technology is the subject of debate in research. This is particularly true for the conservation of existing carbon stocks.

TABLE 3 | Definition and examples of technological carbon sinks as described in the climate strategies.

BECC(U)S	DACC(U)S	Enhanced weathering on land	Ocean liming	Bioplastics
CO_2 that is removed from the atmosphere and sequestered through vegetation growth is captured and stored when the plant material is used to generate energy CCS or CCUS technologies combined with sustainable biomass use, including at power plants	Artificially separating and capturing CO_2 directly from the atmosphere Capturing CO_2 from ambient air and either utilizing it or storing it underground	Use minerals to absorb atmospheric CO_2 and transform minerals, potentially utilized in construction Crushing suitable rocks that react with CO_2 and spreading them over land	A form of enhanced weathering based on dissolving lime or crushed minerals (such as olivine) in oceans to increase alkalinity that enables the oceans to absorb more atmospheric CO_2	Manufacture plastics and biofuels by using biomass resources such as microalgae and plants that absorb CO_2 Retain the CO_2 captured in vegetation beyond the harvest by producing and recycling bioplastics

The claims made in the climate strategies sometimes likely overstate the potential of CDR by including activities whose status as a removal technology is the subject of debate in research. This is particularly true for the concepts involving carbon utilization and bioplastics.

TABLE 4 | References to carbon dioxide removal (CDR) methods in long-term climate strategies by country (reference to CDR is marked by an x; absence of CDR is marked by a dash).

	Type[a]	AT	CA	CR	CZ	DE	DK	EE	FI	FJ	FR	JP	KR	LV	MH[b]	MX	NL	NO	PT	SE	SG	SK	UA	UK	US	ZA
Nature-based	Forest sink	X	X	X	X	X	X	X	X	X	X	X	X	X	–	X	X	X	X	X	X	X	X	X	X	X
	Soil sink	X	X	X	X	X	X	X	X	X	X	X	X	X	–	X	X	X	X	X	X	X	X	X	X	X
	Blue carbon	–	–	–	–	–	–	–	–	X	–	X	X	–	–	–	–	–	–	–	X	–	–	–	–	–
	Biochar	–	X	–	–	–	X	–	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	HWP	X	X	–	X	X	–	X	X	X	X	X	X	X	–	X	X	–	–	X	–	X	X	X	X	–
Technological	BECC(U)S	–	X	–	–	–	X	–	X	–	X	X	–	–	–	–	X	X	–	X	–	–	–	X	X	–
	DACC(U)S	–	–	–	–	–	X	–	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	X	X	–
	Enhanced weathering	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	X	X	–
	Ocean liming	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	X	–	–
	Bioplastics	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	X	–	–	–	–	–	–	–	–	–

[a] *Some of the strategies refer to forest and soil sinks in aggregate, in the LULUCF (land use, land-use change, and forestry) or AFOLU (agriculture, forestry, and other land use) sectors.*
[b] *The Marshall Islands refers to CDR in its strategy (as indicated in **Table 1**), although not to any specific type of CDR. See **Appendix A** for the explanation of ISO country codes. Please note that claims made in the climate strategies sometimes likely overstate the potential of CDR by including activities whose status as a removal technology is the subject of debate in research.*

required to process biomass into biochar, and then bury it in soil, serving as both a soil supplement and a form of carbon storage. At the end of the production cycle, biochar becomes a component of soil, yet it is often referred to as a separate CDR method. In terms of carbon sequestration capability, the potential of biochar is high (Fuss et al., 2018), although it has not yet become a widely implemented or discussed method, and it is only mentioned in three strategies (Canada, Denmark and Japan). Finally, HWP is the third most frequently mentioned CDR approach. It often appears alongside discussions about forest carbon sink in the strategies, described as an alternative to standing forests for long-term carbon storage, while also being a substitute for emission-intensive materials. Technology-based CDR is significantly less present in the strategies compared to nature-based carbon removal. Bioenergy with carbon capture and storage (BECCS) is mentioned most frequently in this category.

Barriers and Opportunities

The described limitations of carbon sequestration include the slow growth of trees, reduction in carbon dioxide absorption with forest age, deterioration of forests and soils due to environmental forces (e.g., fires and storms, draft, pathogens), limited capacity of land (e.g., Canada, Ukraine, The Netherlands, Portugal, Slovakia). Thus, a few strategies project a *reduction* in the level of carbon dioxide sequestration by forests and lands by 2050 (e.g., Republic of Korea), and other strategies indicate that their land and forest sectors are currently net emitters (e.g., Denmark, Mexico). Uncertainties in the quantification of resources and a lack of robust modeling tools are also emphasized. As stated by Fiji, "Seagrasses have not been considered in this LEDS due to lack of data specific to Fiji." (Fiji, p. 141). Germany is also hesitant: "Accounting for emissions from land use and forestry is subject to considerable methodological difficulties. Therefore, the German government does not include this sector directly in the national climate targets." (Germany, p. 29). Slovakia points out that it "has not yet quantified emissions/removals from the Wetland category as there is no sufficiently accurate input data" (p. 60). Costa Rica and Finland highlight a high level of uncertainty related to carbon absorption by forests. A lack of consensus on how to account for carbon in different nature-based CDR is a barrier that is also linked to questions about the permanence of carbon storage that could affect the feasibility of implementation. The USA highlights the potential competition in the forestation approach with other sectors of the economy and land uses: "Some stakeholders have expressed concerns that a forest expansion program could create competition for agricultural production" (p. 73).

However, an opportunity has been described for synergies between some sectors of the economy and between CDR as the multifunctionality of forests, including biodiversity, bio-economy and sustainable management, are extensively promoted. Austria states that the use of wood for the bio-economy might have a higher value in climate mitigation measures than a standing forest in capturing CO_2: "Effect of avoiding fossil CO_2 emissions (substitution effect) is at least twice as high as the effect of climate measures from capturing CO_2 in forests" (Austria, p. 64). Thus, for example, the sustainable management of forests and soils could be a more desirable policy if it appealed to a broader societal use, rather than solely for the purpose of carbon removal.

With respect to barriers of technologically-based CDR—safety concerns, uncertainties of effects and potential, as well as significant energy input demands [particularly relevant to DACC(U)S], high costs and capacity constraints are listed as barriers. Austria rejects the use of CCS technologies on its territory (at least until 2023), citing unresolved safety issues. Denmark acknowledges the financial impediments faced by companies otherwise able to scale-up. The US claims DACC(U)S are not economically competitive until all point sources utilize CCS, while BECCS carbon removal potential "depends on the upstream land carbon effects of biomass production" (US, p. 39). Japan warns that "DAC faces many challenges, including the necessity for significant energy input and cost reductions" (p. 81). The most frequently discussed opportunity for BECC(U)S and DACC(U)S proliferation is connected to the expansion of CCS technologies via their use in existing coal and natural gas power plants, which is more economically justifiable at this stage of technological development. Consequently, CCS could be used also in facilities using bioenergy.

International Cooperation

By and large, proposals for CDR-focused international cooperation are absent in LT-LEDS or poorly described, even though cross-country efforts, particularly with respect to the implementation of technologically-based CDR, might be the most cost-effective opportunity, and "owing to the uneven distribution of key resources (e.g., CO_2 storage or biomass), delivering large-scale atmospheric removal of CO_2 is likely to require active collaboration" (Fajardy and Mac Dowell, 2020, p. 215). There are a few exceptions in LT-LEDS: The Netherlands advocates for cross-border partnerships, keeping in mind each country own national commitments, and offering space for CO_2 storage in the North Sea for other countries lacking such resources; France refers to an international program on soil carbon research; and the UK highlights international climate diplomacy and the country's investments in overseas deforestation programs, e.g., the Colombian Amazon. However, a high number of strategies acknowledge the importance of global cooperation on climate action in general, while implying the possible collaboration on CDR solutions as part of the process. Japan states that as "the climate change problem cannot be solved by one country alone, it is necessary to gather wisdom of the world" (Japan, p. 16). Further, the government of Norway stresses that "[c]ooperation and the development of climate technology are important elements of Norway's contribution to global transformation" (Norway, p. 44).

Thus, as with the planning discussions, we found that references to international cooperation are lacking in detail. This could either be due to the nature of the documents, i.e., that long-term strategies by their very nature cannot be too specific, and that more detailed information can be found in domestic policy documents, or it reflects an actual lack of comprehensive planning.

Perceptions of CDR Amongst Climate Experts

In order to contextualize the results from the document analysis, we gauged the perceptions of climate diplomats, practitioners and researchers on the role of CDR in addressing climate change. Their views largely reflect what was found in the LT-LEDS, but also add nuances and additional insights into the different types of CDR, their potential, barriers to proliferation and the role of international collaboration.

The first finding of interest from the interviews is that several of the respondents stated that they are not aware or familiar with the concept of CDR or negative emission technologies. Many respondents described carbon capture and storage (CCS), although CCS on its own is not considered a CDR—but could contribute to CDR if the technology is used for bio-CCS. This indicates that even amongst climate experts, the knowledge of CDR is inconsistent and, in some cases, very insufficient.

Regarding the need for CDR in addressing climate change, a few of the respondents referred to IPCC reports that highlight CDR as being necessary for achieving the Paris Agreement temperature objective. Other respondents highlighted difficult-to-abate sectors such as agriculture, aviation, cement, aluminum and other heavy industry sectors, and that CDR is very important because it "gives us some runway because we're going to need it. We need it right now because we're so off track" (M25, see **Appendix B**).

On different types of CDR, the respondents highlighted the different potentials of various forms of CDR depending on the geographical location of the country and its economic and industrial profile. Types of CDR frequently mentioned were natural climate solutions (afforestation, grasslands, mangroves, regenerative agriculture), carbon capture and storage with biomass, bio-methane and direct air capture.

Regarding opportunities and barriers, most respondents distinguished and emphasized the differences between various types of CDR. Some types were considered uncontroversial as they are commonly included in decarbonization plans. These are natural climate solutions such as blue carbon habitat and afforestation. However, the respondents agreed that technological solutions need further development before they can be scaled up and become cost-effective. Some solutions are regarded as "more speculative measures" that may come to fruition in the future (B14). Respondents highlighted the legal challenges of carbon capture and storage, which legislation does not permit in some jurisdictions. However, most respondents referred to the issue of cost and finance regarding bio methane and BECCS, as such technologies are not yet "commercially viable" (R13). Issues of permanence, storage and access to the required amount of biomass without causing other environmental problems were also raised regarding BECCS. According to one respondent, there is no proof that technological CDR can work on the required scale and therefore believes that "it is completely irresponsible to have them as an important part of any long-term plan right now. We just don't know that we can have them" (F12). Another respondent also warned of relying on unproven technologies and referred to technological CDR as "still a bit sort of science fiction-ish" (T22). Similarly, another respondent warned of the risk of moral hazard, whereby global expectations of CDR are too high compared to what may be feasible: "Companies and organizations aren't putting into place ambitious enough plans [e.g., emission reduction plans] because they think it [CDR] is available, then maybe it ends up not being available and then they haven't met their climate targets" (R13). Even in the case of natural climate solutions that are considered to be more reliable, the risks of permanence and accounting were described by some of the respondents.

Several respondents specified the importance of international collaboration on RD&D (research, development and deployment) in sharing the financial burden and the risks involved in the expansion of CDR technologies: "If we went down the route of competing with one another to try and gain some advantage with some of these technologies, we're less likely to produce solutions at a global scale that we require in a timely fashion" (B14). Most respondents agreed that more investment was needed for realizing the potential of CDR and that planning and RD&D requirements had to be met sooner rather than later.

In terms of overcoming the costs of CDR, several respondents spoke of the need for policymakers to signal that the price of carbon must rise in the coming decades. According to these respondents, the demand for CDR needs to be generated in advance in order to attract investment and bring down costs.

In sum, most respondents acknowledged that CDR is crucial in addressing climate change but raised questions about its feasibility and how to realize its potential without causing other environmental problems and crowding out alternative climate solutions.

THE ENVISAGED ROLE OF CDR IN ADDRESSING CLIMATE CHANGE

We could discern different understandings of the potential role of CDR in achieving the promised climate targets. At face value, the fact that references to CDR appear in all the climate strategies studied arguably indicates the alignment of countries with the consensus on the current global climate regime exemplified by the Paris Agreement and the IPCC reports. Increasing national commitments to net-zero emission targets by 2050 also inevitably force countries to consider CDR, regardless of local idiosyncrasies. This broadly suggests the further normalization of CDR as a strategy to achieving the climate goals (Markusson et al., 2017; Minx et al., 2018; Low and Boettcher, 2020; Mace et al., 2021; Schenuit et al., 2021) and the continued disassociation of carbon removal methods from climate engineering proposals (Bellamy and Geden, 2019).

Thus, the overarching view that transpired is that CDR is needed to help achieve mid-century climate targets. Since the ambition of mid-century targets are insufficient, CDR is also described as needed to compensate for a temporary carbon budget deficit by continued CDR deployment in the second half of the century. However, this alone is not an unexpected finding. Existing research shows that countries are already starting to integrate CDR into their existing climate policy instruments (Schenuit et al., 2021), suggesting that CDR as a climate mitigation method is perhaps reaching a point of broader acceptability and desirability in policy circles. Yet, this does not tell the whole story. As our analysis has shown, there is a variation in how countries envisage the role of CDR. Interpretive analysis used in this study does not necessarily focus on what is being described or how countries perceive the role of CDR, but rather how the underlying positions on CDR can be simplified in order to highlight their potential roles in climate action. The roles of CDR are described below: CDR as a panacea, CDR as a necessary fallback and CDR as a chimera. While these are distinct visions, they are not mutually exclusive and can partially overlap. They do not represent polarizing views but rather synthesize the different ways that the role of CDR in climate action appears in LT-LEDS and interviews.

CDR as a Panacea

This vision is the most optimistic about the role of CDR in climate action. It presents emission reduction and CDR targets in non-specific terms, creating flexibility in the extent to which CDR could be allowed to substitute emission reductions in achieving net-zero targets. We also note this discussion in Schenuit et al. (2021), who describe the domestic policies of Australia, New Zealand and the UK as having no cap on the amount of CDR allowed to meet the overall targets. LT-LEDS' CDR projections are mainly described using qualitative but promising terms, suggesting an opportunity for other sectors to delay decarbonization, yet keeping climate action on track through CDR implementation. The USA and UK strategies explicitly state that CDR (mainly BECCS) could allow other sectors to decarbonize more slowly. Strategies exemplary of this vision highlight the highest number of CDR solutions (e.g., Japan, USA, UK, Denmark and Canada) and the highest number of technologically-based CDR (e.g., Japan, The Netherlands and Denmark). Indeed, technologically-based CDR, if implemented at scale, has the potential to remove large amounts of carbon (Fuss et al., 2018). In addition, the opportunity for CDR development through international cooperation is emphasized by Japan and The Netherlands. The Netherlands states that it could offer other countries CO_2 storage in the North Sea.

While conceptually attractive and a great opportunity for climate action, this vision risks deterring mitigation actions. If plans for future CDR deployment are described as creating headroom for slower decarbonization, so that less ambitious near-term decarbonization is expected to be compensated by CDR in the long term, such mitigation deterrence may indeed trigger the moral hazard that Anderson and Peters (2016) have warned could become a reality. If CDR does not deliver as expected, there would be no option for compensating for the lost abatement opportunity. This issue was also described by one of the interview respondents. The risk of mitigation deterrence is also potentially enhanced as the strategies that adhere to this vision are supposed to rely on a number of technologically-based CDR. As discussed by the countries themselves, there are a number of safety concerns, uncertainties about effects and the potential, as well as significant energy input demands that are still unresolved in relation to these types of CDR (Japan, Denmark, US.). Similar challenges, including high costs and questions about the permanence of carbon removal created by these technologies, were described by the respondents.

Thus, not only is it vital to plan for mid-century targets with clearly articulated expectations for CDR, it is also vital to articulate the same kind of expectations for milestone targets on the road to the long-term target and to plan for their delivery. Hedging against the moral hazard requires clear plans regarding the type and role of CDR for achieving the targets, but also—importantly—the timing of CDR implementation. Thus, CDR as a panacea highlights the benefits of CDR deployment at scale. According to Anderson et al. (2020), if the developed countries did not bet on the successful deployment of large-scale

CDR and wanted to comply with their commitments under the Paris Agreement, they would need to commit to a double-digit reduction in emissions annually. Thus, for policymakers in the developed countries, the allure of CDR becomes clear—but its risks should not be ignored.

CDR as a Necessary Fallback

In the second vision, carbon removal methods are outlined as an opportunity to offset emissions from the 'hard-to-eliminate' sectors (e.g., industrial processes, agricultural activities and aviation) and to substitute for highly polluting materials (e.g., iron, steel and cement), offering support to primary emission reduction measures. In this vision, the problem of moral hazard and uncertainty in the tradeoffs between emission reductions and removals are reduced by articulating the emission reduction targets and scenarios, as well as giving CDR a clearer supporting role in emission reductions efforts (e.g., Finland, Slovakia, Sweden, Germany). At the same time, the fact that carbon removal receives attention alongside emission reduction approaches, illustrates an opportunity for "experimentation with [CDR] technology development, regulation and public deliberations" (Geden et al., 2019), which is needed in the near future if we want to realize the potential of CDR and apply it to meaningful climate action, as the interviewed climate experts also state.

Nature-based sinks are described as key approaches among the types of CDR in supporting climate action, with the potential for growth. The LULUCF (land use, land-use change and forestry) sector, especially forests, have served as a carbon sequestration sink for decades (Bäckstrand and Lövbrand, 2006; Carton et al., 2020) and therefore, not surprisingly, remain a low-hanging fruit when it comes to the potential and interest in the sector's expansion and inclusion in climate frameworks by many countries, a view that was also supported by a few of the interviewees. However, the future of nature-based sinks is not unambiguous. Schenuit et al. (2021) argue that the growing institutionalization of CDR policies has changed the political status of LULUCF sinks, opening a debate on their status and how to account for various forms of climate actions. The issues to be reconciled include, *inter alia*, managing the overlaps of LULUCF sinks with other types of CDR and balancing the multiple social and economic interests that are embedded in the sector. The challenges faced by nature-based CDR on the road to its wider implementation are also described in some of the strategies. However, despite potential objections, based on the overall representation of nature-based sinks in LT-LEDS, there are reasons to assert that they will play a key role in supporting the achievement of mid-century climate targets. Some countries, such as Sweden and Finland, also describe BECCS as an opportunity to achieve their long-term ambitions. These countries both have large forestry sectors and are technologically advanced and, with their relative proximity to carbon storage sites in Norway (Rodriguez et al., 2021), they view BECCS as being realizable within the near future. The second vision thus envisions CDR as a necessary fallback that will be needed to achieve net-zero targets, while acknowledging barriers and challenges to their use.

CDR as a Chimera

The third vision features the ambiguities and lack of details in many of the plans. Thus, CDR could become an unrealizable dream, or a chimera. Specifications regarding timing and scale are essential if climate targets are to be achieved, with or without CDR. However, they are largely missing in most of the strategies, particularly regarding CDR targets and implementation plans. Discussions about CDR's potential and opportunity engender a sense of hope yet might delay the necessary measures. The lack of clarity and details on CDR in most of the strategies means that the role of CDR in achieving long-term climate targets had to be often deduced on a piecemeal basis and, ultimately, it is still not clear whether CDR will play a meaningful role in climate efforts, or to what extent. Also, there is a degree of uncertainty in understanding the potential of CDR in the first place, identifying accounting mechanisms and planning for the integration of CDR into broader climate policies and frameworks. For example, it is not always clear whether the countries that propose to maintain or enhance nature-based sinks do so mainly because they want to balance out the simultaneously increasing emissions in the same sectors. These doubts were also expressed by some of the interview respondents, who highlighted several barriers to CDR implementation that are yet to be addressed in the short term. One respondent even voiced their concern that CDR would not achieve its intended purpose of achieving the Paris temperature targets but argued for the need for more advanced geo-engineering options.

Planning for the future always involves an element of uncertainty, but missing the specificities of the role of CDR in long-term plans—if they reflect an actual lack of planning—means that CDR may remain an illusion. If, on the other hand, countries have actually made progress in their intentions regarding CDR than what was reflected in the studied documents, it may be beneficial to convey such intentions to a global audience in order to encourage more cross-border cooperation. However, if countries do not actually want to rely on CDR or only use it as a last resort, then their emission reduction targets and pathways should also be specified.

The way in which CDR is described in most long-term strategies appears to be a form of constructive ambiguity (Jegen and Mérand, 2014), whereby deliberately vague language is used to describe a controversial topic. Public discussions on how to achieve net-zero targets have barely been raised in most countries, even less so on the role of CDR therein. Thus, social acceptance is a variable that needs to be taken into account when developing future plans for CDR (Thoni et al., 2020).

DISCUSSION AND CONCLUSION

Carbon dioxide removal (CDR) is expected to play a crucial role in achieving the targets of the Paris Agreement, yet we have scant understanding of how countries envisage the role of CDR in climate action. This paper has analyzed 25 long-term climate strategies and 23 interviews with policy experts to examine how CDR is described in documents and perceived by academics, policymakers and climate diplomats. The results demonstrate that CDR is acknowledged as being necessary for achieving mid-century climate goals, but also show variation in what role CDR should play. Based on the differences in target specification, types of CDR, barriers and opportunities to implementation and the discussion of international cooperation, we highlight three visions of the different roles envisaged for CDR in long-term climate action.

Overall, we found a lack of specificity in the planning and the role of CDR in meeting climate targets, even though some of the strategies clearly intend to rely on CDR in the future. Perhaps LT-LEDS are not the right forum for such discussions and the ambiguity of language can be used to achieve a strategic advantage. However, the lack of focus on detailed planning can also be described as a lost opportunity. While not fully explored in this research, LT-LEDS also lack specific policy interventions to encourage a demand for CDR. Without such measures being implemented and communicated, CDR is unlikely to be adopted at scale—something that some of our respondents highlighted as a real risk. If a lack of demand-pull policy for CDR is combined with postponing emission reductions, the moral hazard that Anderson and Peters (2016) described would most likely be effectuated. Future research could more broadly examine LT-LEDS regarding the specification of CDR policy mechanisms or policy proposals for climate action. Future studies could also examine domestic climate policy documents and processes, as suggested by Schenuit et al. (2021), in order to understand more about how CDR is envisaged in achieving the communicated climate goals. Domestic policy proposals may contain more nuanced details and targets, although our interviews suggest that much of the policy discussions on (particularly technological) CDR have only recently started and are therefore at an early stage.

Overall, the role of CDR in climate action as described in the strategies and interviews could be regarded as an emission offset strategy (Meadowcroft, 2013) that exists in a broader paradigm of technological solutions to the climate change problem (e.g., Minx et al., 2018; Mace et al., 2021). While this vision is common to all LT-LEDS, the divergent roles of CDR also emerge from the strategies: a *panacea* that highlights the benefits of CDR, particularly its ability to create headroom for slower emission reductions, yet risks mitigation deterrence; a *necessary fallback* to help achieve mid-century climate targets, capitalizing on the existing resources of countries with specific milestone targets and detailed plans about how to achieve them; and a *chimera*, with CDR at risk of being an illusion that distracts attention away from concrete near-term mitigation measures, due to largely missing targets and specified plans for implementing CDR measures.

Only a few LT-LEDS include an outlook on net-negative emissions later in the century and refer to CDR as an opportunity to enhance climate action in the net-negative territory (e.g., Sweden, Canada, Finland). Thus, CDR as a climate recovery strategy (Meadowcroft, 2013) is less visible and arguably not sufficiently mature to be adopted by most countries. CDR is mainly positioned as an opportunity to offset emissions.

The results of this research add to the discussion about the specification of pathways to carbon neutrality and achieving the Paris Agreement temperature goals, as well as the role of CDR therein. Moreover, LT-LEDS are a recognized platform for communicating national climate goals to a global audience. These strategies could influence the direction of future policy by indicating what different countries value and assuring future trajectories by setting transparent targets and plans. The lack of articulation might be a lost opportunity to accelerate decarbonization and climate action. Enhancing the transparency and clarity of national long-term emission trajectories is crucial for the ability to take stock of the collective global climate ambition and its potential contribution to achieving the temperature objective of the Paris Agreement. LT-LEDS are an appropriate and established platform that could accommodate the need for enhanced transparency. We therefore recommend that countries update their LT-LEDS with new targets once such targets have been decided. This opportunity is readily available for all countries that have already submitted LT-LEDS. It is clear that the race to net-zero emissions has advanced over the past couple of years and that it is conceivable that future iterations of LT-LEDS may need to reflect more ambitious targets.

DATA AVAILABILITY STATEMENT

The datasets analyzed for this study can be found in the UNFCCC's online repository for LT-LEDS (https://unfccc.int/process/the-paris-agreement/long-term-strategies) and the European Commission's online repository for LTS (https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-long-term-strategies_en).

AUTHOR CONTRIBUTIONS

AB coded all document data and contributed to the literature review, materials, results, and analysis. MF contributed to the literature review, materials, design of the analytical framework, compiled information on target specification, and was part of the grant that funded this project. NN developed the interview guide with GR, analyzed the interview data, contributed to the literature review, materials, analysis, and was a part of the grant that funded this project. GR developed the interview guide with NN, contributed to the analysis, and was part of the grant that funded this project. All authors were part of the research design, contributed to the article, and approved the final version.

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REFERENCES

Anderson, K. (2015). Duality in climate science. *Nat. Geosci.* 8:898. doi: 10.1038/ngeo2559

Anderson, K., Broderick, J. F., and Stoddard, I. (2020). A factor of two: how the mitigation plans of "climate progressive" nations fall far short of Paris-compliant pathways. *Clim. Policy* 20, 1290–1304. doi: 10.1080/14693062.2020.1728209

Anderson, K., and Peters, G. (2016). The trouble with negative emissions. *Science* 354, 182–183. doi: 10.1126/science.aah4567

Bäckstrand, K., and Lövbrand, E. (2006). Planting trees to mitigate climate change: contested discourses of ecological modernization, green governmentality and civic environmentalism. *Glob. Environ. Politics* 6, 50–75. doi: 10.1162/glep.2006.6.1.50

Bellamy, R. (2013). *Framing Geoengineering Assessment. Opinion Article, Geoengineering Our Climate Working Paper and Opinion Article Series*. Available online at: http://wp.me/p2zsRk-9H (accessed May 1, 2020).

Bellamy, R., and Geden, O. (2019). Govern CO 2 removal from the ground up. *Nat. Geosci.* 12, 874–876. doi: 10.1038/s41561-019-0475-7

Bellamy, R., and Osaka, S. (2020). Unnatural climate solutions? *Nat. Clim. Chang.* 10, 98–99. doi: 10.1038/s41558-019-0661-z

Bodansky, D. (2013). The who, what, and wherefore of geoengineering governance. *Clim. Change* 121, 539–551. doi: 10.1007/s10584-013-0759-7

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., et al. (2018). Carbon capture and storage (CCS): the way forward. *Energy Environ. Sci.* 11, 1062–1176. doi: 10.1039/C7EE02342A

Butler, T. M., Lode, B., Parker, A., Mar, K. A., Schmidt, F., and Lawrence, M. G. (2015). *Long-term Climate Goals. Decarbonisation, Carbon Neutrality, and Climate Neutrality*. Potsdam: Institute for Advanced Sustainability Studies (IASS).

Caldeira, K. (2009). "Climate engineering: solution, curse, or chimera?" in *IOP Conference Series: Earth and Environmental Science,* Vol. 6 (IOP Publishing), 452001. doi: 10.1088/1755-1307/6/45/452001

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *Wiley Interdisc. Rev. Clim. Change* 11:e671. doi: 10.1002/wcc.671

Fajardy, M., and Mac Dowell, N. (2020). Recognizing the value of collaboration in delivering carbon dioxide removal. *One Earth* 3, 214–225. doi: 10.1016/j.oneear.2020.07.014

Falduto, C., and Rocha, M. (2020). *Aligning Short-Term Climate Action With Long-Term Climate Goals: Opportunities and Options for Enhancing Alignment Between NDCs and Long-Term Strategies.* OECD Report. doi: 10.1787/2227779X

Fawzy, S., Osman, A. I., Doran, J., and Rooney, D. W. (2020). Strategies for mitigation of climate change: a review. *Environ. Chem. Lett*. 18, 1–26. doi: 10.1007/s10311-020-01059-w

Felix, B. (2019). *France Sets 2050 Carbon-Neutral Target With New Law*. Reuters. Available online at: https://www.reuters.com/article/us-france-energy-idUSKCN1TS30B (accessed February 21, 2021).

Fridahl, M. (2017). Socio-political prioritization of bioenergy with carbon capture and storage. *Energy Policy* 104, 89–99. doi: 10.1016/j.enpol.2017.01.050

Fridahl, M., Bellamy, R., Hansson, A., and Haikola, S. (2020b). Mapping multi-level policy incentives for bioenergy with carbon capture and storage in Sweden. *Front. Clim*. 2:604787. doi: 10.3389/fclim.2020.604787

Fridahl, M., Hansson, A., and Haikola, S. (2020a). Towards indicators for a negative emissions climate stabilisation index: problems and prospects. *Climate* 8:75. doi: 10.3390/cli8060075

Fridahl, M., and Lehtveer, M. (2018). Bioenergy with carbon capture and storage (BECCS): global potential, investment preferences, and deployment barriers. *Energy Res. Soc. Sci*. 42, 155–165. doi: 10.1016/j.erss.2018.03.019

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., et al. (2014). Betting on negative emissions. *Nat. Clim. Chang.* 4, 850–853. doi: 10.1038/nclimate2392

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., et al. (2018). Negative emissions—Part 2: costs, potentials and side effects. *Environ. Res. Lett.* 13:063002. doi: 10.1088/1748-9326/aabf9f

Geden, O., and Löschel, A. (2017). Define limits for temperature overshoot targets. *Nat. Geosci.* 10, 881–882. doi: 10.1038/s41561-017-0026-z

Geden, O., Peters, G. P., and Scott, V. (2019). Targeting carbon dioxide removal in the European Union. *Climate Policy* 19, 487–494. doi: 10.1080/14693062.2018.1536600

Geden, O., and Schenuit, F. (2020). *Unconventional Mitigation: Carbon Dioxide Removal as a New Approach in EU Climate Policy*. SWP Research Paper (Berlin). doi: 10.18449/2020RP08

Gough, C., Garcia-Freites, S., Jones, C., Mander, S., Moore, B., Pereira, C., et al. (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C. *Glob. Sustainab.* 1:E5. doi: 10.1017/sus.2018.3

Hennink, M. M., Kaiser, B. N., and Marconi, V. C. (2017). Code saturation versus meaning saturation: how many interviews are enough? *Qual. Health Res.* 27, 591–608. doi: 10.1177/1049732316665344

Himmelsbach, R. (2018). How scientists advising the European Commission on research priorities view climate engineering proposals. *Sci. Pub. Policy* 45, 124–133. doi: 10.1093/scipol/scx053

Honegger, M., Michaelowa, A., and Roy, J. (2020). Potential implications of carbon dioxide removal for the sustainable development goals. *Clim. Policy*. 21, 1–21. doi: 10.1080/14693062.2020.1843388

Honegger, M., and Reiner, D. (2018). The political economy of negative emissions technologies: consequences for international policy design. *Clim. Policy* 18:306. doi: 10.1080/14693062.2017.1413322

Huttunen, S., and Hildén, M. (2014). Framing the controversial: geoengineering in academic literature. *Sci. Commun.* 36, 3–29. doi: 10.1177/1075547013492435

IPCC (2018). *Global Warming of 1.5 °C: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge: Intergovernmental Panel on Climate Change.

IPCC (2019). *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Cambridge: Intergovernmental Panel on Climate Change.

Jaber, A. A., Anderson, B., Nachtigall, D., and Ngom, F. (2020). *Long-term Low Emissions Development Strategies: Cross-Country Experience*. Paris: OECD.

Jegen, M., and Mérand, F. (2014). Constructive ambiguity: comparing the EU's energy and defence policies. *West Eur. Polit.* 34, 182–203. doi: 10.1080/01402382.2013.818325

Kartha, S., Kemp-Benedict, E., Ghosh, E., Nazareth, A., and Gore, T. (2020). *The Carbon Inequality Era: An Assessment of the Global Distribution of Consumption Emissions Among Individuals From 1990 to 2015 and Beyond*. Stockholm: Stockholm Environment Institute.

Kulovesi, K., and Oberthür, S. (2020). Assessing the EU's 2030 climate and energy policy framework: incremental change toward radical transformation? *Rev. Eur. Comp. Int. Environ. Law* 29, 151–166. doi: 10.1111/reel.12358

Lefale, P. F., and Anderson, C. L. (2018). "Climate engineering and small island states: panacea or catastrophe?" in *Geoengineering Our Climate?* (Routledge), 159–163.

Levihn, F., Linde, L., Gustafsson, K., and Dahlen, E. (2019). Introducing BECCS through HPC to the research agenda: the case of combined heat and power in Stockholm. *Energy Rep*. 5, 1381–1389. doi: 10.1016/j.egyr.2019.09.018

Low, S., and Boettcher, M. (2020). Delaying decarbonization: climate governmentalities and sociotechnical strategies from Copenhagen to Paris. *Earth Syst. Govern.* 5:100073. doi: 10.1016/j.esg.2020.100073

Low, S., and Schäfer, S. (2019). Tools of the trade: practices and politics of researching the future in climate engineering. *Sustain. Sci.* 14, 953–962. doi: 10.1007/s11625-019-00692-x

Mace, M. J., Fyson, C. L., Schaeffer, M., and Hare, W. L. (2021). *Governing Large-Scale Carbon Dioxide Removal: Are We Ready?* – An Update. New York, NY: Carnegie Climate Governance Initiative (C2G).

Markusson, N., Gjefsen, M. D., Stephens, J. C., and Tyfield, D. (2017). The political economy of technical fixes: the (mis) alignment of clean fossil and political regimes. *Energy Res. Soc. Sci.* 23, 1–10. doi: 10.1016/j.erss.2016.11.004

McLaren, D., and Corry, O. (2021). Clash of geofutures and the remaking of planetary order: faultlines underlying conflicts over geoengineering governance. *Global Policy* 12, 20–23. doi: 10.1111/1758-5899.12863

McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B., and Markusson, N. O. (2019). Beyond "Net-Zero": a case for separate targets for emissions reduction and negative emissions. *Front. Clim*. 1:4. doi: 10.3389/fclim.2019.00004

Meadowcroft, J. (2013). Exploring negative territory Carbon dioxide removal and climate policy initiatives. *Clim. Change* 118: 137–149. doi: 10.1007/s10584-012-0684-1

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions – part 1: research landscape and synthesis. *Environ. Res. Lett*. 13:063001. doi: 10.1088/1748-9326/aabf9b

Möller, I. (2020). Political perspectives on geoengineering: navigating problem definition and institutional fit. *Glob. Environ. Politics* 20, 57–82. doi: 10.1162/glep_a_00547

Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., et al. (2020). Principles for thinking about carbon dioxide removal in just climate policy. *One Earth* 3, 150–153. doi: 10.1016/j.oneear.2020.07.015

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., et al. (2018). Negative emissions – part 3: innovation and upscaling. *Environ. Res. Lett*. 13:063003. doi: 10.1088/1748-9326/aabff4

Patel, S. (2020). *South Korea Joins Japan and China with Carbon-Neutral Pledge*. Power. Available online at: https://www.powermag.com/south-korea-joins-japan-and-china-with-carbon-neutral-pledge/ (accessed February 24, 2021).

Reynolds, J. L. (2019). Solar geoengineering to reduce climate change: a review of governance proposals. *Proc. R. Soc. A* 475:20190255. doi: 10.1098/rspa.2019.0255

Rodriguez, E., Lefvert, A., Fridahl, M., Grönkvist, S., Haikola, S., and Hansson, A. (2021). Tensions in the energy transition: Swedish and Finnish company perspectives on bioenergy with carbon capture and storage. *J. Clean. Prod.* 280:124527. doi: 10.1016/j.jclepro.2020.124527

Sapinski, J. P., Buck, H. J., and and, A., Malm (2020). *Has It Come to This?: The Promises and Perils of Geoengineering on the Brink.* Rutgers University Press.

Schenuit, F., Colvin, R., Fridahl, M., McMullin, B., Reisinger, A., Sanchez, D. L., et al. (2021). Carbon dioxide removal policy in the making: assessing developments in 9 OECD cases. *Front. Clim*. 3:7. doi: 10.3389/fclim.2021.638805

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., et al. (2015). Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Chang.* 6:42. doi: 10.1038/nclimate2870

Thoni, T., Beck, S., Borchers, M., Förster, J., Görl, K., Hahn, A., et al. (2020). Deployment of negative emissions technologies at the national level: a need for holistic feasibility assessments. *Front. Clim*. 2:590305. doi: 10.3389/fclim.2020.590305

UNFCCC (2016). *COP21 Report (addendum* 1*), Paris* 2015. *FCCC/CP/*2015/10/*Add.*1. Bonn: United Nations Framework Convention on Climate Change.

United Nations Environment Programme (2020). *Emissions Gap Report 2020.* Nairobi.

Williamson, P. (2016). Emissions reduction: scrutinize CO 2 removal methods. *Nature* 530, 153–155. doi: 10.1038/530153a

Workman, M., Dooley, K., Lomax, G., Maltby, J., and Darch, G. (2020). Decision making in contexts of deep uncertainty – an alternative approach for long-term climate policy. *Environ. Sci. Policy* 103, 77–84. doi: 10.1016/j.envsci.2019.10.002

Woroniecki, S., Wendo, H., Brink, E., Islar, M., Krause, T., Vargas, A. M., et al. (2020). Nature unsettled: how knowledge and power shape "nature-based" approaches to societal challenges. *Glob. Environ. Change* 65:102132. doi: 10.1016/j.gloenvcha.2020.102132

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APPENDIX A: COUNTRY ISO CODES

Austria (AT)
Canada (CA)
Costa Rica (CR)
Czech Republic (CZ)
Denmark (DK)
Germany (DE)
Estonia (EE)
Finland (FI)
Fiji (FJ)
France (FR)
Japan (JP)
Korea (KR)
Latvia (LV)
Marshall Islands (MH)
Mexico (MX)
The Netherlands (NL)
Norway (NO)
Portugal (PT)
Singapore (SG)
Slovakia (SK)
Sweden (SE)
Ukraine (UA)
United Kingdom of Great Britain and Northern Ireland (UK)
United States of America, USA (US)
South Africa (ZA)

APPENDIX B: INTERVIEWS

B14, policymaker, Ireland
F12, practitioner, Costa Rica
M25, diplomat, UK
R13, researcher, UK
T22, diplomat, Denmark

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The Oxymoron of Carbon Dioxide Removal: Escaping Carbon Lock-In and yet Perpetuating the Fossil Status Quo?

*Shinichiro Asayama**

Social Systems Division, National Institute for Environmental Studies, Tsukuba, Japan

There appears to be a paradox in the debate over carbon dioxide removal (CDR) technologies. On the one hand, CDR is recognised as a crucial technical option to offset residual carbon emissions from fossil fuel use, so that it can help a transition to the net-zero energy system. But on the other hand, a serious concern is raised about CDR as a way to circumvent necessary emissions reduction, hence perpetuating the status quo of fossil fuel use. This apparent paradox of CDR, however, has less to do with technology itself but more with the difficulty to move away from *carbon lock-in*—the deeply entrenched fossil-fuel-based energy system. The challenge of decarbonisation is indeed about eroding the deep lock-ins that perpetuate the production and consumption of fossil fuels. To understand the role of CDR in overcoming carbon lock-in, looking back the past debate on carbon capture and storage (CCS) is instructive. Although both CCS and CDR are criticised for keeping the fossil status quo, there is a crucial difference between them. Unlike CCS, CDR can possibly avoid the risk of *reinforced lock-in*, given its physical decoupling from fossil fuel use. And yet CDR has the risk of *undue substitution* that continues unjustly fossil carbon emissions. A change of the framing question is thus needed to puzzle out the paradox of CDR. To rightly place CDR in the challenge of rapid decarbonisation, we should ask more how CDR technologies can be used in alignment with a managed decline to fossil fuel production.

Keywords: carbon dioxide removal, negative emissions technologies, carbon capture and storage, carbon lock-in, mitigation deterrence, fossil fuels, decarbonisation

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Edited by:
James Palmer,
University of Bristol, United Kingdom

Reviewed by:
Kevin Surprise,
Mount Holyoke College, United States
Holly Jean Buck,
University of California, Los Angeles, United States

***Correspondence:**
Shinichiro Asayama
asayama.shinichiro@nies.go.jp
orcid.org/0000-0001-6817-3862

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INTRODUCTION

Achieving the climate goal of the Paris Agreement of keeping global temperature rise well below 2 or 1.5°C requires rapid, deep decarbonisation of the entire global economy (Rockström et al., 2017). This basically means that the world must transition, at *unprecedented* pace, from fossil-fuel-based energy systems into the ones powered by non-carbon energy sources such as renewable, nuclear and hydrogen energy. The pace of change required is really extraordinary. In 2020, by wrecking the global economy, the COVID-19 pandemic caused the largest drop in global CO_2 emissions in a single year, by about 7% relative to 2019 (Friedlingstein et al., 2020; Le Quéré et al., 2021). For meeting the 1.5°C target, the roughly same rate of emissions reduction will have to happen every year until 2030 (IPCC, 2018; UNEP, 2019).

However, the infrastructural inertia of fossil fuel energy system is already jeopardising the challenge of rapid decarbonisation. If existing (and already proposed) fossil-fuel-burning electricity and industry facilities were allowed to operate for historical average lifetimes (e.g., 40 years for power plants), the "committed emissions" from existing energy infrastructure would likely exceed the remaining carbon budget for 1.5°C (Tong et al., 2019). To have a reasonable chance of meeting the 1.5°C target, therefore, not only should a new construction of fossil-fuel power plants be banned but also the early retirement of existing infrastructure must be pursued (Cui et al., 2019; Fofrich et al., 2020). Or otherwise, the current fossil fuel infrastructure has to be retrofitted with carbon capture and storage (CCS) or compensated by carbon dioxide removal (CDR) technologies.

Here, the pictures of "decarbonising" energy systems become murky. On the one hand, there is a growing call for deliberately reducing—and even prohibiting—the production and consumption of fossil fuels (Green, 2018; Piggot et al., 2018, 2020; Rosenbloom and Rinscheid, 2020). The assumption of such a call is that building an anti-fossil fuel norm and increasing the risk of stranded assets through financial divestment and other means will lead to more immediately phasing out fossil fuels and hence accelerating a transition towards non-fossil energy. On the other hand, there is a wide recognition that full decarbonisation would be infeasible without CDR options that offset "residual emissions" from fossil fuels—particularly from the hard-to-abate sectors such as steel and cement manufacturing, long-distance freight, shipping or aviation (Davis et al., 2018; Luderer et al., 2018). The prospect of CDR technologies stems from our *perception* that a complete phase-out of fossil fuels is impractical (at least for a required timescale). The risk of becoming stranded may also be effectively avoided by retrofitting fossil fuel infrastructure with CCS (Johnson et al., 2015).

Fossil fuel use is deeply entrenched in our economy and culture. Our society as a whole is built around fossil fuel energy infrastructure. Given this entrenchment—often called *carbon lock-in*—the role that CDR technologies play in energy decarbonisation is both crucial and risky. Whilst CDR is largely seen as part and parcel of decarbonising fossil fuels, there remains a serious concern that CDR might be used as an excuse for perpetuating the reliance on fossil fuels. This sounds like an oxymoron. It's partly because whether CDR sustains (unnecessarily) fossil fuel dependence is an ideological question—the answer can differ by political preferences between radicalism and pragmatism. But it is also rooted in the difficulty to overcome carbon lock-in by steering the managed decline of fossil fuels.

The challenge of decarbonisation is to erode the deep lock-ins that perpetuate the incumbent fossil-fuel-based energy system. In this article, I explore how carbon removal methods will help or hinder the unlocking of carbon lock-in.

To understand the relationship between carbon removal and carbon lock-in, looking back the past debate on carbon capture technology is illustrative. This is because both CCS and CDR receive the same criticism of perpetuating the lock-in to fossil fuels. However, such criticism often overlooks a crucial, underlying difference between CCS and CDR. As shall be discussed later, whilst CCS involves the risk of *reinforced lock-in* through an increase of the infrastructural inertia, CDR is associated more with the risk of *undue substitution*—allowing unjustly the continued fossil emissions by carbon offsetting. Recognising this difference is key to the understanding of the role of CDR in decarbonisation.

The idea of CCS emerged as a pragmatic response to overcoming carbon lock-in with leaving the existing fossil fuel infrastructure in place. Despite initial enthusiasm, the CCS progress has stagnated, and its promise of decarbonising fossil fuels is yet to be delivered. Now a policy focus is shifting from "capture" (retrofit with CCS) to "removal" (compensation by CDR). This may signal a new promise of overcoming carbon lock-in. And yet the promise of CDR is seen as a latest example of "technologies of prevarication" that may justify another delay of essential mitigation and preserve the status quo (McLaren and Markusson, 2020).

To puzzle out this apparent paradox of CDR, I argue, we need to change the framing of a question to be asked. Rather than asking whether CDR will perpetuate fossil fuels, we should pose a different kind of question: How can CDR technologies be used in alignment with a managed decline to fossil fuels? This eventually comes down to the challenge of mitigating a resistance from old fossil incumbents and involving them more progressively into the politics of decarbonisation.

THE CONUNDRUM OF UNLOCKING CARBON LOCK-IN

Despite a growing sense of urgency for avoiding dangerous climate change, the world is still staggering to embark on rapid decarbonisation. What makes the challenge of decarbonisation so daunting is the self-perpetuating inertia of fossil-fuel-based energy system, which inhibits the emergence of low-carbon alternatives and slows the pace of change towards a sustainable energy future. This energy system's inertial resistance to change is generally known as *carbon lock-in* or sometimes referred to as *fossil fuel lock-in* (Unruh, 2000, 2002). The challenge of rapid decarbonisation is practically about how fast we can move away from—or "unlock"—carbon lock-in (cf. Bernstein and Hoffmann, 2019).

Since Unruh (2000) coined the term carbon lock-in, the concept has attracted a fair amount of scholarly attention for identifying the causes, types or mechanisms of lock-in (e.g., Cairns, 2014; Bertram et al., 2015; Erickson et al., 2015; Seto et al., 2016; Buschmann and Oels, 2019; Janipour et al., 2020; Trencher et al., 2020). A seminal review of the relevant literature by Seto et al. (2016) suggested three types of lock-in that are mutually reinforcing and create collective inertia: infrastructural, institutional, and behavioural lock-ins. Some argue that other forms of lock-in (e.g., cognitive or discursive lock-in) should also be taken into account (Buschmann and Oels, 2019; Trencher et al., 2020). An important point is however that the interactions among technological infrastructures, governing institutions, social practises and cognitive frames give rise to an entrenchment of the energy system that favours the continued use of carbon intensive technologies. Not a single individual factor but a complex *socio-technical entanglement* does cause and sustain carbon lock-in (cf. Cairns, 2014).

Lock-in is the outcome of path dependent processes driven by the mechanism of increasing returns or self-reinforcing positive feedback. Once in place, any locked-in systems—technological, social, political, economic, and cultural—are resistant to changes and seek to keep the status quo. Crucially, as Seto et al. (2016) pointed out, lock-in favours the status quo but is normatively neutral: it can be either positive or negative (for an example of positive lock-in, see Ürge-Vorsatz et al., 2018). Lock-in becomes a problem when already entrenched systems inhibit changes deemed desirable. In this respect, carbon lock-in is arguably a negative condition because it perpetuates high carbon emissions, leading to dangerous consequences.

Moreover, lock-in is not a "permanent condition" but rather a "persistent state" that creates systemic barriers to alternatives (Unruh, 2000). As Cairns (2014) noted, the term lock-in perhaps serves more like a metaphor than in a literal sense of the word. Whether a particular system is "locked in" or not depends on the one's normative view on the timescale within which desired changes *should* happen. Insomuch as a rapid fossil fuel phase-out becomes a political and moral imperative, there is now (we could say) an ever-greater sense among the public of *being* locked into resistant fossil energy regime.

Despite that, carbon intensive technologies such as coal-fired power plants are particularly difficult to unlock. This is because these technologies are costly to build but relatively inexpensive to operate over long infrastructure lifetimes (Erickson et al., 2015). Large capital costs and long lead times create substantial sunk costs; and therefore, prematurely retiring coal-fired power plants would necessarily bear significant financial costs, which in turn makes such a decision politically difficult (cf. Trencher et al., 2020).

FROM CAPTURE TO REMOVAL—ESCAPING CARBON LOCK-IN?

The difficulty to unlock carbon lock-in provides a political economic ground that CCS and CDR could come into the politics of decarbonisation. On the surface, these technological options are appealing because they *promise* to decarbonise fossil fuel infrastructure while preserving it. There is however an important difference between CCS and CDR. That is, since CCS is mainly assumed to be retrofitted with fossil-fuel-burning facilities like coal or gas power plants, CCS deployment is largely inseparable from fossil fuel *use*. On the other hand, CDR use is not necessarily physically tied to the infrastructure that burns fossil fuels. CCS entails the risk of deepening carbon lock-in, which hinges on the infrastructural *inseparability* of CCS from fossil fuel use. A policy shift from CCS to CDR can possibly avoid this risk of reinforced lock-in. Given the physical *separability* from fossil fuel use, CDR is nevertheless associated with the risk of undue substitution for cutting fossil carbon emissions.

CCS and the Risk of Reinforced Lock-In

In the early phase of CCS debate, those who advocated CCS appeared to view this technological option as a sort of pragmatic compromise that could resolve the political dilemma arises from carbon lock-in. To justify the investment into CCS research and development, CCS was often presented as a "bridging technology" towards a renewable energy future (Hansson and Bryngelsson, 2009; Meadowcroft and Langhelle, 2009; Vergragt et al., 2011). The metaphor of bridge was used to emphasise that CCS is a temporary solution to buy time only until better options (i.e., renewables) become available.

This bridge framing fitted well into the perception of CCS advocates that industrial economies are deeply locked into fossil-fuel-burning technologies such as coal power plants, so unlocking them (right now!) is too costly. Because of their recognition—not ignorance—of the difficulty in overcoming carbon lock-in, retrofit with CCS might appear more pragmatic than immediate phase-out. The appeal of CCS was predicated exactly on its promise as a non-disruptive "end-of-pipe" technology to allow the continued use of fossil fuels while mitigating CO_2 emissions (Unruh and Carrillo-Hermosilla, 2006).

Though it might sound reasonable at that time, framing CCS as a bridging technology has turned out be the opposite. As the cost of renewable electricity generation has fallen dramatically over a decade, renewable energy is now the cheapest source of electricity in many places (IEA, 2020). While on the other hand, the progress in CCS development stalled and the technology has not been yet deployed at scale (Reiner, 2016; Bui et al., 2018). The slow progress in CCS was partly due to a lack of political and economic support for closing the financial gap, necessary to operate large-scale demonstration projects (Gaede and Meadowcroft, 2016). Rather than a bridge to renewable energy, the framing of CCS is now "recalibrated" as a *long-term* solution for fully decarbonising the whole energy system (Bui et al., 2018).

More importantly, however, the bridge framing was wrong with its presumption that CCS could somehow provide a way out of carbon lock-in. Instead, it is largely believed that adding CCS on fossil-fuel power plants would risk deepening or reinforcing carbon lock-in—known as *reinforced carbon lock-in* (Unruh and Carrillo-Hermosilla, 2006; Markusson and Haszeldine, 2010; Vergragt et al., 2011; Markusson, 2012; Shackley and Thompson, 2012; Stephens, 2014). This is because "adding CCS" means the building of an entirely new infrastructure for capturing, transporting and storing CO_2 underground as an integrated socio-technical system. Building new CCS infrastructures (capture facility, pipeline, and geological storage) requires large capital investments with long lead-times. This increases substantially the infrastructural inertia of fossil fuel energy system, keeping it in place for several decades. CCS would likely reinforce the lock-in of—and make it difficult to transition away from—fossil fuel system.

It is however worth noting the nuances of the term "reinforced lock-in." Although CCS perpetuates the use of fossil fuels, if worked successfully, it could abate CO_2 emissions from fossil fuel use, which is not necessarily bad. The reinforced lock-in becomes a serious problem when new fossil-fuel power plants are constructed on the promise that CCS will be installed at some point in the future (so-called "capture readiness") but will never actually be deployed, then leaving these plants *unabated* (Markusson and Haszeldine, 2010; Shackley and Thompson, 2012). In short, the over-promise of CCS has the risk of a further lock-in to unabated fossil fuels. According to Markusson and Haszeldine (2010), the only safe way to make sure to avoid this risk of *unabated carbon lock-in* is to not build new fossil plants in the first place.

CDR and the Risk of Undue Substitution

Alternatively, the risk of reinforced lock-in can possibly be avoided by shifting a policy focus from CCS onto CDR (Vergragt et al., 2011). The so-called engineered CDR methods such as bioenergy with CCS (BECCS) or direct air carbon capture and storage (DACCS) use almost identical technologies for CO_2 transport and storage to those used for fossil energy CCS (FECCS). Both BECCS and DACCS are a sort of cousins of CCS-family technologies. However, unlike FECCS, which is retrofitted with fossil fuel facilities, the deployment of BECCS and DACCS does not have to be *physically* coupled with fossil fuel infrastructure (cf. Markusson, 2012). For example, the value of BECCS does not rest only on its ability to provide negative emissions; it also comes from the fact that BECCS serves as an alternative energy source to fossil fuels (Köberle, 2019). FECCS makes an already heavy fossil-fuel system even heavier, but this is not necessarily true for CDR. Theoretically at least, CDR can offset CO_2 emissions from fossil fuels without reinforcing the lock-in to them.

Nevertheless, there is a serious concern about CDR that might deter or delay necessary mitigation (Markusson et al., 2018; McLaren et al., 2019). This concern over "mitigation deterrence" (or otherwise known as "moral hazard") originally comes from the debate over solar geoengineering or solar radiation management (SRM) (see McLaren, 2016). In the geoengineering debate, one of the most lingering, serious concerns is that SRM might become *undue substitution* for mitigation to stop global warming. It is widely recognised that SRM cannot replace mitigation since it doesn't address CO_2 emissions. Despite that, the concern over mitigation deterrence remains acute. This is because SRM has the characteristics that it can act quickly to stop the warming and its use comes with a low-price tag. So, there is a real risk that SRM may well be used as a "cheap, fast and imperfect" substitute for costly mitigation (Keith et al., 2010).

CDR faces the similar concern as dose SRM about being used as poor substitutes for mitigation (Markusson et al., 2018). This is partly because CDR and SRM were often grouped together under the common rubric "geoengineering." Yet this concern over undue substitution is real for CDR. Take for example terrestrial CDR methods such as afforestation.

Afforestation (or tree planting) is now often viewed as a form of land-based CDR methods. But afforestation has also long been recognised as an "accepted" mitigation strategy. For example, the removal by afforestation and reforestation was included in the Kyoto Protocol under the land-use, land-use change and forestry (LULUCF) category. However, there was a huge, political controversy over this decision to include biological carbon sinks as mitigation options (Dooley and Gupta, 2017; Moe and Røttereng, 2018; Carton et al., 2020). The use of terrestrial carbon sinks as carbon offset was—and is still—severely criticised as a way to circumvent necessary mitigation, thereby perpetuating the continued use of fossil fuels.

Ironically, this fear of mitigation deterrence is rooted in an exact reason why CDR is recognised as a crucial policy option. CDR is politically appealing because it *decouples* the nature and cost of emissions reduction from emissions sources in time and space (Kriegler et al., 2013; Lomax et al., 2015). Offsetting by CDR can provide an alternative route to reducing emissions at sectors or sources that are difficult to decarbonise directly, such as aviation or shipping (Davis et al., 2018). As a result, fossil fuels can continue to be used in these hard-to-abate sectors, but this continued reliance on fossil fuels may not necessarily be considered "undue" substitution.

After all, whether CDR causes mitigation deterrence is a matter of definition of *substitutability* between "emissions reduction" and "negative emissions." As Markusson et al. (2018) argued, if the policy goal was determined only in narrow economic terms (e.g., reducing net emissions in the least cost way), the widespread use of CDR might appear a rational choice. But this would likely lead to *misperceived* substitutability that causes harmful consequences and undermines the integrity of mitigation policy. For example, the unrestricted use of land-based CDR might create a perverse incentive to offset industrial carbon emissions from fossil fuels by terrestrial carbon sinks with no considerations of social, ethical and environmental impacts (Dooley and Gupta, 2017; Dooley and Kartha, 2018). Likewise, the prospect of overshoot—i.e., that future large-scale CDR will compensate delayed mitigation today—does not only justify the slow act on mitigation but also risk putting future generations on an unjust gamble (Anderson and Peters, 2016; Lenzi et al., 2018; Asayama and Hulme, 2019).

To prevent such undue substitutions, there is a growing number of the proposals for the "appropriate" use of CDR. For example, McLaren et al. (2019) argue for setting two separate targets for emission reduction and carbon removal rather than a single "net-zero" target. Smith (2021) emphasises the importance of a greater transparency for different storage risks of biological and geological sinks. Others also suggest the principles for guiding the decisions about carbon removal and carbon offsetting (Allen et al., 2020; Morrow et al., 2020).

However, what is the "appropriate" use of CDR is inherently a *political* question. This is actually not so much about technology itself. Rather it is more about how political interests of fossil fuel industry tamper with the use of CDR methods.

DIVORCE FROM FOSSIL FUEL INTERESTS

As discussed above, CCS and CDR typically receive the same criticism made against them: that is, both technologies perpetuate the continued use of fossil fuels. From this perspective, the core aim of both CCS and CDR is to reduce or cancel out fossil CO_2 emissions while preserving (to some degree) the existing fossil fuel infrastructure. Indeed, Markusson et al. (2017), for this reason, have even proposed that CCS and CDR (including SRM) should be referred to as "clean fossil" technologies that promise to defend the incumbent fossil interests and more broadly the fossil-fuel-based economy. But is it really the case that both CCS and CDR must inevitably be closely tied to fossil fuel interests?

In this regard, the relationship between CCS and fossil fuel interests is fairly straightforward. In the public discourse, CCS has been repeatedly described as a pragmatic compromise—or "political glue"—that brings together the competing interests between climate change mitigation and fossil fuel dominance (Hansson and Bryngelsson, 2009; Tjernshaugen and Langhelle, 2009; Pollak et al., 2011; Asayama and Ishii, 2017). From the viewpoint of fossil fuel industry, CCS has an *instrumental* value of serving as a "hedge" to defend their interests and maintain the status quo (Gunderson et al., 2020).

That the material interest of fossil fuel industry is strongly attached to CCS is also evident in a fact that the countries in advance of CCS demonstrations are so far major fossil fuel producers such as Australia, Canada, Norway and the United States (Gaede and Meadowcroft, 2016; Reiner, 2016). CCS with enhanced oil recovery (EOR) is particularly instrumental for those fossil-fuel-rich countries in justifying the continued extraction of massive fossil reserves. This is also why CCS investment from the government is strongly criticised as an additional form of "fossil fuel subsidy" (Stephens, 2014) and is faced with the public scepticism of its legitimacy (Mabon and Littlecott, 2016).

However, not all fossil fuel companies got actively involved in CCS development as their corporate climate strategies. Tjernshaugen (2012) found that the companies like ExxonMobil who took a resistant strategy (i.e., denying the scientific reality of global warming and opposing the governmental regulations) largely stayed away from CCS activities. On the other hand, those companies like BP and Statoil were more actively engaged with promoting CCS as a legitimate mitigation option. These differences show clearly that the fossil fuel industry is far from being homogeneous in its approach to climate change. On top of that, they suggest that the *promise* of CCS—rather than its actual use—has the power of defending fossil fuel interests, regardless of whether or not such promise is delivered.

Meanwhile, CDR has a more modest relationship with fossil fuel interests. In a sense, CDR seems like an "orphan technology"—the technology that does not have the private sector (i.e., the parent), who is willing to bear the costs of its development despite its apparent public benefit (Wagner, 1992). Without any financial support from the public sector, CDR technologies would be more likely to go undeveloped. Whilst the similar argument can be made for CCS development (cf. Gaede and Meadowcroft, 2016), CCS *deployment* is largely inseparable from fossil fuel use (except its application to industrial processes). On the other hand, CDR need not necessarily be of principal interest to fossil fuel companies but to a much wider range of actors, because its use is physically decoupled from fossil fuel use.

The physical decoupling does not of course mean that CDR is independent from the financial and political interests of fossil fuel industry. As seen above, there is always the risk that CDR could be used expediently as a substitute for cutting fossil carbon emissions. For example, a global oil major Shell recently announced that the company sought to achieve net-zero carbon emissions by 2050, but their net-zero pledge resorts to carbon offset from tree planting to a large degree (Ambrose, 2021). In January 2020, the World Economic Forum launched the One Trillion Trees initiative for the fight against climate change. And this captured immediate attention from former US President Donal Trump who sowed doubt on global warming and withdrew from the Paris Agreement. As Ellis et al. (2020) argued, this renewed attention to tree planting may risk being a dangerous diversion from the efforts to end the use of fossil fuels (see also Carton et al., 2020; Seymour, 2020).

At the end of the day, what really matters to the governance of CDR seems to be the prevention of fossil fuel interests from having an "undue" influence on policy decisions about the development and deployment of CDR technologies.

ALIGN WITH FOSSIL FUEL DECLINE

Here, I argue that, rather than asking whether CDR will perpetuate the status quo of fossil fuel use, we should flip the question and ask instead: How can we align the use of CDR methods with managing a phase-out of fossil fuel production? Insomuch as CDR deployment could be compatible with the continued use of fossil fuels, it could also be aligned with the managed decline to fossil fuels. This is because, unlike CCS, CDR can be physically independent of specific emission sources (Kriegler et al., 2013; Lomax et al., 2015). CDR development and fossil fuel decline doesn't have to come into conflict with each other.

For example, fossil fuel divestment emerged as the global social movement that aims at undermining the legitimacy of fossil fuel industry (Rosenbloom and Rinscheid, 2020). While being successful as effective media campaigns for spreading an anti-fossil fuel norm (Green, 2018), the divestment movement largely failed to alter the capital flow into fossil fuel stocks in financial markets as a whole (Mormann, 2020). This is, according to Mormann (2020), partly due to the movement's focus on divestment from fossil fuel stocks but little guidance on reinvestment choices. Here, we can take advantage of the funds divested from fossil fuel stocks to reinvest into the development of CDR technologies. Such reinvestment strategy may face a backlash from climate activist groups. But assessing and informing the risk and benefit of financial investment on CDR technologies could help investors to make better investment decisions. There is no reason to preclude CDR as low-carbon investment choices.

Furthermore, we need to pluralise our views on fossil fuel incumbencies (Turnheim and Sovacool, 2020). The divestment movement often portrays fossil fuel companies as villains that irremediably resist the change and therefore should be dismantled all together. But not all fossil fuel companies are created equal (cf. Mormann, 2020). This was evidenced by different strategies on CCS activities among big oil companies (Tjernshaugen, 2012).

It is true that some fossil fuel companies, particularly in the US, were behind the organised denial machine to sow doubt on global warming (Dunlap and McCright, 2011; Supran and Oreskes, 2017). A dark history of climate change disinformation by fossil fuel industry should not be ignored. Nevertheless, it is also true that the industry's *expertise* is applicable not only to the extraction of fossil resources themselves; many fossil fuel companies also have significant geological and engineering expertise as well as capital assets that could be repurposed for large-scale CDR deployment (Hastings and Smith, 2020).

Catalysing a rapid phase-out of fossil fuels disrupts the financial stability of fossil fuel industry. It is no surprise that such efforts meet the resistance of incumbent fossil regime (Geels, 2014). But not all incumbents will remain stuck in old paradigms—their behaviours and strategies change over time following the political dynamics (Turnheim and Sovacool, 2020). They may seek to leverage their resources to diversify into new domain of activities. Here, CDR could become a political middle ground for mitigating a regime resistance and involving old incumbents more progressively into a low-carbon transition. Practically, this means that fossil fuel industry should morph into the "carbon disposal industry," the core mission of which focuses primarily on permanent storage of CO_2 in geological reservoirs (Allen et al., 2009; Buck, 2020; Hastings and Smith, 2020).

Of course, this kind of industrial transformation will not happen on its own. Nor will fossil fuel industry make a shift by itself. It is only through raising political pressures that we could perhaps "responsibly incentivise" fossil fuel industry to make a radical change towards carbon disposal industry (cf. Bellamy, 2018). And to get a democratic grip on such transition, it is crucial to articulate geological CO_2 disposal as a *public good* rather than private enterprises (Buck, 2020).

CONCLUSIONS

Since the Paris Agreement, the net-zero target has emerged as an anchor of climate policy debate (Geden, 2016). Accordingly, the boundary between mitigation and CDR becomes increasingly blurred (Cox et al., 2018; Minx et al., 2018). Now CDR methods are more or less normalised as an "extension of mitigation" or "unconventional mitigation" (Geden and Schenuit, 2020).

From the viewpoint of carbon budget, insofar as positive emissions are being compensated by negative emissions, the risk of "mitigation" deterrence might appear as a marginal concern. So, why are we still debating about how to "mitigate" carbon emissions? It is precisely because "decarbonising" the energy system cannot be taken as synonymous with meeting the "net-zero" target. There are many different decarbonisation pathways towards a net-zero future. What is hidden under this ambitious policy goal is the contested politics on the ground about decarbonising fossil fuels.

A climate policy tends to focus on the technicality of reaching net-zero emissions. This is evident in the fact that the phrase "fossil fuels" is missing from the text of the Paris Agreement (Piggot et al., 2018). It may however risk losing slight of a real challenge in the politics of decarbonisation—how to erode the deep lock-ins that perpetuate the production and consumption of fossil fuels. Perhaps the debate on CDR governance too has been narrowly caught up in delivering the promise of net-zero. But, as curbing fossil fuel supply is becoming a major topic in the climate policy conversation (Piggot et al., 2020), now is a time to turn around the question about the role of CDR in energy decarbonisation.

Gaede and Meadowcroft (2016) argued that CCS was a "Janus-faced technology" that could both slow and accelerate the transition to a decarbonised energy future. Likewise, CDR is a double-edged sword for rapid decarbonisation. CDR could be a useful complement to balancing out "recalcitrant" emissions from the hard-to-abate sectors. At the same time, they could serve as an expedient substitute for reducing "superfluous" emissions to preserve the status quo of fossil fuel use. This dilemma is however not so much a problem of technology. CDR is at the middle of our love and hate relationship with fossil fuels. To get out of this dilemma, we should ask more how developing CDR technologies can be aligned with managing the decline to fossil fuel production.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

The author confirms sole responsibility of the study conception, analysis, and manuscript preparation.

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REFERENCES

Allen, M., Axelsson, K., Caldecott, B., Hale, T., Hepburn, C., Hickey, C., et al. (2020). *The Oxford Principles for Net Zero Aligned Carbon Offsetting*. Oxford: Smith School of Enterprise and the Environment, University of Oxford. Available online at: https://www.smithschool.ox.ac.uk/publications/reports/Oxford-Offsetting-Principles-2020.pdf (accessed June 10, 2021).

Allen, M. R., Frame, D. J., and Mason, C. F. (2009). The case for mandatory sequestration. *Nat. Geosci.* 2, 813–814. doi: 10.1038/ngeo709

Ambrose, J. (2021). Shell to expand gas business despite pledge to speed up net zero carbon drive. *The Guardian*. Available online at: https://www.theguardian.com/business/2021/feb/11/shell-grow-gas-business-energy-net-zero-carbon (accessed June 10, 2021).

Anderson, K., and Peters, G. (2016). The trouble with negative emissions. *Science* 354, 182–183. doi: 10.1126/science.aah4567

Asayama, S., and Hulme, M. (2019). Engineering climate debt: temperature overshoot and peak-shaving as risky subprime mortgage lending. *Clim. Policy* 19, 937–946. doi: 10.1080/14693062.2019.1623165

Asayama, S., and Ishii, A. (2017). Selling stories of techno-optimism? The role of narratives on discursive construction of carbon capture and storage in the Japanese media. *Energy Res. Soc. Sci.* 31, 50–59. doi: 10.1016/j.erss.2017.06.010

Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nat. Energy* 3, 532–534. doi: 10.1038/s41560-018-0156-6

Bernstein, S., and Hoffmann, M. (2019). Climate politics, metaphors and the fractal carbon trap. *Nat. Clim. Chang.* 9, 919–925. doi: 10.1038/s41558-019-0618-2

Bertram, C., Johnson, N., Luderer, G., Riahi, K., Isaac, M., and Eom, J. (2015). Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technol. Forecast. Soc. Change* 90, 62–72. doi: 10.1016/j.techfore.2013.10.001

Buck, H. J. (2020). Should carbon removal be treated as waste management? Lessons from the cultural history of waste. *Interface Focus* 10:20200010. doi: 10.1098/rsfs.2020.0010

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., et al. (2018). Carbon capture and storage (CCS): the way forward. *Energy Environ. Sci.* 11, 1062–1176. doi: 10.1039/C7EE02342A

Buschmann, P., and Oels, A. (2019). The overlooked role of discourse in breaking carbon lock-in: the case of the German energy transition. *Wiley Interdiscip. Rev. Clim. Chang.* 10:e574. doi: 10.1002/wcc.574

Cairns, R. (2014). Climate geoengineering: issues of path-dependence and socio-technical lock-in. *Wiley Interdiscip. Rev. Clim. Chang.* 5, 649–661. doi: 10.1002/wcc.296

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *Wiley Interdiscip. Rev. Clim. Chang.* 11:e671. doi: 10.1002/wcc.671

Cox, E. M., Pidgeon, N., Spence, E., and Thomas, G. (2018). Blurred lines: the ethics and policy of greenhouse gas removal at scale. *Front. Environ. Sci.* 6:38. doi: 10.3389/fenvs.2018.00038

Cui, R. Y., Hultman, N., Edwards, M. R., Mcjeon, H., Iyer, G., Patel, P., et al. (2019). Quantifying operational lifetimes for coal power plants under the Paris goals. *Nat. Commun.* 10:4759. doi: 10.1038/s41467-019-12618-3

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., et al. (2018). Net-zero emissions energy systems. *Science* 360:eaas9793. doi: 10.1126/science.aas9793

Dooley, K., and Gupta, A. (2017). Governing by expertise: the contested politics of (accounting for) land-based mitigation in a new climate agreement. *Int. Environ. Agreements Polit. Law Econ.* 17, 483–500. doi: 10.1007/s10784-016-9331-z

Dooley, K., and Kartha, S. (2018). Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *Int. Environ. Agreements Polit. Law Econ.* 18, 79–98. doi: 10.1007/s10784-017-9382-9

Dunlap, R. E., and McCright, A. M. (2011). "Organized climate change denial," in *The Oxford Handbook of Climate Change and Society*, eds. J. S. Dryzek, R. B. Norgaard, and D. Schlosberg (Oxford: Oxford University Press) 144–160.

Ellis, E., Maslin, M., and Lewis, S. (2020). Planting trees won't save the world. *The New York Times*. Available at: https://www.nytimes.com/2020/02/12/opinion/trump-climate-change-trees.html (accessed June 10, 2021).

Erickson, P., Kartha, S., Lazarus, M., and Tempest, K. (2015). Assessing carbon lock-in. *Environ. Res. Lett.* 10:084023. doi: 10.1088/1748-9326/10/8/084023

Fofrich, R. A., Tong, D., Calvin, K. V., de Boer, H. S., Emmerling, J., Fricko, O., et al. (2020). Early retirement of power plants in climate mitigation scenarios. *Environ. Res. Lett.* 15:094064. doi: 10.1088/1748-9326/ab96d3

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., et al. (2020). Global carbon budget 2020. *Earth Syst. Sci. Data* 12, 3269–3340. doi: 10.5194/essd-12-3269-2020

Gaede, J., and Meadowcroft, J. (2016). "Carbon capture and storage demonstration and low-carbon energy transitions: explaining limited progress," in *The Palgrave Handbook of the International Political Economy of Energy*, eds T. van de Graaf, B. K. Sovacool, A. Ghosh, F. Kern, and M. T. Klare (London: Palgrave Macmillan), 319–340.

Geden, O. (2016). An actionable climate target. *Nat. Geosci.* 9, 340–342. doi: 10.1038/ngeo2699

Geden, O., and Schenuit, F. (2020). *Unconventional Mitigation: Carbon Dioxide Removal as a New Approach in EU Climate Policy*. Berlin: Stiftung Wissenschaft und Politik. doi: 10.18449/2020RP08

Geels, F. W. (2014). Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective. *Theory, Cult. Soc.* 31, 21–40. doi: 10.1177/0263276414531627

Green, F. (2018). Anti-fossil fuel norms. *Clim. Change.* 150, 103–116. doi: 10.1007/s10584-017-2134-6

Gunderson, R., Stuart, D., and Petersen, B. (2020). The fossil fuel industry's framing of carbon capture and storage: faith in innovation, value instrumentalization, and status quo maintenance. *J. Clean. Prod.* 252:119767. doi: 10.1016/j.jclepro.2019.119767

Hansson, A., and Bryngelsson, M. (2009). Expert opinions on carbon dioxide capture and storage—a framing of uncertainties and possibilities. *Energy Policy* 37, 2273–2282. doi: 10.1016/j.enpol.2009.02.018

Hastings, A., and Smith, P. (2020). Achieving net zero emissions requires the knowledge and skills of the oil and gas industry. *Front. Clim.* 2:601778. doi: 10.3389/fclim.2020.601778

IEA (2020). *World Energy Outlook 2020*. Paris: International Energy Agency.

IPCC (2018). *Global Warming of 1.5°C*. Geneva: World Meteorological Organization.

Janipour, Z., de Nooij, R., Scholten, P., Huijbregts, M. A. J., and de Coninck, H. (2020). What are sources of carbon lock-in in energy-intensive industry? A case study into Dutch chemicals production. *Energy Res. Soc. Sci.* 60:101320. doi: 10.1016/j.erss.2019.101320

Johnson, N., Krey, V., McCollum, D. L., Rao, S., Riahi, K., and Rogelj, J. (2015). Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants. *Technol. Forecast. Soc. Change* 90, 89–102. doi: 10.1016/j.techfore.2014.02.028

Keith, D. W., Parson, E., and Morgan, M. G. (2010). Research on global sun block needed now. *Nature* 463, 426–427. doi: 10.1038/463426a

Köberle, A. C. (2019). The value of BECCS in IAMs: a review. *Curr. Sustain. Energy Rep.* 6, 107–115. doi: 10.1007/s40518-019-00142-3

Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G., and Klein, D. (2013). Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Clim. Change* 118, 45–57. doi: 10.1007/s10584-012-0681-4

Le Quéré, C., Peters, G. P., Friedlingstein, P., Andrew, R. M., Canadell, J. G., Davis, S. J., et al. (2021). Fossil CO_2 emissions in the post-COVID-19 era. *Nat. Clim. Chang.* 11, 197–199. doi: 10.1038/s41558-021-01001-0

Lenzi, D., Lamb, W. F., Hilaire, J., Kowarsch, M., and Minx, J. C. (2018). Weigh the ethics of plans to mop up carbon dioxide. *Nature* 561, 303–305. doi: 10.1038/d41586-018-06695-5

Lomax, G., Workman, M., Lenton, T., and Shah, N. (2015). Reframing the policy approach to greenhouse gas removal technologies. *Energy Policy* 78, 125–136. doi: 10.1016/j.enpol.2014.10.002

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O. Y., Pietzcker, R. C., Rogelj, J., et al. (2018). Residual fossil CO_2 emissions in 1.5–2°C pathways. *Nat. Clim. Chang.* 8, 626–633. doi: 10.1038/s41558-018-0198-6

Mabon, L., and Littlecott, C. (2016). Stakeholder and public perceptions of CO_2-EOR in the context of CCS—results from UK focus groups and implications for policy. *Int. J. Greenh. Gas Control.* 49, 128–137. doi: 10.1016/j.ijggc.2016.02.031

Markusson, N. (2012). Born again: the debate on lock-in and CCS. *Energy Environ.* 23, 389–394. doi: 10.1260/0958-305X.23.2-3.389

Markusson, N., Dahl Gjefsen, M., Stephens, J. C., and Tyfield, D. (2017). The political economy of technical fixes: the (mis)alignment of clean fossil and political regimes. *Energy Res. Soc. Sci.* 23, 1–10. doi: 10.1016/j.erss.2016.11.004

Markusson, N., and Haszeldine, S. (2010). "Capture ready" regulation of fossil fuel power plants—Betting the UK's carbon emissions on promises of future technology. *Energy Policy* 38, 6695–6702. doi: 10.1016/j.enpol.2010.06.039

Markusson, N., Mclaren, D., and Tyfield, D. (2018). Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Glob. Sustain.* 1:e10. doi: 10.1017/sus.2018.10

McLaren, D. (2016). Mitigation deterrence and the "moral hazard" of solar radiation management. *Earth's Fut.* 4, 596–602. doi: 10.1002/2016EF000445

McLaren, D., and Markusson, N. (2020). The co-evolution of technological promises, modelling, policies and climate change targets. *Nat. Clim. Chang.* 10, 392–397. doi: 10.1038/s41558-020-0740-1

McLaren, D., Tyfield, D., Willis, R., Szerszynski, B., and Markusson, N. (2019). Beyond "net-zero": a case for separate targets for emissions reduction and negative emissions. *Front. Clim.* 1:4. doi: 10.3389/fclim.2019.00004

Meadowcroft, J., and Langhelle, O. (2009). *Caching the Carbon: The Politics and policy of Carbon Capture and Storage*. Cheltenham: Edward Elgar Publishing.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Lenzi, D., et al. (2018). Negative emissions-Part 1: research landscape, ethics and synthesis. *Environ. Res. Lett.* 13:063001. doi: 10.1088/1748-9326/aabf9b

Moe, E., and Røttereng, J.-K. S. (2018). The post-carbon society: rethinking the international governance of negative emissions. *Energy Res. Soc. Sci.* 44, 199–208. doi: 10.1016/j.erss.2018.04.031

Mormann, F. (2020). Why the divestment movement is missing the mark. *Nat. Clim. Chang.* 10, 1067–1068. doi: 10.1038/s41558-020-00950-2

Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., et al. (2020). Principles for thinking about carbon dioxide removal in just climate policy. *One Earth* 3, 150–153. doi: 10.1016/j.oneear.2020.07.015

Piggot, G., Erickson, P., van Asselt, H., and Lazarus, M. (2018). Swimming upstream: addressing fossil fuel supply under the UNFCCC. *Clim. Policy* 18, 1189–1202. doi: 10.1080/14693062.2018.1494535

Piggot, G., Verkuijl, C., van Asselt, H., and Lazarus, M. (2020). Curbing fossil fuel supply to achieve climate goals. *Clim. Policy* 20, 881–887. doi: 10.1080/14693062.2020.1804315

Pollak, M., Phillips, S. J., and Vajjhala, S. (2011). Carbon capture and storage policy in the United States: a new coalition endeavors to change existing policy. *Glob. Environ. Chang.* 21, 313–323. doi: 10.1016/j.gloenvcha.2011.01.009

Reiner, D. M. (2016). Learning through a portfolio of carbon capture and storage demonstration projects. *Nat. Energy* 1:15011. doi: 10.1038/nenergy.2015.11

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., and Schellnhuber, H. J. (2017). A roadmap for rapid decarbonization. *Science* 355, 1269–1271. doi: 10.1126/science.aah3443

Rosenbloom, D., and Rinscheid, A. (2020). Deliberate decline: an emerging frontier for the study and practice of decarbonization. *Wiley Interdiscip. Rev. Clim. Chang.* 11:e669. doi: 10.1002/wcc.669

Seto, K. C., Davis, S. J., Mitchell, R., Stokes, E. C., Unruh, G., and Ürge-Vorsatz, D. (2016). Carbon lock-in: types, causes, and policy Implications. *Annu. Rev. Environ. Resour.* 41, 425–452. doi: 10.1146/annurev-environ-110615-085934

Seymour, F. (2020). Seeing the forests as well as the (trillion) trees in corporate climate strategies. *One Earth* 2, 390–393. doi: 10.1016/j.oneear.2020.05.006

Shackley, S., and Thompson, M. (2012). Lost in the mix: will the technologies of carbon dioxide capture and storage provide us with a breathing space as we strive to make the transition from fossil fuels to renewables? *Clim. Change* 110, 101–121. doi: 10.1007/s10584-011-0071-3

Smith, S. M. (2021). A case for transparent net-zero carbon targets. *Commun. Earth Environ.* 2:24. doi: 10.1038/s43247-021-00095-w

Stephens, J. C. (2014). Time to stop investing in carbon capture and storage and reduce government subsidies of fossil-fuels. *Wiley Interdiscip. Rev. Clim. Chang.* 5, 169–173. doi: 10.1002/wcc.266

Supran, G., and Oreskes, N. (2017). Assessing ExxonMobil's climate change communications (1977–2014). *Environ. Res. Lett.* 12:084019. doi: 10.1088/1748-9326/aa815f

Tjernshaugen, A. (2012). Technological power as a strategic dilemma: CO_2 capture and storage in the international oil and gas industry. *Glob. Environ. Polit.* 12, 8–29. doi: 10.1162/GLEP_a_00095

Tjernshaugen, A., and Langhelle, O. (2009). "Technology as political glue: CCS in Norway," in *Caching the Carbon. The Politics and Policy of Carbon Capture and Storage*, eds J. Meadowcroft and O. Langhelle (Cheltenham: Edward Elgar Publishing), 98–124.

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., et al. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target. *Nature* 572, 373–377. doi: 10.1038/s41586-019-1364-3

Trencher, G., Rinscheid, A., Duygan, M., Truong, N., and Asuka, J. (2020). Revisiting carbon lock-in in energy systems: explaining the perpetuation of coal power in Japan. *Energy Res. Soc. Sci.* 69:01770. doi: 10.1016/j.erss.2020.101770

Turnheim, B., and Sovacool, B. K. (2020). Forever stuck in old ways? Pluralising incumbencies in sustainability transitions. *Environ. Innov. Soc. Trans.* 35, 180–184. doi: 10.1016/j.eist.2019.10.012

UNEP (2019). *Emissions Gap Report 2019*. Nairobi: United Nations Environment Programme.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy* 28, 817–830. doi: 10.1016/S0301-4215(00)00070-7

Unruh, G. C. (2002). Escaping carbon lock-in. *Energy Policy* 30, 317–325. doi: 10.1016/S0301-4215(01)00098-2

Unruh, G. C., and Carrillo-Hermosilla, J. (2006). Globalizing carbon lock-in. *Energy Policy* 34, 1185–1197. doi: 10.1016/j.enpol.2004.10.013

Ürge-Vorsatz, D., Rosenzweig, C., Dawson, R. J., Sanchez Rodriguez, R., Bai, X., Barau, A. S., et al. (2018). Locking in positive climate responses in cities. *Nat. Clim. Chang.* 8, 174–177. doi: 10.1038/s41558-018-0100-6

Vergragt, P. J., Markusson, N., and Karlsson, H. (2011). Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in. *Glob. Environ. Chang.* 21, 282–292. doi: 10.1016/j.gloenvcha.2011.01.020

Wagner, J. L. (1992). Orphan technologies: defining the issues. *Int. J. Technol. Assess. Health Care* 8, 561–565. doi: 10.1017/S0266462300002269

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POLICY BRIEF
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A Deliberative Orientation to Governing Carbon Dioxide Removal: Actionable Recommendations for National-Level Action

Amanda C. Borth[1]* *and Simon Nicholson*[2]

[1] Department of Communication, George Mason University, Fairfax, VA, United States, [2] Institute for Carbon Removal Law and Policy, American University, Washington, DC, United States

Effective and legitimate governance of carbon dioxide removal (CDR) requires that the needs, interests, and perspectives of those liable to bear the burdens of CDR's effects be present in decision-making and oversight processes. This ideal has been widely recognized in prior academic work. How, though, in a practical sense, is this deliberative aspect of CDR governance to be understood? In this policy brief, we look at the future incorporation of carbon removal pledges into the nationally determined contributions (NDCs) of countries under the Paris Agreement, and we argue for and explore a *deliberative orientation* when it comes to the inclusion of CDR into country-level climate change response goals. The aim is to provide practical guidance on deliberation as a toolkit and set of practices.

Keywords: carbon dioxide removal (CDR), Paris Agreement, Nationally Determined Contribution (NDC), deliberation, deliberative democracy, communication

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***Correspondence:**
Amanda C. Borth
aborth@gmu.edu

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INTRODUCTION

Scientific assessment of the future trajectories and impacts of climate change now suggest that carbon dioxide removal (CDR) must be part of humanity's response to climate change (IPCC, 2018). Drawing down carbon dioxide from the atmosphere at a scale that would help to avoid the worst effects of climate change calls for a range of potential CDR approaches alongside other climate change response options. However, not all CDR options are created equal. Each has its own suite of drawbacks, co-benefits, and questions having to do with appropriate utilization and scale (Morrow et al., 2018). How, then, can governance architectures—and the people working in and around those architectures—juggle technical, social, and environmental considerations to ensure that development and any scaling up of the use of CDR approaches are safe, just, effective, and sustainable?

The starting point for this policy brief is that the governance challenges associated with CDR suggest a role for a set of ideas and approaches often lumped together as *deliberation.* While significant work has been done on deliberation and CDR via group facilitations, we argue that an expanded role for deliberative thinking is needed to ensure governance frameworks and democratic processes account for societal values and knowledge while also handling conflicting interests in pursuit of the common good (Parkhill et al., 2013; Burns and Flegal, 2015; Bellamy and Lezaun, 2017; Pidgeon, 2021). We make the case that negotiators, specifically, and others who work within governments to construct nationally determined contribution (NDC), generally, ought to take a *deliberative orientation*—approaching their verbal and written communication by enacting standards of good deliberative practice—to the work of CDR governance.

We have in mind that CDR looks set to play a more prominent role in the NDCs of parties to the Paris Agreement. The development, negotiation, and implementation of NDCs, in turn, constitute ripe sites for the broader and constructive adoption of deliberative practice. We outline a deliberative orientation centered on the NDCs by: (1) describing the features of CDR uptake that call for deliberative practice; (2) defining deliberation; (3) explaining what deliberation can do for the governance of CDR; and (4) evaluating what deliberation has done thus far for CDR governance. These learnings are used to craft the concept of a deliberative orientation and to offer actionable recommendations on how a deliberative orientation can be used in the further development of country-level climate action pledges that incorporate CDR.

CDR IN THE NDCs: AN OPPORTUNITY FOR A DELIBERATIVE ORIENTATION

In this opening section, we set the context for this brief by first providing a primer on the NDC process and CDR's current role within it. We then highlight features of CDR's further incorporation into NDCs that call for a deliberative orientation in the process of developing these country-level pledges.

Where CDR Meets the NDCs

The nationally determined contributions (NDCs) are the mechanism under the Paris Agreement by which countries that are party to the agreement make pledges for climate action. Article 4(2) of the Paris Agreement calls on each party to "prepare, communicate and maintain successive [NDCs] that it intends to achieve" (Paris Agreement, 2015). NDCs are meant to signal and to drive domestic climate action and to be strengthened through time via what is known in the Paris Agreement framework as the "global stocktake".[1]

The potential for countries to bring CDR into NDC commitments is invited by Article 4(1) of the Paris Agreement, with its call for "… a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century …." (Paris Agreement, 2015) However, CDR has, to this point, been largely in the background of Paris Agreement activities. While more than 75% of the first round of NDCs contained forest sector targets, very few of those targets called expressly for the counting of carbon removals via biological sinks toward country net emissions goals (Sato et al., 2019, p. 3). Additionally, none of the first round NDCs suggested a planned reliance by any country on engineered carbon removal options or on an ambitious scaling up of non-forest biological CDR pathways.

This, though, looks set to change. Some recent net-zero pledges from countries are giving express reference to CDR options. Switzerland, for instance, has been explicit about a necessary reliance on some amount of technological CDR to meet a net-zero by 2050 target, while the European Union has outlined technological CDR options in the analysis supporting its net-zero target setting (European Commission, 2018; The Federal Council, 2020). As further net-zero pledges are made, a sharper focus on the necessary role to be played by CDR approaches can be expected, and, in fact, CDR-relevant domestic policymaking is already very much underway (Schenuit et al., 2021). There has also been a surge of corporate carbon removal pledges which are likely, in time, to inform country-level policy and target setting[2].

Such announcements raise an important consideration for CDR's future incorporation into NDCs as they speak to how NDCs are created. Each country government has followed its own NDC development process. One of the results of this heterogeneity is that the first- and second-round NDCs, revealed to date, are highly varied in terms of their content, length, and degrees of attention to various climate-relevant subject matters[3]. This represents a general shift produced by the NDCs within international climate negotiations significantly marked by, as Keohane and Oppenheimer (2016) have put it, a movement from a Kyoto-era system of "mandates and simplicity" to a structure premised on "discretion and vagueness" (p. 146). This vagueness is, to some extent, by design, giving individual countries latitude in the establishment and conveyance of climate action priorities. For some countries, though, the vagueness in NDCs signals a set of capacity issues, as governments were required by first-round NDCs, in some instances for the first time, to identify national-level climate change mitigation and adaptation targets without an infrastructure or set of processes for the development of such targets (Röser et al., 2020).

Across the variance described above, there are some common opportunities and challenges presented by the likely further incorporation of CDR into NDCs. The case we set out in the remainder of this note is that it is essential, as CDR finds its way more fully into pledges under the Paris Agreement, that more than lip service be given to the art and actions of deliberation. As a starting point, we outline here two features associated with the broader uptake of CDR that suggest the need and give a starting point for the characterization of effective CDR-focused deliberative practice and that direct attention to some of the required steps associated with consideration of CDR in national-level climate action and target setting.

[1]Article 14 of the Paris Agreement calls on the Conference of the Parties to "periodically take stock of this Agreement to assess the collective progress toward achieving the purpose of the Agreement," indicates that such a stocktake should occur every five years beginning in 2023, and directs that the outcomes of the stocktake "shall inform Parties in updating and enhancing, in a nationally determined manner, their actions and support." This last point is a supplement to language in Article 4(9), directing each party to "communicate a nationally determined contribution every five years … and be informed by the outcomes of the global stocktake referred to in Article 14" (Paris Agreement, 2015). The global stocktake and relevant provisions are meant to serve as a rachet mechanism in the agreement, such that the NDCs of each party express greater ambition and lay the path to greater levels of climate action for each party through time.

[2]See the Institute for Carbon Removal Law and Policy's corporate carbon removal action tracker: https://docs.google.com/spreadsheets/d/1vf--uXsf6fo7MuNpPya2Kz82Dxte0hHgtOXimgpRA3c/.

[3]The degree of differentiation in second round NDCs can be expected to be far lower than in the first round, due to the guidance on NDC subject matter and accounting provided by the Paris Rulebook.

Feature 1: CDR Entails Domestic Action Toward International Goals

Incorporating CDR into NDCs is, at face-value, a country-level task; however, it is truly an international endeavor. The chief reason to explore CDR's role in country-level NDCs is in response to global climate change targets set out by the Paris Agreement. This feature—the synergy between domestic actions and international goals—both calls for national-level consultation of international voices when developing NDCs and presents an opportunity for deliberative practices to answer that call.

More precisely, we are pointing out that the CDR component of an individual country's NDC cannot, ultimately, be established without reference to the CDR plans and targets of other countries nor without regard to possible spillover impacts. Scaling CDR projects undertaken largely or fully within a country could conflict with targets developed and actions taken by other countries. For instance, the carbon drawdown potential via afforestation is large, but limited, such that equity considerations ought to be at play in how CDR from afforestation is distributed across NDCs (Pozo et al., 2020). The same can broadly be said among other forms of carbon removal. This suggests a need for efforts by those developing NDCs to work in close consultation with counterparts in other countries, even in the production of targets. A deliberative approach speaks to this need: Enacting the characteristics of deliberative practice—expressed later in **Table 1**—may aid those responsible for the establishment of NDCs to bring the perspectives of other countries into conversation with their own when it comes to the roles CDR may play in pursuit of Paris targets.

Feature 2: CDR Interacts With Other Environmental and Social Imperatives

Tackling climate change is about much more than limiting atmospheric concentrations of greenhouse gases. As Morrow et al. (2020) have noted, when it comes to CDR, "it's not all about the carbon" (at p. 151). The precise actions taken in pursuit of climate goals matter for people and the planet, such that climate action must be structured in ways that account for all dimensions of particular response options—social impacts, technical characteristics, and environmental co-benefits and risks. This suggests a need to keep environmental justice considerations to the fore, ensuring that activities are crafted with benefits and costs to the most vulnerable top of mind, with the practical implication that those liable to be impacted by CDR developments have a strong voice in the creation of those developments. This suggests both a need and an opportunity for a deliberative orientation when it comes to the development of NDCs.

The need is that high-level targets be attentive to the potential distributional and direct impacts of CDR developments. The opportunity comes in the enlisting of a wider array of voices and perspectives in the establishment of NDC targets, including from those likely to be impacted. We have more to say on these points below. At its broadest, the establishment of CDR-specific targets in NDCs invites more attention to the climate action roles of non-state actors and the incorporation of non-state actors into NDC creation processes (Hsu et al., 2019). This suggests coordination and consultation not just with public sector but also private sector entities. Governments can be expected to invest directly in CDR schemes and set the conditions for CDR to emerge (or not) in particular jurisdictions. At the same time, much, and perhaps most, CDR development will be driven by and come from actions by and activities in the private sector. There is a need, presented by the further incorporation of CDR into NDCs, to establish

TABLE 1 | Qualities of good deliberative practice.

Quality	Description
Guiding Qualities	*Attributes of deliberation that are basic to and undergird all other qualities of deliberation*.
Mutual respect	Working to understand one another's motivations, experiences, and interpretations of reality.
Absence of coercive power	Addressing and redressing power imbalances. Attempting to move others against their will should have no place in deliberation. Rather, those involved ought to open space for free, equal communication and provide one another with the resources necessary to have equal opportunity for shared understanding.
Core Qualities	*Attributes of deliberation that set it apart from other forms of communication*.
Reason-giving	Giving arguments that carefully link premise to conclusion. This quality must accommodate differences in speaking and reasoning (rational arguments, rhetoric, storytelling, etc.) among those from diverse cultural backgrounds. It also entails an emotional commitment to, at minimum, the process of reasoning.
Active listening	Listening *to* others and *for* previously unheard voices. The listener actively engages with a speaker through verbal communication to check that they understand the speaker's perceptions and experiences that underlie their reason-giving as completely as possible (e.g., eliciting reflexive feedback via clarifying questions) and is attentive to how non-verbal communication may enhance that understanding.
Elevating Qualities	*Attributes of deliberation that are sometimes contested, not specific to deliberation* per se, *but enhance its ability to achieve the various goals of deliberation (i.e., arriving at the best answer to a collective problem, advancing democratic principles, etc.)*.
Clarifying conflict	Mapping alternative views and opinions in an effort to better see a range of solutions, and their appraisals, to inform immediate consensus or future decision-making.
Common good orientation	Exhibiting empathy that enables the consideration of one another's and greater communities' well-being. This does not negate self-interest.
Accountability	Acting on the responsibility—as a decision-maker—to consider, respond to, and incorporate different perspectives into final decisions.
Publicity	Ensuring transparency—to the degree possible—so that participants are informed about every step of the process.
Sincerity	Demonstrating authenticity in conversations to understand one another, as opposed to purely strategic goal attainment.

These qualities of deliberation continue to be revised, questioned, and contested through development of academic literatures and deliberative practice. This table is not to be viewed as definitive but as a guide toward more deliberative communication across contexts and scales.

dialogue-focused practices that can encompass private sector activities and the implications of those activities for individuals and communities.

In summary, the CDR options that countries are now examining will have direct impacts on a range of peoples and places. CDR demands not just in-country work but also cross-boundary target setting with attendance to a wide variety of potential positive and negative spillover effects. Full consideration of CDR options requires work within countries encompassing an array of potentially impacted actors, from frontline communities to powerful corporations. The undertaking of "stakeholder consultation" is suggested in the first-round NDCs of 118 countries (Khan, 2019). As with CDR commitments, though, precisely what is meant by stakeholder consultation has not been well-specified, and nor have the political challenges associated with identifying and characterizing "stakeholders" been resolved. In what follows we characterize the *what, why, and how* of a deliberative orientation that can be taken toward country-level CDR commitments, suggesting this orientation can use characteristics of good deliberation to infuse communication, assessment, and evaluation of CDR options at all levels in service of sound CDR governance.

GROUNDING A DELIBERATIVE ORIENTATION: LESSONS FROM DELIBERATIVE DEMOCRATIC THEORY AND CLIMATE ENGINEERING LITERATURES

What Is Deliberation?

Deliberation, at its core, refers to mutual communication that is grounded in *reason-giving* and *active listening* (Bächtiger et al., 2018; Bächtiger and Parkinson, 2019c). This minimalist definition leaves room for deliberation to take many shapes and occur in many sites at the local, regional, national, and international levels (Bächtiger et al., 2018; Maia, 2018; Setälä and Smith, 2018; Bächtiger and Parkinson, 2019c). Deliberation can take the shape of a deliberative democratic system or an interpersonal interaction: It can occur in an organized mini-public—an institution where a diverse group of citizens are randomly selected to reason about a public concern—or in a mass-media environment (Bächtiger et al., 2018; Maia, 2018; Setälä and Smith, 2018). What matters is that regardless of the shape, site, or level, communication among those involved is rooted in the deliberative core—*reason-giving* and *active listening*—and strives toward the standards for "good" deliberation, as outlined in **Table 1** (Mansbridge, 1999; Burkhalter et al., 2002; Steenbergen et al., 2003; Mansbridge et al., 2010; Dobson, 2014a,b; Bächtiger et al., 2018; Morrell, 2018; Bächtiger and Parkinson, 2019b,c; Scudder, 2020)[4].

These standards for good deliberation provide a guide for what deliberative engagements ought to strive toward; however, these standards continue to be questioned and revised as theories of deliberative democracy evolve (Bächtiger et al., 2018)[5]. In **Table 1** we draw a distinction between "guiding qualities," "core qualities," and "elevating qualities" of good deliberative practice. The guiding qualities in **Table 1** are largely accepted and their definitions settled (Steenbergen et al., 2003; Bächtiger et al., 2018). The core qualities in **Table 1**, by contrast, are essential for constituting communication as deliberative, but, unlike the guiding qualities, their definitions have either evolved significantly (e.g., reason-giving) or are still ill defined (e.g., active listening) (Mansbridge, 1999; Burkhalter et al., 2002; Steenbergen et al., 2003; Bächtiger et al., 2018; Bächtiger and Parkinson, 2019b). When defining those core qualities, we worked to craft a set of robust and concrete definitions given existing literature. The elevating qualities in **Table 1** represent qualities that enhance the deliberativeness of an interaction but have and continue to undergo revision: We comprised this cluster of qualities by collecting practices that are routinely cited as ideal for good deliberation and worked to capture their essence (Mansbridge et al., 2010; Bächtiger et al., 2018). As Bächtiger et al. (2018) explain, deliberative democracy—including its ideal qualities—remains an essentially contested concept. These ideal standards are a normative guide to right action, and their realization in the real-world affords avenues for further research (Black et al., 2013; Bächtiger and Parkinson, 2019a).

Why Deliberation?

The characteristics of deliberation listed in **Table 1** are more than a set of abstract definitions: They also represent why deliberation is useful for the development of effective CDR governance. The features of CDR outlined in section CDR in the NDCs: An Opportunity for a Deliberative Orientation above make clear that technical target-setting alone is an insufficient guide to CDR development. CDR will be researched, tested, and deployed in particular social and political contexts. The different qualities of good deliberation can aid those tasked with integrating CDR into NDCs by garnering relevant perspectives, situating CDR development within competing interests and values-sets, and ensuring that CDR decision-making is attentive to the needs of the most vulnerable. The stakes are high, and the decisions made today about CDR will impact individuals and communities tomorrow. The aforementioned qualities and values of deliberation, at minimum, serve as a set of pointers toward best-possible decision-making.

How Experiments in Deliberation Have Advanced Thinking About CDR Governance

Since the characteristics and values of deliberation can help with navigation of the challenges associated with CDR governance, it is not surprising that there have been significant calls for

[4]Thank you to Reviewer 1 for their insights regarding **Table 1**.

[5]Bächtiger et al. (2018) provides a useful summary of how these standards for good deliberation have matured and where contestation still exists. Their Table 1.1 Standards for Good Deliberation provided a touchstone for the development of **Table 1** in this policy brief.

deliberation in "climate engineering"[6] governance and research (Parkhill et al., 2013; Burns and Flegal, 2015; Bellamy and Lezaun, 2017; Pidgeon, 2021). Research in this area can be traced back to calls for public engagement in The Royal Society (2009) report *Geoengineering the climate: Science, governance and uncertainty*[7] (Bellamy and Lezaun, 2017). These calls raised the question: How can societies meaningfully engage diverse perspectives in the responsible innovation of climate engineering technologies (Parkhill et al., 2013)? In response, researchers have conducted group, workshop-style deliberative public engagements around the subject matter of climate engineering, particularly in the UK, to: (1) explore public appraisals of these technologies and (2) determine how to best facilitate deliberative exercises to deepen public engagement (Corner et al., 2012; Parkhill et al., 2013; Burns and Flegal, 2015; Bellamy, 2016; Bellamy et al., 2016, 2017; Bellamy and Lezaun, 2017; Cox et al., 2020; Pidgeon, 2021).

This experimental and workshop-based work has significantly advanced thinking about CDR governance by garnering public insights into the risks and uncertainties that CDR options pose (Cox et al., 2020; Pidgeon, 2021). We seek to build on such work by arguing that a broader *deliberative orientation* ought to be taken into consideration and development of the roles to be played by CDR in national-level climate strategy. Our intent here, in other words, is to take learnings from experimental and workshop-based work and to apply those learnings in the broader arena constituted by CDR consideration in national-level climate policymaking. In particular, the aforementioned work offers two lessons that can help us do so and broaden the conversation from group deliberation toward a set of insights and strategies with wider application for CDR governance.

Lesson 1: Unframing

The practice of *unframing* was coined by Bellamy and Lezaun (2017) and can be a useful tool for practicing a deliberative orientation beyond group facilitations. *Framing* refers to a way of presenting information about an issue that highlights the salience of a specific aspect of that issue (Wardekker and Lorenz, 2019). Those aspects can be causal interpretations—the why, who, what, and how of an issue—ways of defining the issue, moral evaluations, and/or recommended solutions (Nisbet, 2009; Swain, 2015; Wardekker and Lorenz, 2019). An example of framing how CDR is defined would be highlighting its naturalness though an analogy: "One technology that we work on acts like an artificial tree by breathing in carbon dioxide from the atmosphere and then storing it underground" (Corner and Pidgeon, 2015, p. 431). We know that different framings of CDR options impact their interpretations as climate change solutions (Corner and Pidgeon, 2015; Campbell-Arvai et al., 2017). It has been recommended that designers of public engagement dialogues recognize what frames they may be imparting on participants and actively avoid introducing those frames so that participants can articulate their own frames of CDR (Bellamy and Lezaun, 2017; Pidgeon, 2021). Doing so enhances the deliberative quality of a group facilitation by opening space for reason-giving. Those involved in CDR governance may also consider making their written and verbal communication more deliberative by recognizing how they themselves frame CDR in their reason-giving, actively listening to understand the frames others use to package CDR, and avoiding imparting their own frames on others.

Lesson 2: Lead With Inquiry

There are a variety of strategies to elicit reason-giving and encourage active listening in deliberatively oriented exchanges (Polletta and Gardner, 2018). However, one strategy that nearly anyone, not just facilitators, can use to practice the qualities expressed in **Table 1** is asking questions. Bellamy and Lezaun (2017) explain how facilitators involved in the Stratospheric Particle Injection for Climate Engineering project (SPICE) workshops steered participants away from defaulting to expert views and toward articulating their own values by asking various iterations of: Why is this important to you? This is a powerful and useful question for opening space for reason-giving and listening. Researchers, practitioners, negotiators, and decision-makers may consider leading their interactions by (1) asking themselves why certain components of the CDR conversation are important to them to possibly open space for more robust reason-giving, and (2) asking others why certain components of the CDR conversation are important to them, which may encourage listening for understanding with mutual respect. Doing so could enhance the deliberative quality of an interaction and steer us away from bad decisions toward better decisions about CDR.

RECOMMENDATIONS: TAKING A DELIBERATIVE ORIENTATION TO CDR AND THE NDCs

> It is not that deliberation needs to expand to include a fuller account of democratic communication. Quite the reverse: it is that deliberative processes can be seen as a cluster of different, often non-deliberative practices which vary by goals and context *without giving up on the idea of core deliberative values* (Bächtiger and Parkinson, 2019c, p. 29).

To summarize, we are arguing here for a move away from treating deliberation as a set of formal workshops and experimental conditions and toward the adoption of a *deliberative orientation* in the range of communications acts that are part of considering the roles CDR might play within the context of NDCs under the Paris Agreement. Deliberation need not only take the shape of a group facilitation in CDR governance, which can be resource intensive and not always appropriate for every decision-making context. In addition, deliberation need not only elicit public perceptions and appraisal, which, to date, has tended to produce a unidirectional flow of information from the public

[6]"Climate engineering" or "geoengineering" was, for a time, used as an umbrella term to describe both CDR and solar radiation management (SRM) climate change response options. The lumping together of CDR and SRM has largely broken down. We support this splitting of SRM and CDR (Jinnah and Nicholson, 2019). Here, we mine older climate engineering governance accounts and more recent accounts that look specifically at CDR governance options for the lessons that can be gleaned concerning deliberative practice.

[7]This report stated, "Public attitudes toward CDR and SRM methods, and public participation in discussion of how development and implementation is managed and controlled, will be critical. Geoengineering methods should be responsible and openly researched, and only deployed by common consent" (The Royal Society, 2009, p. 50).

to decision-makers. Deliberation can also be a part of any instance of communication and include a multi-directional flow of information and perspectives.

We have argued that the features of incorporating CDR into NDCs presents an opportunity for negotiators—and others involved in NDC decision-making—to adopt a deliberative orientation for better CDR governance and better CDR outcomes. We acknowledge that CDR is a highly technocratic arena of climate policy that has the potential to work against the deliberative democratic governance of the climate, but that does not mean that we should not, as a global community, put our best foot forward to work toward more deliberative democratic governance[8]. Here, we offer three overlapping recommendations: Our intent is to take the insights from deliberative theory and lessons from prior deliberation-oriented work outlined above and to marry them to the specific considerations raised by growing interest in CDR options. Note that being overly prescriptive in these recommendations would run somewhat counter to the deliberative orientation we are urging. Deliberative programs and interventions ought best be co-designed with participants, taking account of specific local needs. That said, we have aimed by way of examples and relevant literature to set clear direction for the operationalization of a deliberative orientation.

Recommendation 1: Move From Broad Calls for "Consultation" in NDCs to the Structuring of Deliberative Interactions

There appears broad acceptance across first-round NDCs of the desirability of "stakeholder consultation." Consultative models of communication tend, though, to produce largely one-way transmission of information from those crafting policies and projects to those experiencing the impacts, with the intent of generating acceptance of a predetermined set of options. In addition, the defining of "stakeholders" is itself a political act, giving access and claim to some while excluding others. A deliberative orientation demands something more. Deliberation, by contrast, means setting up engagements intent on redressing power imbalances and providing the political space for new potential pathways to emerge.

This intent can be expressed directly in NDCs when referencing CDR developments and target-setting, by dropping vague calls for stakeholder consultation in favor of clear, structured plans for deliberative engagement with a full array of impacted individuals and communities. The objective should be the coproduction of goals, projects, and evaluative mechanisms. Such an orientation and commitment to structuring deliberative interactions has been modeled by the 2020 Climate Assembly UK. Six committees of the United Kingdom's House of Commons commissioned this assembly to garner public guidance on how the UK should meet its 2050 target of reaching net-zero greenhouse gas emissions (Climate Assembly UK, 2020). This assembly redressed power imbalances by including 108 members representative of the UK population in the coproduction of principles to guide the UK's path to net-zero and industry specific recommendations (Climate Assembly UK, 2020). A different variant of a deliberative orientation can be seen developing in the United States, for instance, with the Biden administration's elevation of environmental justice as a new fulcrum for environmental action and decision-making. The administration is working to establish a White House Advisory Justice Council and an interagency process to work with local communities and leaders on the identification and redressing of environmental injustices. Carbon removal and the potential roles to be played by carbon removal in US national-level climate planning, including via the NDCs, will be structured by this new attention to environmental justice as outcome and process. More specifically, planning for the testing and siting of new carbon removal schemes backed by US federal government spending will, according to officials, require deliberative community engagement with environmental justice principles to the fore[9].

Another way to open space for the coproduction of knowledge and appraisals is to act on the "unframing" lesson outlined above. This means avoiding prematurely imposing frames in NDC language, supporting documents, and accompanying processes, but instead seeking actively to create space for fruitful reason-giving, active listening, and understanding toward more equitable burden sharing. Part of deliberative planning means recognizing that CDR developments will have impacts for equitable burden sharing beyond state boundaries even if CDR activities themselves are confined within a particular state's borders. There is also a clear need to work with private sector actors. This suggests that deliberative communications strategies must be designed with cross-border dimensions and a full array of interested actors in mind.

Recommendation 2: Ensure That People Are Considered Along With the Technical Dimensions of CDR Developments

CDR targets are typically expressed in technical terms, prioritizing metrics like dollars per ton of carbon dioxide sequestered and technical scalability constraints. A deliberative orientation invites moving beyond technical considerations in the setting of CDR targets to more fully consider, evaluate, and incorporate the human dimensions of CDR developments. The "leading with inquiry" insight is instructive. Asking questions of those who will be impacted by the implementation of national-level targets and working actively to uncover and engage with the values of those impacted can help a weaving of deliberative practice into target-setting toward a richer understanding of what CDR means for the lives it may affect. This type of inquiry can assist, as CDR options are brought more fully into the NDCs, with the paying of more particular attention to establishment of plausible social co-benefits and risks along with deliberative means to more fully characterize such co-benefits and risks and to evaluate them over time.

One place to embed this kind of thinking and structuring is directly within the expert institutions that are largely responsible for shaping the roles that carbon removal will play within the

[8] We thank Reviewer 2 for this insight as well.

[9] This assertion is based on conversations between one of the authors and officials inside the US Department of Energy.

broader sweep of climate policy[10]. A deliberative orientation, engaging with a full array of potentially impacted actors to define "good" carbon removal and to measure its development across social, technical, and environmental dimensions, corresponds with the kind of reflexive "responsible assessment" that Beck and Mahony (2018a,b) have called for in relation to the Intergovernmental Panel on Climate Change (IPCC). Beck and Mahony note that expert bodies like the IPCC have tended to this point to foster a policy-neutral stance, facilitated by creating and policing artificial boundaries between science creation and policymaking. Science creation is never, though, a politically neutral act, and a too-narrow self-definition of the IPCC's role serves to mask the political implications of the IPCC's assessment work. A "responsible assessment" would in part entail clear identification and incorporation of the broader social and environmental implications of technical findings and modeled pathways incorporating carbon removal. This demands that scientific assessment bodies widen the voices enlisted, the approaches utilized, and the concerns and interests examined. National scientific bodies and policy processes concerned with the creation of NDCs and longer-term country-level climate strategies would do well to embrace such advice.

Recommendation 3: Ensure a Correspondence Between Project-Level Questions and Country-Level Targets

Country-level target setting for CDR, focusing on the roles that CDR can play in meeting broad society-wide net emissions targets, can seem divorced from the kinds of questions that should be asked of individual CDR projects. A deliberative orientation suggests that even in the highest-level goal setting, the implications for people and the planet of the growth of particular kinds of CDR projects ought to be given consideration. Another way of saying this is that multiscalar thinking is needed in the incorporation of CDR into NDCs. Attentiveness to the needs and voices of a full range of stakeholders can take CDR from abstract representation in an emissions pathways figure to the reality of CDR as a set of activities with demonstrable effects on actual people. However, attentiveness to these voices does not mean just listening. It requires more. It requires (1) eliciting voices and (2) actively listening to what they have to say. The "lead with inquiry" notion shows that negotiators and others can ask stakeholders about their values and perspectives and actively work to understand them.

Said differently, deliberation is often conveyed as a kind of panacea, with the implication that more talk will produce better outcomes. This is not the case. Instead, deliberation is best understood as a guide and set of practices that are basic to, but not supplanting of, good governance. We have argued here that a *deliberative orientation* should be adopted by those working on national-level CDR policymaking and incorporation into climate action pledges. Such an orientation seems appropriate given the complexity of the decisions that need to be taken around CDR and the implications for societies and environments of differently constituted CDR portfolios. Deliberation becomes real with careful attention to equitable burden sharing, a prioritizing of people over technical characteristics alone of CDR options, and a structured attentiveness to the impacts of big plans on real people.

[10]Thanks to Reviewer 1 for this insight.

CONCLUSION

Ultimately, this policy brief marries theory, a secondary account of empirical research, and practice to provide actionable recommendations that decision-makers and others can implement immediately in their day-to-day work. We have developed general, high-level recommendations by standing on the shoulders of deliberative democratic theory and the innovative work previously conducted on CDR deliberation, communication, and public engagement. It is our hope that this policy brief makes the sometimes lofty and idealistic notion of deliberation into something more tangible and accessible to anyone working in CDR governance, not just those who specialize in facilitating group deliberations. Geden (2016), however, provides us, as researchers, a sobering reminder that we are not expert negotiators in the NDC process and "should resist the temptation to act like political entrepreneurs peddling [our] advice..." (p. 796). In the spirit of deliberation, we put forth our understanding of deliberation in CDR governance and encourage the broadening of this conversation to include a wider array of perspectives. In the end, by taking deliberation seriously and expanding our visualization of what it can be and do for CDR governance, our global community has a better chance at steering CDR decision-making away from the bad and toward the common good.

AUTHOR CONTRIBUTIONS

AB was lead author on this paper, defined deliberation, created **Table 1**, drew lessons from previous literature on CDR and deliberation, and led the development of a deliberative orientation as a concept. AB and SN co-developed the ideas presented in this policy brief. SN examined the relevance of CDR in the NDCs and conceived the features in section CDR in the NDCs: An Opportunity for a Deliberative Orientation and led the formation of the actionable recommendations. All authors contributed to the article and approved the submitted version.

REFERENCES

Bächtiger, A., Dryzek, J. S., Mansbridge, J., and Warren, M. E. (eds.). (2018). "Deliberative democracy: an introduction," in *The Oxford Handbook of Deliberative Democracy* (Oxford: Oxford University Press), 1–34.

Bächtiger, A., and Parkinson, J. (2019a). "Assessing and measuring deliberativeness," in *Mapping and Measuring Deliberation: Towards a New Deliberative Quality* (Oxford: Oxford Scholarship Online), 132–151.

Bächtiger, A., and Parkinson, J. (2019b). "Locating 'deliberativeness,'" in *Mapping and Measuring Deliberation: Towards a New Deliberative* Quality (Oxford: Oxford Scholarship Online), 104–131.

Bächtiger, A., and Parkinson, J. (2019c). "Unpacking deliberation," in *Mapping and Measuring Deliberation: Towards a New Deliberative* Quality (Oxford: Oxford Scholarship Online), 19–44.

Beck, S., and Mahony, M. (2018a). The IPCC and the new map of science and politics. *Wiley Interdisc. Rev. Clim. Change* 9:e547. doi: 10.1002/wcc.547

Beck, S., and Mahony, M. (2018b). The politics of anticipation: the IPCC and the negative emissions technologies experience. *Glob. Sustain.* 1:e8. doi: 10.1017/sus.2018.7

Bellamy, R. (2016). A sociotechnical framework for governing climate engineering. *Sci. Technol. Hum. Values* 41, 135–162. doi: 10.1177/0162243915591855

Bellamy, R., Chilvers, J., and Vaughan, N. E. (2016). Deliberative mapping of options for tackling climate change: citizens and specialists 'open up' appraisal of geoengineering. *Public Understand. Sci.* 25, 269–286. doi: 10.1177/0963662514548628

Bellamy, R., and Lezaun, J. (2017). Crafting a public for geoengineering. *Public Understand. Sci.* 26, 402–417. doi: 10.1177/0963662515600965

Bellamy, R., Lezaun, J., and Palmer, J. (2017). Public perceptions of geoengineering research governance: an experimental deliberative approach. *Glob. Environ. Change* 45, 194–202. doi: 10.1016/j.gloenvcha.2017.06.004

Black, L. W., Burkhalter, S., Gastil, J., and Stromer-Galley, J. (2013). "Methods for analyzing and measuring group deliberation," in *The Sourcebook for Political Communication Research: Methods, Measures, and Analytical Techniques*, eds E. P. Bucy and R. L. Holbert (New York, NY: Routledge), 323–345.

Burkhalter, S., Gastil, J., and Kelshaw, T. (2002). A conceptual definition and theoretical model of public deliberation in small face-to-face groups. *Commun. Theory* 12, 398–422. doi: 10.1111/j.1468-2885.2002.tb00276.x

Burns, W. C. G., and Flegal, J. A. (2015). Climate geoengineering and the role of public deliberation: a comment on the US National Academy of Sciences' recommendations on public participation. *Climate Law* 5, 252–294. doi: 10.1163/18786561-00504006

Campbell-Arvai, V., Hart, P. S., Raimi, K. T., and Wolske, K. S. (2017). The influence of learning about carbon dioxide removal (CDR) on support for mitigation policies. *Clim. Change* 143, 321–336. doi: 10.1007/s10584-017-2005-1

Climate Assembly UK (2020). *The Path to Net Zero*. London: House of Commons. Available online at: https://www.climateassembly.uk/recommendations/index.html

Corner, A., and Pidgeon, N. (2015). Like artificial trees? The effect of framing by natural analogy on public perceptions of geoengineering. *Clim. Change* 130, 425–438. doi: 10.1007/s10584-014-1148-6

Corner, A., Pidgeon, N., and Parkhill, K. (2012). Perceptions of geoengineering: public attitudes, stakeholder perspectives, and the challenge of 'upstream' engagement. *WIREs Clim. Change* 3, 451–466. doi: 10.1002/wcc.176

Cox, E., Spence, E., and Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nat. Clim. Chang.* 10, 744–749. doi: 10.1038/s41558-020-0823-z

Dobson, A. (2014a). "Learning about listening," in *Listening for Democracy: Recognition, Representation, Reconciliation* (New York, NY: Oxford University Press), 48–80.

Dobson, A. (2014b). "Deliberative and dialogic democracy," in *Listening for Democracy: Recognition, Representation, Reconciliation* (New York, NY: Oxford University Press), 81–108.

European Commission (2018). *In-Depth Analysis in Support of the Commission Communication COM(2018) 773: A Clean Planet for all a European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy.* Brussels.

Geden, O. (2016). The Paris Agreement and the inherent inconsistency of climate policymaking. *WIREs Clim. Change* 7, 790–797. doi: 10.1002/wcc.427

Hsu, A., Brandt, J., Widerberg, O., Chan, S., and Weinfurther, A. (2019). Exploring links between national climate strategies and non-state and subnational climate actions in nationally determined contributions (NDCs). *Clim. Policy* 20, 443–457. doi: 10.1080/14693062.2019.1624252

IPCC (2018). "Summary for policymakers," in *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, eds V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla. Available online at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf

Jinnah, S., and Nicholson, S. (2019). Introduction to the symposium on 'geoengineering: governing solar radiation management'. *Env. Polit.* 28, 385–396. doi: 10.1080/09644016.2019.1558515

Keohane, R. O., and Oppenheimer, M. (2016). Paris: beyond the climate dead end through pledge and review? *Politics Govern.* 4, 142–151. doi: 10.17645/pag.v4i3.634

Khan, F. (2019). NDC score card: measuring the nationally determined contributions (NDCs) under the Paris Agreement. *123. M-RCBG Associate Working Paper Series* (Cambridge, MA: Mossavar-Rahmani Center for Business and Government, Harvard Kennedy School).

Maia, R. C. M. (2018). "Deliberative media." in *The Oxford Handbook of Deliberative Democracy*, eds A. Bächtiger, J. S. Dryzek, J. Mansbridge, and M. E. Warren (Oxford University Press), 348–364.

Mansbridge, J. (1999). "Everyday talk in the deliberative system," in *Deliberative Politics: Essays on Democracy and Disagreement*, ed S. Macedo (New York, NY: Oxford University Press), 211–242.

Mansbridge, J., Bohman, J., Chambers, S., Estlund, D., Føllesdal, A., Fung, A., et al. (2010). The place of self-interest and the role of power in deliberative democracy. *J. Polit. Philos.* 18, 64–100. doi: 10.1111/j.1467-9760.2009.00344.x

Morrell, M. E. (2018). "Listening and deliberation," in *The Oxford Handbook of Deliberative Democracy*, eds A. Bächtiger, J. S. Dryzek, J. Mansbridge, and M. E. Warren (Oxford, UK: Oxford University Press), 237–250.

Morrow, D. R., Buck, H. J., Burns, W. C. G., Nicholson, S., and Turkaly, C. (2018). *Why Talk About Carbon Removal?* Washington, DC: Institute for Carbon Removal Law and Policy, American University.

Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., et al. (2020). Principles for thinking about carbon dioxide removal in just climate policy. *One Earth* 3, 150–153. doi: 10.1016/j.oneear.2020.07.015

Nisbet, M. C. (2009). Communicating climate change: why frames matter for public engagement. *Environ. Sci. Policy Sustain. Dev.* 51, 12–23. doi: 10.3200/ENVT.51.2.12-23

Paris Agreement (2015). *Conclusion Date: December 12, 2015*. United Nations Treaty Series Online, Registration no. I-54113.

Parkhill, K., Pidgeon, N., Corner, A., and Vaughan, N. (2013). "Deliberation and responsible innovation: a geoengineering case study," in *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society* (West Sussex, UK: John Wiley and Sons, Ltd.), 219–239.

Pidgeon, N. (2021). Engaging publics about environmental and technology risks: frames, values and deliberation. *J. Risk Res.* 24, 28–46. doi: 10.1080/13669877.2020.1749118

Polletta, F., and Gardner, B. G. (2018). "The forms of deliberative communication," in *The Oxford Handbook of Deliberative Democracy*, eds A. Bächtiger, J. S. Dryzek, J. Mansbridge, and M. E. Warren (Oxford: Oxford University Press), 70–85.

Pozo, C., Galán-Martín, Á., Reiner, D. M., Mac Dowell, N., and Guillén-Gosálbez, G. (2020). Equity in allocating carbon dioxide removal quotas. *Nat. Clim. Chang.* 10, 640–646. doi: 10.1038/s41558-020-0802-4

Röser, F., Widerberg, O., Höhne, N., and Day, T. (2020). Ambition in the making: analysing the preparation and implementation process of the nationally determined contributions under the Paris Agreement. *Clim. Policy* 20, 415–429. doi: 10.1080/14693062.2019.1708697

Sato, I., Langer, P., and Stolle, F. (2019). Enhancing NDCs: opportunities in the forest and land-use sector. *Working Paper* (Washington, DC: World Resources Institute).

Schenuit, F., Colvin, R., Fridahl, M., McMullin, B., Reisinger, A., Sanchez, D. L., et al. (2021). Carbon dioxide removal policy in the making: assessing developments in 9 OECD cases. *Front. Clim.* 3, 1–22. doi: 10.3389/fclim.2021.638805

Scudder, M. F. (2020). "Listening for difference in democracy," in *Beyond Empathy and Inclusion: The Challenge of Listening in Democratic Deliberation* (New York, NY: Oxford Scholarship Online), 145–174.

Setälä, M., and Smith, G. (2018). "Mini-publics and deliberative democracy," in *The Oxford Handbook of Deliberative Democracy*, eds A. Bächtiger, J.

S. Dryzek, J. Mansbridge, and M. E. Warren (Oxford: Oxford University Press), 300–314.

Steenbergen, M. R., Bachtiger, A., Sporndli, M., and Steiner, J. (2003). Measuring political deliberation: a discourse quality index. *Comp. Eur. Politics* 1, 21–48. doi: 10.1057/palgrave.cep.6110002

Swain, K. A. (2015). "Mass media roles in climate change mitigation," in *Handbook of Climate Change Mitigation and Adaptation*, eds M. Lackner, B. Sajjadi, and W. Y. Chen (New York, NY: Springer), 162–195.

The Federal Council (2020). *Climate Change: Federal Council Adopts Report on Negative CO_2 Emissions*. Available online at: https://www.admin.ch/gov/en/start/documentation/media-releases.msg-id-80271.html (accessed March 22, 2021).

The Royal Society (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. London: The Royal Society. Available online at: https://royalsociety.org/~/media/royal_society_content/policy/publications/2009/8693.pdf

Wardekker, A., and Lorenz, S. (2019). The visual framing of climate change impacts and adaptation in the IPCC assessment reports. *Clim. Change* 156, 273–292. doi: 10.1007/s10584-019-02522-6

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POLICY BRIEF
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Governing Carbon Dioxide Removal in the UK: Lessons Learned and Challenges Ahead

Javier Lezaun[1]*, *Peter Healey*[1], *Tim Kruger*[2] and *Stephen M. Smith*[3]

[1] *Institute for Science, Innovation and Society, School of Anthropology and Museum Ethnography, University of Oxford, Oxford, United Kingdom,* [2] *Oxford Martin School, University of Oxford, Oxford, United Kingdom,* [3] *Smith School of Enterprise and the Environment, University of Oxford, Oxford, United Kingdom*

This Policy Brief reviews the experience of the UK in developing principles for the governance of carbon dioxide removal (CDR) at scale. Early discussions on CDR governance took place in two separate and somewhat disjointed policy domains: forestry, on the one hand, and R&D support for novel "geoengineering" technologies, on the other. The adoption by the UK government of a 2050 "net zero" target is forcing an integration of these disparate perspectives, and should lead to a more explicit articulation of the role CDR is expected to play in UK climate strategy. This need for clarification is revealing some of underlying tensions and divisions in public views on CDR, particularly when it comes to forms of capture and sequestration deemed to be "non-natural." We propose some principles to ensure that the development and deployment of carbon dioxide removal at scale strengthens a commitment to ambitious climate change mitigation and can thus enjoy broad public support.

Keywords: carbon dioxide removal, governance, net zero, negative emission technologies, geoengineering

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***Correspondence:**
Javier Lezaun
javier.lezaun@insis.ox.ac.uk

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INTRODUCTION

Over the last decade, the UK has taken steps to develop technological options for the removal of carbon dioxide from the atmosphere. This component in UK climate strategy has gained relevance and urgency with the adoption by the UK government in 2019 of a legal commitment to bring all UK-based greenhouse gas emissions to "net zero" by 2050. The new policy context demands greater clarity in the role that carbon dioxide removal (CDR) is expected to play in UK climate action, and creates an opportunity to develop a CDR governance system with broad public legitimacy.

Action toward CDR at scale in the UK must be seen in the context of a relatively consensual climate policy. The Climate Change Act 2008 established an ambitious goal for the reduction of greenhouse gas emissions (80% of 1990 levels by 2050), and created a set of institutions, most notably the Committee on Climate Change, tasked with monitoring progress toward that target. The Climate Change Act also set a series of recurrent obligations on the UK government, including the publication of an annual statement of UK emissions, the setting of five-yearly interim limits to emissions on the path to 2050 ("carbon budgets"), and a report every five years of its plans and policies to achieve those carbon budgets.

The Climate Change Act included greenhouse gas removals (GGR) under its remit, specifically removals "due to land use, land-use change or forestry activities in the United Kingdom." At the time, this implied an almost complete overlap between CDR and forestry policy. Traditionally UK forestry policy has been oriented toward biodiversity preservation and what the Independent Panel on Forestry described as the UK's distinctive "woodland culture," but it has progressively been reframed as a key component in the country's climate change mitigation efforts. Since 2011, the Woodland Carbon Code has provided an incentive to preserve or expand woodland through the issuance of carbon credits, which can be sold to the government at a guaranteed price every five or 10 years, or used to compensate for UK-based greenhouse gas emissions. Under the Environmental Land Management schemes (ELMs) that will replace the support programmes of the EU's Common Agricultural Policy, the capacity of agricultural and forest management practices to sequester carbon will be a key metric guiding "landscape-scale land use changes" in the UK (DEFRA, 2020).

In parallel to this strand of policy development, public debate on CDR governance in the UK began to crystallize in the late 2000s in the context of R&D policy, specifically around the question of whether to incentivize the development of novel forms of "climate engineering." It was in this context that governance principles for large-scale CDR were first developed, in conjunction with the scientific assessments of largely untested technological options and social-scientific research into emerging public opinion on "geoengineering."

CDR GOVERNANCE IN THE CONTEXT OF R&D POLICY

The landmark 2009 Royal Society report *Geoengineering the Climate: Science, Governance and Uncertainty* considered several forms of large-scale carbon dioxide removal (including land use and afforestation) alongside techniques for solar radiation management (SRM). The report noted that "the greatest challenges to the successful deployment of geoengineering may be the social, ethical, legal and political issues associated with governance, rather than scientific and technical issues" (Royal Society, 2009, p. xi). It recommended a 10-year government-funded research programme to explore different technical options, and called for an international code of practice to govern this research, noting that "perception of the risks involved, levels of trust in those undertaking research or implementation, and the transparency of actions, purposes and vested interests, will determine the political feasibility of geoengineering" (Royal Society, 2009, p. xii). In the wake of the report, research funding bodies launched several initiatives in this area, supporting both technical assessments of different kinds of geoengineering and an embryonic public debate over their desirability. The 2010 *Experiment Earth?*, a public dialogue sponsored by the Natural Environment Research Council (NERC), included specific discussions on afforestation, biochar, ocean liming, ocean iron fertilization and direct air capture (a decade later, Climate Assembly UK would revisit these and other forms of CDR as part of its remit).

The understanding of large-scale CDR as a form of geoengineering framed the problem as one of regulating emerging, often speculative technologies. It lumped together highly heterogeneous modalities of intervention—from peatland conservation to stratospheric aerosol injection—and yielded governance principles focused on the criteria for responsible research and development of climate engineering options (Royal Society, 2009; Rayner et al., 2013; Stilgoe et al., 2013). Formal deliberation exercises like those conducted under *Experiment Earth?*, and social scientific research on the public acceptability of CDR at scale, emphasized concerns over mitigation deterrence, and revealed a sharp distinction in public opinion between those removal options that were perceived to be "natural" and offer significant environmental co-benefits (e.g., enhancing the storage of carbon in soils, peatland and wetland preservation, better forest management), and those seen as "artificial" or "engineered" (Corner et al., 2013; McLaren, 2016; see also Bellamy and Lezaun, 2017).

During the 2010s, the assessment of CDR options was progressively decoupled from solar radiation management, becoming increasingly conceptualized as the development of a set of novel "negative emissions technologies." This coincided with the greater relevance of CDR in IPCC mitigation scenarios, and the commitment, expressed in the Paris Agreement, to balancing greenhouse gas emission sources and sinks in the second half of the century (Anderson and Peters, 2016; see also Bellamy and Healey, 2018). In the UK, the first publicly-funded R&D initiative dedicated exclusively to CDR was the 2017–2021 Greenhouse Gas Removal from the Atmosphere programme. Funded jointly by the UK Research Councils and Government, the programme assessed the "real world" feasibility of greenhouse gas removal techniques, and sought to synthesize scientific and technical knowledge for use by national and international policymakers. It funded university-based research only, and evaluated a variety of CDR options, including agroforestry, bioenergy with carbon capture and storage (BECCS), soil sequestration, biochar, and enhanced rock weathering. Notably, it did not included any direct air capture (DAC) projects.

Governmental support for university-based R&D activities coincided with the development of CDR capabilities by some UK corporations. The most notable example, in terms of potential scale and stage of development, is Drax, the UK's largest thermal power station, which in 2019 began trialing carbon capture on its biomass-fired unit in North Yorkshire. A field of start-ups and small-scale enterprises began to explore and advocate for several technologies of carbon dioxide removal, particularly DAC. In 2019, the Committee on Climate Change called on the Government to expand support for early-stage research and demonstration projects, and to clarify the governance rules and market mechanisms that would ensure payment for removals, in order to create a set of signals that would allow companies and economic sectors to invest in the development of CDR at scale (Committee on Climate Change, 2019).

The first part of this recommendation has been addressed with the recent establishment of five Greenhouse Gas Removal Technology Demonstrators. Funded by UK Research and Innovation (the public body created by the merger of several research funding organizations) and scheduled to run from 2021 to 2025, the Demonstrators are expected to advance the "technology readiness" of CDR options. The selected projects are oriented primarily toward biological forms of carbon capture: accelerated peat formation, assessing the most effective species and locations for carbon sequestration through afforestation, biochar, perennial bioenergy crops, and enhanced rock weathering in farmland. In addition to the five Demonstrators, UKRI is funding a GGR Directorate Hub, charged with conducting cross-cutting research and exploring the economic, social and legal conditions for a scaled-up deployment of these and other GGR options.

Demonstrators and Hub carry the legacies of the UK approach to CDR governance in the context of R&D policy: an emphasis of interdisciplinary research (including social-scientific research on public perceptions), a commitment to the principles of Responsible Research and Innovation, and the design of processes of stakeholder engagement to assess the real-world acceptability of the proposed forms of removal. These tools are useful to create a more robust assessment frameworks for pilot projects, but it is remarkable how embryonic and "early stage" the field of CDR remains more than a decade after the Royal Society *Geoengineering the Climate* report. In the meantime, the policy context has changed significantly, due to the continuing failure to curb global emissions and the international aims enshrined in the 2016 Paris Agreement. The result is a greater urgency to develop a clear set of expectations as to the role CDR at scale ought to play in UK climate action in the near future.

CDR GOVERNANCE AND NET ZERO UK 2050

In June 2019 the UK government adopted a legally binding commitment to reach "net zero" by 2050. While a specific plan outlining the role that greenhouse gas removals should play in UK climate strategy is still to be published at the time of writing, this policy target has increased the visibility of CDR in public debate.

Currently, the only policy domain with explicit targets is forestry. Tree planning became in fact a prominent campaign issue during the last UK general election, with political parties vying with one another to offer the most ambitious goal (the Conservatives pledged to plant 30 million trees a year by 2025, the Liberal Democrats committed to 60 million trees per year, Labor announced plans to plant 2 billion trees by 2040, and the Scottish Nationalist Party promised to plant 36 million trees in Scotland by 2030). Subsequently, the UK has adopted a target of 30,000 hectares of new woodland per year by the end of the current Parliament, and the government has defined tree planting as "a central pillar in the efforts to reach net zero emissions by 2050" (UK Government, 2021). That political parties see tree planting as a vote-winning issue underlines the evidence that this remains a popular "climate solution" in the UK, but the scale of afforestation implied by these pledges points to a clear potential for conflict with other environmental public goods. Announcing an ambitious target for tree planting or woodland expansion is much easier than making sure that the right tree is planted in the right place and for the right reasons (Broadmeadow, 2020). "Forests and better forest management" was by far the most popular form of greenhouse gas removal among participant in the 2020 Climate Assembly UK, but support was explicitly conditional on the capacity of this policy to deliver clear co-benefits (promotion of biodiversity, access to nature, prevention of erosion, etc.). Tree planting is also the preferred (often the only) form of carbon dioxide removal mentioned in corporate net zero pledges, but these commitments tend to include no details on the location, management, or species composition of the new plantations, nor of the criteria that will be used to ensure permanence of storage. If carbon capture becomes the preeminent consideration in forest management, it is possible that, under certain conditions, commercial afforestation might deliver better outcomes than woodland expansion (Forster et al., 2021).

In the meantime, other forms of CDR have shown a more controversial public profile. As part of its plans for a "green recovery" from the Covid-19 pandemic, the UK government recently announced a scaling up Carbon Capture and Storage (CCS) technologies, and the creation of a fund dedicated to promote Direct Air Capture. The DAC announcement received a great deal of attention in the media, where it was presented as the brainchild of a party-political advisor with a track-record for favoring technological solutions (newspapers reported skepticism about the initiative in government circles, and it is noteworthy that there was little if any analysis published justifying the size of the fund, in contrast to the systematic assessments that support funding for other areas of low-carbon innovation). Key environmental groups singled out the DAC announcement for criticism. "It's a bit like sailing a ship toward an iceberg and the captain on the ship telling you not to worry about the iceberg as he would soon invent a machine that will help you fly. It's ridiculous. We shouldn't hope some magical solution will come in the future" (Head of Science, Friends of the Earth UK).

The debate over DAC suggests that support for large-scale CDR beyond expanded forms of "natural sequestration" is far from assured. Research on public perceptions of CDR in the UK suggests that industrial forms of carbon dioxide removal are often seen as "non-transition" technologies, that is, as incompatible or in conflict with prevailing visions of decarbonisation and sustainable development (Cox et al., 2020). Experimental research on the acceptability of CDR also indicates that public support may be contingent on the type of incentive used to promote its development (Bellamy et al., 2019). To some extent these concerns and apprehensions reflect the structure of public views on carbon capture and storage (CCS), where concerns over technical risk (e.g., leakage) and concerns over political risk (e.g., adoption of a technological solution to displace other, more acceptable methods of climate change mitigation) are often difficult if not impossible to disentangle (Thomas et al., 2018; see also Selma et al., 2014). The ambivalence and fluidity of public opinion on this matter is perhaps best grasped by analogy with evolving views of nuclear power in the context of the climate crisis. Studies of UK public attitudes describe a position of "reluctant acceptance" toward nuclear power when this form of energy generation is reframed as an instrument of climate action (Bickerstaff et al., 2008), but also underline that this position is highly conditional, and only emerges when all other (preferred) mitigation options have been excluded (Pidgeon et al., 2008; Corner et al., 2011).

This suggests that public support for CDR at scale will hinge on whether its development takes place in the context of a climate change mitigation strategy that enjoys broad legitimacy. The Climate Change Committee has emphasized this point in its call for policies that "place GGRs in the context of a wider strategic approach to reaching Net Zero, setting out a plan for development and deployment of removals, but also for actions elsewhere to limit the need for them" (Climate Change Committee, 2021, p. 198). This is consistent with the "precautionary" approach that Greenpeace UK advocates in relation to CDR in companies' climate plans. Such an approach, the campaign organization argues, "would put efforts into developing CDR technologies, while also cutting emissions at the level that would be needed assuming limited CDR availability" (Greenpeace UK, 2021).

Net zero provides a framework within which this set of issues, in particular the relationship between greenhouse gas removals and emissions reductions targets, can be made explicit and subjected to broad consultation. Some have argue for a clear separation of targets for removals and emissions reductions (McLaren et al., 2019) and a detailed specification of the relative role that removals are expected to play in achieving net zero targets (Rogelj et al., 2021). It might even be possible to develop taxonomies of removals that take into consideration whether they serve to enhance emissions reductions or simply remedy mitigation failures (Shue, 2021). Accepting that greater transparency and accountability are essential conditions for a national CDR governance system that can claim broad public legitimacy, we propose a set of recommendations tailored to current policy discussions in the UK.

ACTIONABLE RECOMMENDATIONS

Greater transparency and accountability should begin with the publication of the detailed mix of measures planned to achieve the UK 2050 net zero target, as required by the Climate Change Act. This would allow interested parties to understand what role this Government sees for specific CDR approaches. A detailed policy operationalization of the country's commitment is now evidently urgent. As the Chair of the CCC's Adaptation Committee, Baroness Brown, recently noted: "The UK is leading in diagnosis but lagging in policy and action" (Climate Change Committee, 2021).

The proposed measures should in fact aim to over-deliver on the net zero objective, given the range of risks that might limit the availability of CDR options in the future. Such over-delivery ought to apply to both emissions reduction measures and to the proposed targets for removals (Smith, 2021).

While creating different targets for emissions cuts and removals will reduce the risk of mitigation deterrence, the development of CDR at scale makes clear that these are not separate domains of climate action. In some cases, CDR systems may be used to produce alternatives to fossil fuels, or incorporate components, technologies and supply chains that are also involved in efforts to decarbonise key sectors of the economy. Given the untested nature of all large-scale CDR options currently under consideration, it may be appropriate to adjust targets to the respective maturity or readiness level of the technology in question, and to the concrete social and environmental context in which they are to be deployed (Smith, 2021).

An accountable strategy for reaching net zero by 2050 should also specify the carbon storage involved. This should be specified by type of storage (biological or geological), and include plans to monitor and manage it. Policy discussions have so far focused on the numbers of trees to be planted or the funding available to subsidize new forms of CDR. The scope of the conversation needs to expand to include what will be done to ensure that carbon, once captured, is rendered inert. The greater the intended use of sinks, the greater the need for monitoring, and for plans to reduce and manage the risk of possible leakage.

There is, finally, a critical international dimension to all these questions. The burden of removing greenhouse gases from the atmosphere must be shared fairly and equitably across countries, and the terms of any scheme for the international trading of carbon credits will need to be defined accordingly (Allen et al., 2020). The UK should also lend its expertise to countries willing to consider CDR options in their respective national climate strategies, for example by contributing to the development of internationally acceptable standards for the measurement, reporting and verification of removals (Healey et al., 2021). Cooperation toward this end would fall squarely within the activities for climate technology transfer and capacity building programs supported by UK International Climate Finance [UK Department for Business, Energy and Industrial Strategy (BEIS), 2019].

CONCLUSION

Although UK climate policy remains relatively consensual (at least in comparison to other countries), the prospect of developing CDR at scale is revealing some underlying tensions. While "natural" forms of carbon removal and sequestration are *a priori* popular, what counts as "natural" becomes contested as soon as specific interventions are proposed, particularly when the scale of sequestration must compensate for the ongoing failure to reduce greenhouse gas emissions in line with Paris Agreement obligations. On the other hand, evidence from public debate and social-scientific research on public perceptions suggests that forms of CDR perceived to be "industrial" or "engineered" and/or involve significant alterations in natural systems remain controversial, their "political feasibility" contingent on whether they are seen to enhance, rather than impede, the transition toward a low-carbon economy. Net zero provides an opportunity to bring transparency and accountability to these issues by making explicit the role that large-scale CDR is expected to play in UK climate policy, and subjecting those terms to extensive public debate. Fulfilling this opportunity requires consensus on the definition of "net zero," and a governance framework capable of ensuring that the deployment of CDR at scale is aligned with the pursuit of a broad range of public goods.

AUTHOR CONTRIBUTIONS

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REFERENCES

Allen, M., Axelsson, K., Caldecott, B., Hale, T., Hepburn, C., Hickey, C., et al. (2020). *The Oxford Principles for Net Zero Aligned Carbon Offsetting*. Oxford: University of Oxford.

Anderson, K., and Peters, G. (2016). The trouble with negative emissions. *Science* 354, 182–183. doi: 10.1126/science.aah4567

Bellamy, R., and Healey, P. (2018). 'Slippery slope' or 'uphill struggle'? broadening out expert scenarios of climate engineering research and development. *Environ. Sci. Policy* 83, 1–10. doi: 10.1016/j.envsci.2018.01.021

Bellamy, R., and Lezaun, J. (2017). Crafting a public for geoengineering. *Public Underst. Sci.* 26, 402–417. doi: 10.1177/0963662515600965

Bellamy, R., Lezaun, J. and Palmer, J. Perceptions of bioenergy with carbon capture and storage in different policy scenarios. *Nat Commun.* 10, 743 (2019). doi: 10.1038/s41467-019-08592-5

Bickerstaff, K., Lorenzoni, I., Pidgeon, N. F., Poortinga, W., and Simmons, P. (2008). Reframing nuclear power in the UK energy debate: nuclear power, climate change mitigation and radioactive waste. *Public Underst. Sci.* 17, 145–169. doi: 10.1177/0963662506066719

Broadmeadow, M. (2020). "Right tree, right place, right reason." Forestry Commission blog. Available online at https://forestrycommission.blog.gov.uk/2020/07/17/right-tree-right-place-right-reason/ (accessed on July 17, 2020).

Climate Change Committee (2021). Time is running out for realistic climate commitments. Available online at: https://www.theccc.org.uk/2021/06/24/time-is-running-out-for-realistic-climate-commitments/ (accessed on June 24, 2021).

Committee on Climate Change (2019). *Net Zero: The UK's Contribution to Stopping Global Warming*. London: Committee on Climate Change.

Corner, A., Parkhill, K., Pidgeon, N., and Vaughan, N. E. (2013). Messing with nature? exploring public perceptions of geoengineering in the UK. *Global Environ. Change* 23, 938–947. doi: 10.1016/j.gloenvcha.2013.06.002

Corner, A., Venables, D., Spence, A., Poortinga, W., Demski, C., and Pidgeon, N. (2011). Nuclear power, climate change and energy security: exploring British public attitudes. *Energy Policy* 39, 4823–4833. doi: 10.1016/j.enpol.2011.06.037

Cox, E., Spence, E., and Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nat. Climate Change* 10, 744–749. doi: 10.1038/s41558-020-0823-z

DEFRA (2020). *The Future for Food, Farming and the Environment: Policy Statement*. London: Department for Environment, Food & Rural Affairs.

Forster, E. J., Healey, J. R., Dymond, C., and Styles, D. (2021). Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. *Nature Commun.* 12, 1–12. doi: 10.1038/s41467-021-24084-x

Greenpeace UK (2021). *Net Expectations: Assessing the Role of Carbon Dioxide Removal in Companies' Climate Plans*. London: Greenpeace.

Healey, P., Scholes,R., Lefale, P., and Yanda, P. (2021). Governing net zero carbon removals to avoid entrenching inequities. *Front. Climate* 3:38. doi: 10.3389/fclim.2021.672357

McLaren, D. (2016). Mitigation deterrence and the "moral hazard" of solar radiation management. *Earth's Future* 4, 596–602. doi: 10.1002/2016EF000445

McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B., and Markusson, N. O. (2019). Beyond "net-zero": a case for separate targets for emissions reduction and negative emissions. *Front. Climate* 1:4. doi: 10.3389/fclim.2019.00004

Pidgeon, N. F., Lorenzoni, I., and Poortinga, W. (2008). Climate change or nuclear power—No thanks! a quantitative study of public perceptions and risk framing in Britain. *Global Environ. Change* 18, 69–85. doi: 10.1016/j.gloenvcha.2007.09.005

Rayner, S., Heyward, C., Kruger, T., Pidgeon, N., Redgwell, C., and Savulescu, J. (2013). The oxford principles. *Clim. Change* 121, 499–512.

Rogelj, J., Geden, O., Cowie, A., and Reisinger, A. (2021). Three ways to improve net-zero emissions targets. *Nature* 591, 365–368. doi: 10.1038/d41586-021-00662-3

Royal Society (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. London: Royal Society.

Selma, L., Seigo, O., Dohle, S., and Siegrist, M. (2014). Public perception of carbon capture and storage (CCS): a review. *Renew. Sustain. Energy Rev.* 38, 848–863. doi: 10.1016/j.rser.2014.07.017

Shue, H. (2021). *The Pivotal Generation: Why We Have A Moral Responsibility to Slow Climate Change Right Now, Chap. 4, "Are There Second Chances in Climate Change?."* Princeton; Oxford: Princeton University Press.

Smith, S. (2021). A case for transparent net-zero carbon targets. *Commun. Earth Environ.* 2:24. doi: 10.1038/s43247-021-00095-w

Stilgoe, J., Owen, R., and Macnaghten, P. (2013). Developing a framework for responsible innovation. *Res. Policy* 42, 1568–1580. doi: 10.1016/j.respol.2013.05.008

Thomas, G., Pidgeon, N., and Roberts, E. (2018). Ambivalence, naturalness and normality in public perceptions of carbon capture and storage in biomass, fossil energy, and industrial applications in the United Kingdom. *Energy Res. Soc. Sci.* 46, 1–9. doi: 10.1016/j.erss.2018.06.007

UK Department for Business, Energy and Industrial Strategy (BEIS) (2019). *UK Fourth Biennial Report*. London: UK Government.

UK Government (2021). Tree planting rates to treble by end of this Parliament. Available online at: https://www.gov.uk/government/news/tree-planting-rates-to-treble-by-end-of-this-parliament (accessed on May 17, 2021).

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Hugging the Shore: Tackling Marine Carbon Dioxide Removal as a Local Governance Problem

*Javier Lezaun**

Institute for Science, Innovation and Society (InSIS), University of Oxford, Oxford, United Kingdom

This Perspective explores the local governance of ocean-based carbon dioxide removal (CDR). Proposals to enhance the ability of oceans and marine ecosystems to absorb atmospheric CO_2 are often discussed as examples of "geoengineering," but this framing obscures the site-specific nature of most of the suggested interventions. The Perspective outlines some of the key local dimensions of marine CDR as currently imagined, and suggests a framework for increasing local participation in its assessment. Robust processes of local participation are essential to address the place-based conflicts that are bound to emerge if any of the proposed methods of CO_2 removal is ever deployed at scale.

Keywords: carbon dioxide removal, geoengineering, governance, marine environment, ocean-based carbon dioxide removal, ocean alkalinity enhancement, ocean iron fertilization

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Wil Burns,
American University, United States

****Correspondence:***
Javier Lezaun
javier.lezaun@insis.ox.ac.uk

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INTRODUCTION

Failure to reduce greenhouse gas emissions at a rate compatible with climate stability has accelerated the search for ways of removing CO_2 from the atmosphere. Some proposed interventions involve manipulating oceans and marine ecosystems to increase, or radically enhance, their ability to absorb CO_2. "Marine carbon dioxide removal" (CDR) is a fluid category that currently encompasses a highly heterogeneous set of options, from the conservation or restoration of vegetated coastal habitats ("blue carbon"), to alterations in the chemistry of the oceans to boost CO_2 uptake (as in artificial ocean alkalinization or ocean iron fertilization). Some of these options, particularly ocean iron fertilization, have a track record of small-scale (and controversial) field experimentation, but the majority remain for the moment limited to preliminary technical assessments and ingenious modeling exercises. Methods such as artificial ocean upwelling and downwelling, or the direct capture of CO_2 from seawater, are currently grounded in speculative technological scenarios and have undergone very limited practical assessment (see Gattuso et al., 2021 for a recent review of the field).

Yet we are at an important juncture in the development of marine CDR. Recent policy initiatives suggest growing interest in creating the scientific and technical infrastructures that would make large-scale marine CDR a realistic proposition. In the United States, the National Academies of Sciences, Engineering, and Medicine is preparing a consensus report on CDR and sequestration in coastal and open ocean waters, while governments in Europe and elsewhere are funding the assessment of detailed deployment scenarios. Research consortia and philanthropic initiatives are planning pilot studies, including offshore mesocosm experiments to characterize the ecological impacts of artificial ocean alkalinization (by the European Union-funded OceanNETs consortium, for example), or the spreading of ground olivine on beaches to increase coastal carbon capture (as in the initiatives sponsored by the non-profit Project Vesta).

These initiatives have generated a lively debate over the appropriate governance mechanisms for marine CDR (McGee et al., 2018; Webb, 2020; Boettcher et al., 2021; Cox et al., 2021). While it is difficult to define principles applicable across such a diverse range of potential interventions, it is urgent that we do so. The history of ocean iron fertilization experiments has bequeathed us a very limited range of conceptual tools and governance criteria; it has also consolidated the view of marine CDR as an "oceanic" or "planetary" mode of action, paradigmatic of the fraught moral issues pertaining to "geoengineering," and best addressed through international regulatory mechanisms. While this framing has served to highlight some of the legal and ethical dimensions of the problem, it obscures the fact that marine CDR, as currently imagined, will in many and relevant ways be *site-specific*: that it represents a *localized* form of climate action, affecting coastal communities and environments most immediately, and presenting them with geographically specific balances of risks and benefits. International governance principles and national regulatory frameworks thus need to be complemented with governance processes oriented toward the place-based dimensions of these novel forms of CO_2 capture.

In what follows, I review briefly how the controversies surrounding ocean iron fertilization have shaped our understanding of marine CDR governance, tilting it toward planetary considerations. To counterbalance this emphasis, I go on to discuss the site-specific nature of proposed marine CDR methods, with a focus on artificial ocean alkalinization. In the final part of the Perspective I discuss possible ways of tackling the local governance of marine CDR, emphasizing its crucial participatory dimensions—that is, the need to establish mechanisms that would allow those constituencies most directly affected by any decision-making process to shape its outcome. National and international legal frameworks tend to devolve key decisions, such as the definition of what constitutes "legitimate scientific research" or the calculation of the relevant "environmental risks," to technical experts, and offer limited opportunities for public consultation and review. The legitimacy of marine CDR will require a more inclusive approach, however, able to tackle the local geographies at stake.

GEOENGINEERING DISTANT OCEANS

Beginning in the late 1990s, a series of ocean iron fertilization experiments crystallized initial positions on the desirability of marine CDR. Expressions of concern about the potential impact of ocean fertilization activities were issued by, among others, the United Nations General Assembly, the United Nations Conference on Sustainable Development, the Conference of the Parties to the Convention on Biological Diversity, and the Intergovernmental Oceanographic Commission of UNESCO. In 2008, the Conference of the Parties to the Convention on Biological Diversity urged national governments "to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities, including an assessment of associated risks, and a global, transparent, and effective control and regulatory mechanism is in place for these activities" [Conference on Biological Diversity (CBD), 2008; see also Strong et al., 2009]. That same year, the London Convention and the London Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter included iron fertilization activities under the scope of its provisions (resolution LC-LP.1 2008). In 2010, the Contracting Parties to the London Convention and London Protocol adopted an "assessment framework for scientific research involving ocean fertilization" that included criteria for the definition of acceptable research activities, and the characterization of attendant environmental risks (LC 32/15, Annex 6).

In 2012, the discharge of iron sulfate and iron oxide by the Haida Salmon Restoration Corporation (HSRC) around the islands of Haida Gwaii, off the coast of British Columbia, triggered a new round of public controversy. Extrapolating from the case of ocean fertilization, the Parties to the Convention on Biological Diversity declared that "there is no single geoengineering approach that currently meets basic criteria for effectiveness, safety, and affordability, and that approaches may prove difficult to deploy or govern" [Conference on Biological Diversity (CBD), 2012]. In 2013, the contracting parties to the London Convention and the London Protocol adopted a resolution (not yet in force) to introduce an amendment "to regulate the placement of matter for ocean fertilization *and other marine geoengineering activities*" (LC 35/15, Annex 4 (my emphasis); see Webb et al., 2021 for an up-to-date discussion of international law in this area).

What is striking about these debates is the extent to which proponents and opponents alike framed the issue in planetary terms. For the proponents of these ocean fertilization activities, their goal was to assess the potential of induced phytoplankton growth "to influence the carbon budget of our planet" (Assmy et al., 2006). They sought to gather empirical data that would strengthen global models of ocean biochemistry and CO_2 uptake. For the critics, the experiments were dangerous, regardless of their scale or immediate scientific purpose, because they "give the wrong signal to the geo-engineers who would like to re-engineer our planet for profit" (ETC Group, 2009; see also Fuentes-George, 2017). Yet, by subsuming these experiments under the rubric of "geoengineering," the discussions elided crucial local dimensions. This was particularly evident in the case of the fertilization activities in Haida Gwaii. The decision by the Haida community of Old Massett to sponsor HSRC's activities in their coastal waters was driven by a host of complex considerations, including a desire to replenish depleted salmon runs and the prospect of direct financial returns through the sale of carbon credits. It also reflected a very specific experience of vulnerability to climate risk, and of neglect by national policy-makers. As Gannon and Hulme point out "when the HSRC is discursively situated within local histories and geographies of (post)colonial indigenous subjugation, resource extraction and Haida battles to restore political autonomy, it is easy to understand how this proposal gained traction within Old Massett" (Gannon and Hulme, 2018, p. 2). Once the debate was framed as a matter of "geoengineering," however, these "local histories and geographies" became peripheral. Actors with global reach and purposes—scientific consortia, environmental campaign organizations, international policy-makers—moved to center stage, while constituencies whose interests and concerns were oriented primarily to their specific socio-ecological context were marginalized (see Buck, 2018).

MARINE CDR AS LOCALIZED INTERVENTION

The local character of marine CDR is difficult to visualize when removal practices are imagined in oceanic terms. Graphic depictions of "marine geoengineering" often revolve around lone ships discharging minerals into ocean eddies (as with ocean alkalinity enhancement or iron fertilization), or present free-floating biochemical processes presumably unfolding somewhere in the high seas (as in many illustrations of ocean upwelling and downwelling). *Localizing* marine CDR is nevertheless crucial if we want to characterize the governance challenge, as it is a necessary condition for identifying the collectives and environments that will be most directly affected by its deployment. It is also crucial for designing mechanisms capable of mitigating the place-based conflicts that are bound to emerge if any of these options is used at scale.

The local nature of marine CDR is most obvious in the case of "blue carbon" strategies, which involve the conservation or restoration of vegetated coastal habitats with high rates of carbon sequestration (e.g., seagrass meadows, mangrove forests, tidal marshes). These strategies are by definition site-specific, and tend to build on existing marine and coastal conservation efforts. While it is difficult to argue *a priori* against any attempt to protect coastal ecosystems, the history of marine conservation suggests the difficulty of anticipating the full range of social, economic, and environmental impacts at the local level. A large body of social scientific literature on marine protected areas indicates the potential for conflict with residents whose livelihoods and cultural resources are directly or indirectly impacted by conservation efforts, and the challenge of devising interventions that operate synergically (McClanahan et al., 2005; Walley, 2010; Jentoft et al., 2012; Pascual-Fernández et al., 2018; Sowman and Sunde, 2018). A recent analysis of "blue carbon" strategies in Tanzania and Mozambique suggests, for example, multiple points of friction with a wide range of subsistence activities—from the reliance on mangrove forests for fuelwood, to small-scale trawling for fish, and crustaceans in seagrass meadows (Gullström et al., 2021; see also Veitayaki et al., 2017). When placed within what Carton and colleagues call "the long history of carbon removal" (Carton et al., 2020), "blue carbon" represents a new chapter to the genealogy of contentious carbon sequestration. Of particular relevance here is what Ehrenstein calls the "metrological inclusiveness" of carbon sink geopolitics; that is, who is in a position to produce globally accepted evidence of removal and sequestration, and how the uneven distribution of this ability to generate facts shapes the political ecology of the areas tasked with locking up carbon (Ehrenstein, 2018; see also Leach et al., 2012). Rather than being seen as a self-evident public good, the design of sustainable "blue carbon" initiatives requires detailed interdisciplinary research, and a robust process of stakeholder engagement (Thomas, 2014).

Local impacts are bound to be more apparent and less nuanced in the case of ocean afforestation and large-scale seaweed cultivation. Here, fast-growing macroalgae are grown at scale to remove CO_2 from the atmosphere through photosynthesis, with the carbon then sequestered through sinking or used to generate "carbon negative" products, as in the production of bioenergy with carbon capture and storage (BECCS). While terrestrial BECCS is probably the best understood (or at least the most extensively modeled) of all proposed large-scale CDR options, we have a very limited sense of how the marine versions of this approach might impact local communities and ecosystems. The experience with farming seaweeds for biofuels and other forms of large-scale mariculture suggests a significant risk of detrimental local environmental impacts (Duarte et al., 2017). Calls to investigate the full range of consequences that BECCS might carry for specific communities are even more pertinent for marine applications of this type of climate mitigation strategy (Buck, 2019a).

The localized character of non-biological forms of marine CDR is more difficult to grasp. This is partly due to the fact that their assessment has so far relied on theoretical models and speculative scenarios that tend to be insensitive toward regional-level dynamics. Models of artificial ocean alkalinization, for example, tend to estimate the "global effectiveness" of the intervention—in terms of the total amount of CO_2 extracted from the atmosphere—and assume an even distribution of the added alkalinity across the surface layer of the world's oceans. When they look at specific oceanic regions, they conclude that the site of intervention is immaterial to the scale of CO_2 removal, provided enough alkalinity is added (Lenton et al., 2018).

Yet artificial ocean alkalinization at scale, if it ever comes to pass, will be geographically specific in ways that will matter a great deal to its governance. For one, it will require extensive land-based infrastructures for the extraction, processing, and transportation of the required materials. Ocean liming, for example, involves the mining, grinding, and calcination of limestone (plus the capture and storage of most of the resulting CO_2, if the process is to result in a net reduction of atmospheric greenhouse gases). Given that transportation will represent a significant proportion of the cost (in both monetary and carbon terms), these infrastructures are likely to be located in or near coastal areas, often in close proximity to ancillary industrial activities (Renforth and Henderson, 2017). In fact, most scenarios for ocean alkalinity enhancement capitalize on already existing industrial activities. Alkalinity enhancement through the addition of magnesium oxide derived from reject brines, for example, implies a co-location with desalination plants (Davies, 2015). The hydrochloric acid that would be generated in the process (which is defined as a hazardous material in most jurisdictions) is also likely to be stored near shore (Webb et al., 2021). The kind of coastal spreading of olivine currently being investigated by Project Vesta would be much more economical if conducted in conjunction with beach nourishment efforts, a kind of "soft" coastal engineering with significant, if poorly understood, impacts on marine environments (Staudt et al., 2021). The point here is that the infrastructures required for artificial ocean alkalinization will likely be built on top of already existing industrial operations on or near shore, potentially intensifying their local environmental impacts even if they were to contribute to a net reduction of atmospheric CO_2. It is important to keep in mind, moreover, that most scenarios for artificial ocean alkalinization anticipate decades, if not centuries, of mineral production and discharge if levels of greenhouse gas emissions remain high (Keller et al., 2014).

Comparable co-location effects are evident in early modeling of CO_2 stripping. Although some of the proposed scenarios present self-supporting, stand-alone deployments (e.g., "clusters of marine-based floating islands, on which photovoltaic cells convert sunlight into electrical energy to produce H_2 and to extract CO_2 from seawater," as in Patterson et al., 2019), the truth of the matter is that these will be, once again, coastal interventions linked to extensive land-based infrastructures, including those required for the transportation and storage of the extracted CO_2 (La Plante et al., 2021). Artificial upwelling is often depicted as an untethered process merely replicating the natural circulation of water between ocean layers (and, because it does not require deliberately adding new materials to the sea, falling outside the purview of the London Convention and the London Protocol). Yet for this type of intervention to have any discernible impact on the climate it would involve deploying millions of devices (plastic pipes, pumps, swimming platforms) across large areas of the oceans. Recent field trials reveal the significant infrastructural preconditions for this sort of "non-invasive" climate action (Fan et al., 2020).

There is, in essence, no free-floating marine CDR. Even if key operations take place relatively far from shore and "out of sight," they are unlikely to be of no concern to coastal actors and communities. Social scientific research on the public acceptability of offshore wind energy, marine oil, and gas extraction, or subsea CO_2 storage makes clear that, far from being distant activities unfolding in unpopulated spaces, these industrial activities tend to be seen as directly impacting human landscapes, often as a new chapter in long histories of local resource exploitation and environmental destruction (Firestone and Kempton, 2007; Mabon et al., 2014; Günel, 2019; see also Bertram and Merk, 2020).

DISCUSSION

Neither an "oceanic" solution nor exclusively land-based, most marine CDR will represent a new kind of *inshore* practice, a compendium of littoral climate technologies with the potential to reshape the way we relate to the seas. Linking up multiple onshore and offshore activities, the impact of marine CDR will be felt most directly in coastal environments and by nearshore communities. Basic economics suggests that these operations will tend to be co-located with already existing extractive, processing, and transportation activities, potentially exacerbating environmental strains in already vulnerable areas. Optimizing the deployment of marine CDR and characterizing its potential net environmental gain thus requires greater attention to the local and regional scale of assessment.

Yet current discussions of marine CDR governance continue to be framed in planetary terms. This is true of most scientific assessments, which adopt spatially homogeneous deployment scenarios with low regional resolution. It is also true of the legal and policy initiatives that emerged in the wake of the controversies over ocean iron fertilization, which address marine CDR as a form of geoengineering and emphasize the role of international regulatory tools in mitigating transnational risks (Buck, 2019b). While this *oceanic* understanding of marine CDR reveals key aspects of the problem at hand, it is of little help in navigating the complex place-based governance challenges that are bound to emerge at smaller geographical scales.

Most immediately, this suggests the need to think more rigorously about local participation in the assessment of marine CDR experiments. International governance mechanisms like the London Convention and the London Protocol hinge on the demarcation of "legitimate scientific research," but they leave the decision of whether any given study has the "proper scientific attributes" to national or international expert bodies (London Convention 32/15). They offer little guidance on how to design a robust participatory process that is attentive to local expectations and concerns beyond the scientific qualities of a proposed experiment. National jurisdictions possess many laws and regulations with potential applicability to experimental marine CDR activities, but the manner in which they should be applied remains uncertain (Webb, 2020), and they allow limited opportunities for local participation in the decision-making process. As a result, the scientific consortia and non-profit initiatives currently planning marine CDR experiments are essentially forced to invent their own, *ad hoc* approaches to public participation.

A participatory turn in the assessment of marine CDR experimentation must start by expanding the range of actors and factors included in these discussions, as has been argued for greenhouse gas removal technologies more generally (Forster et al., 2020). One possible way to do this would be to consider CDR proposals within existing frameworks for marine spatial planning (MSP). The key advantages of MSP is that it operates at the ecosystem level, takes into account land–sea interactions, and makes explicit the tensions—and also any potential synergies—between alternative uses of marine space. Moreover, in some jurisdictions MSP is supported by legally-binding frameworks that include explicit mandates for transparency, participation, and accountability (as in the EU Marine Spatial Planning Directive).

Incorporating marine CDR into institutionalized spatial planning processes is obviously no guarantee of good governance or of meaningful public participation; the struggle to make MSP planning a properly "public" process, not subordinated to elite interests, remains as urgent as ever (Gopnik et al., 2012; Smith, 2018; Twomey and O'Mahony, 2019). But at least MSP would embed participatory practices within a reasoned consideration of the medium-term socio-ecological impacts of marine CDR. It would visualize potential conflicts with other uses of the marine environment, and help define criteria for their co-existence.

"Blue carbon" provides an obvious starting point for such an approach, as it builds on decades of experience—good and bad—in the governance of coastal conservation areas and carbon sinks. Some regional-level "blue carbon" audits and action plans already draw on the participation of a wide range of stakeholders (Porter et al., 2020), or integrate "blue carbon" into sub-national climate strategies that sanction the involvement of a diverse set of local actors (Wedding et al., 2021; see also Duarte et al., 2017). The road is less clear for marine CDR options with a more oblique link to conservation, and were the potential for far-reaching environmental impacts is much more significant but also much more uncertain. Part of the problem here is that it is more difficult to articulate—let alone quantify—the potential benefits that might accrue at the local or regional level from any given CDR intervention. In this regard, a formal MSP process can be a useful forum to discuss the direct economic benefits that might derive from hosting particular CDR infrastructures, or the allocation of any potential monetary carbon credits associated with CO_2 removals.

In sum, tackling marine CDR as a local governance challenge will necessarily shifts the parameters of the discussion. While the oceans trigger understandings of planetary fragility and demands for the protection of the global commons, coastal environments, and the communities they support are exposed to more proximate versions of climate risk and must contend with a complex mix of demands upon marine space. Under these circumstances, the governance of marine CDR becomes a vital local matter that cannot be delegated to international agreements or expert working groups. It also becomes entangled with geographically specific imaginaries of climate action and economic development, giving marine CDR a broader range of connotations than those implicit in the concept of "geoengineering." If, as Bellamy and Geden (2019) have argued, the governance of carbon dioxide removal should be tackled "from the ground up," marine CDR governance should be understood "from the coast out," placing the interests, expectations, and concerns of coastal actors at its center.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

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

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REFERENCES

Assmy, P., Cisewski, B., Henjes, J., Klaas, C., Sachs, O., Smetacek, V., et al. (2006). *Plankton Rain in the Southern Ocean: The European Iron Fertilization Experiment EIFEX. Das AWI in den Jahren* 2004 und 2005-Report *2004*, 38–41.

Bellamy, R., and Geden, O. (2019). Govern CO_2 removal from the ground up. *Nat. Geosci.* 12, 874–876. doi: 10.1038/s41561-019-0475-7

Bertram, C., and Merk, C. (2020). Public perceptions of ocean-based carbon dioxide removal technologies: the nature-engineering divide. *Front. Clim.* 2:31. doi: 10.3389/fclim.2020.594194

Boettcher, M., Brent, K., Buck, H. J., Low, S., McLaren, D., and Mengis, N. (2021). Navigating potential hype and opportunity in governing marine carbon removal. *Front. Clim.* 3:47. doi: 10.3389/fclim.2021.664456

Buck, H. J. (2018). "Village science meets global discourse: the Haida salmon restoration corporation's ocean iron fertilization experiment," in *Geoengineering Our Climate?: Ethics, Politics, and Governance*, eds J. J. Blackstock and S. Low (London: Earthscan-Routledge). 107–112.

Buck, H. J. (2019a). Challenges and opportunities of bioenergy with carbon capture and storage (BECCS) for communities. *Curr. Sustain. Renew. Energy Rep.* 6, 124–130. doi: 10.1007/s40518-019-00139-y

Buck, H. J. (2019b). After *Geoengineering: Climate Tragedy, Repair, and Restoration*. London: Verso Trade.

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *Wiley Interdiscipl. Rev. Clim. Change* 11:e671. doi: 10.1002/wcc.671

Conference on Biological Diversity (CBD) (2012) *Decision adopted by the Conference of the Parties to the Convention on Biological Diversity at its Eleventh Meeting*. 8–19 October 2012 (Hyderabad).

Conference on Biological Diversity (CBD). (2008). *Decision adopted by the Conference of the Parties to the Convention on Biological Diversity at its Ninth Meeting*. 19–30 May 2008 (Bonn).

Cox, E., Boettcher, M., Spence, E., and Bellamy, R. (2021). Casting a wider net on ocean NETs. *Front. Clim.* 3:4. doi: 10.3389/fclim.2021.576294

Davies, P. A. (2015). Solar thermal decomposition of desalination reject brine for carbon dioxide removal and neutralisation of ocean acidity. *Environ. Sci. Water Res. Technol.* 1, 131–137. doi: 10.1039/C4EW00058G

Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., and Krause-Jensen, D. (2017). Can seaweed farming play a role in climate change mitigation and adaptation?. *Front. Mar. Sci.* 4:100. doi: 10.3389/fmars.2017.00100

Ehrenstein, V. (2018). Carbon sink geopolitics. *Econ. Soc.* 47, 162–186. doi: 10.1080/03085147.2018.1445569

ETC Group. Throwing Precaution (and iron) to the Wind (and waves). News Release (2009). Available online at: https://www.etcgroup.org/content/lohafex-update-throwing-precaution-and-iron-wind-and-waves (accessed on August 7, 2021).

Fan, W., Zhang, Z., Yao, Z., Xiao, C., Zhang, Y., Zhang, Y., et al. (2020). A sea trial of enhancing carbon removal from Chinese coastal waters by stimulating seaweed cultivation through artificial upwelling. *Appl. Ocean Res.* 101:102260. doi: 10.1016/j.apor.2020.102260

Firestone, J., and Kempton, W. (2007). Public opinion about large offshore wind power: underlying factors. *Energy Policy* 35, 1584–1598. doi: 10.1016/j.enpol.2006.04.010

Forster, J., Vaughan, N. E., Gough, C., Lorenzoni, I., and Chilvers, J. (2020). Mapping feasibilities of greenhouse gas removal: key issues, gaps and opening up assessments. *Glob. Environ. Change* 63:102073. doi: 10.1016/j.gloenvcha.2020.102073

Fuentes-George, K. (2017). Consensus, certainty, and catastrophe: discourse, governance, and ocean iron fertilization. *Glob, Environ. Polit.* 17, 125–143. doi: 10.1162/GLEP_a_00404

Gannon, K. E., and Hulme, M. (2018). Geoengineering at the "Edge of the World": exploring perceptions of ocean fertilisation through the Haida Salmon Restoration Corporation. *Geo Geogr. Environ.* 5:e00054. doi: 10.1002/geo2.54

Gattuso, J. P., Williamson, P., Duarte, C. M., and Magnan, A. K. (2021). The potential for ocean-based climate action: negative emissions technologies and beyond. *Front. Clim.* 2:37. doi: 10.3389/fclim.2020.575716

Gopnik, M., Fieseler, C., Cantral, L., McClellan, K., Pendleton, L., and Crowder, L. (2012). Coming to the table: early stakeholder engagement in marine spatial planning. *Mar. Policy* 36, 1139–1149. doi: 10.1016/j.marpol.2012.02.012

Gullström, M., Dahl, M., Lindén, O., Vorhies, F., Forsberg, S., Ismail, R. O., et al. (2021). *Coastal Blue Carbon Stocks in Tanzania and Mozambique*. IUCN, Global Marine and Polar Programme.

Günel, G. (2019). *Spaceship in the Desert: Energy, Climate Change, and Urban Design in Abu Dhabi.* https://www.google.com/search?rlz=1C1CHWA_enIN952IN954&sxsrf=ALeKk00_w0j9-GLSCSL6sQF-zt_iGGCKCw:1627746975962&q=Durham,+North+Carolina&stick=H4sIAAAAAAAAAOPgE-LSz9U3MLIwS4qvUOIEsQ2NMyrKtLSyk63084vSE_MyqxJLMvPzUDhWGamJKYWliUUlqUXFi1jFXEqLMhJzdRT88otKMhScE4vyczLzEnewMgIAr2hEP2EAAAA&sa=X&ved=2ahUKEwjX36SC1o3yAhVvgdgFHcCQBCkQmxMoATApegQIMxAD NC: Duke University Press. doi: 10.1215/9781478002406

Jentoft, S., Pascual-Fernandez, J. J., De la Cruz Modino, R., Gonzalez-Ramallal, M., and Chuenpagdee, R. (2012). What stakeholders think about marine protected areas: case studies from Spain. *Hum. Ecol.* 40, 185–197. doi: 10.1007/s10745-012-9459-6

Keller, D. P., Feng, E. Y., and Oschlies, A. (2014). Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nat. Commun.* 5, 1–11. doi: 10.1038/ncomms4304

La Plante, E. C., Simonetti, D. A., Wang, J., Al-Turki, A., Chen, X., Jassby, D., et al. (2021). Saline water-based mineralization pathway for gigatonne-scale CO_2 management. *ACS Sustain. Chem. Eng.* 9, 1073–1089. doi: 10.1021/acssuschemeng.0c08561

Leach, M., Fairhead, J., and Fraser, J. (2012). Green grabs and biochar: revaluing African soils and farming in the new carbon economy. *J. Peas. Stud.* 39, 285–307. doi: 10.1080/03066150.2012.658042

Lenton, A., Matear, R. J., Keller, D. P., Scott, V., and Vaughan, N. E. (2018). Assessing carbon dioxide removal through global and regional ocean alkalinization under high and low emission pathways. *Earth Syst. Dyn.* 9, 339–357. doi: 10.5194/esd-9-339-2018

Mabon, L., Shackley, S., and Bower-Bir, N. (2014). Perceptions of sub-seabed carbon dioxide storage in Scotland and implications for policy: a qualitative study. *Mar. Policy* 45, 9–15. doi: 10.1016/j.marpol.2013.11.011

McClanahan, T., Davies, J., and Maina, J. (2005). Factors influencing resource users and managers' perceptions towards marine protected area management in Kenya. *Environ. Conserv.* 32, 42–49. doi: 10.1017/S0376892904001791

McGee, J., Brent, K., and Burns, W. (2018). Geoengineering the oceans: an emerging frontier in international climate change governance. *Aust. J. Marit. Ocean Aff.* 10, 67–80. doi: 10.1080/18366503.2017.1400899

Pascual-Fernández, J. J., De la Cruz Modino, R., Chuenpagdee, R., and Jentoft, S. (2018). Synergy as strategy: learning from La Restinga, Canary Islands. *Marit. Stud.* 17, 85–99. doi: 10.1007/s40152-018-0091-y

Patterson, B. D., Mo, F., Borgschulte, A., Hillestad, M., Joos, F., Kristiansen, T., et al. (2019). Renewable CO_2 recycling and synthetic fuel production in a marine environment. *Proc. Nat. Acad. Sci. U.S.A.* 116, 12212–12219. doi: 10.1073/pnas.1902335116

Porter, J., Austin, W., Burrows, M., Clarke, D., Davies, G., Kamenos, N., et al. (2020). Blue *Carbon Audit* of Orkney *Waters*. Aberdeen: Marine Scotland Science.

Renforth, P., and Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Rev. Geophys.* 55, 636–674. doi: 10.1002/2016RG000533

Smith, G. (2018). Good governance and the role of the public in Scotland's marine spatial planning system. *Mar. Policy* 94, 1–9. doi: 10.1016/j.marpol.2018.04.017

Sowman, M., and Sunde, J. (2018). Social impacts of marine protected areas in South Africa on coastal fishing communities. *Ocean Coast. Manage.* 157, 168–179. doi: 10.1016/j.ocecoaman.2018.02.013

Staudt, F., Gijsman, R., Ganal, C., Mielck, F., Wolbring, J., Hass, H. C., et al. (2021). The sustainability of beach nourishments: a review of nourishment and environmental monitoring practice. *J. Coast. Conserv.* 25, 1–24. doi: 10.1007/s11852-021-00801-y

Strong, A., Chisholm, S., Miller, C., and Cullen, J. (2009). Ocean fertilization: time to move on. *Nature* 461, 347–348. doi: 10.1038/461347a

Thomas, S. (2014). Blue carbon: knowledge gaps, critical issues, and novel approaches. *Ecol. Econ.* 107, 22–38. doi: 10.1016/j.ecolecon.2014.07.028

Twomey, S., and O'Mahony, C. (2019). "Stakeholder processes in marine spatial planning: ambitions and realities from the European Atlantic experience," in *Maritime Spatial Planning*, eds J. Zaucha and K. Gee (Cham: Palgrave Macmillan) 295–325. doi: 10.1007/978-3-319-98696-8_13

Veitayaki, J., Waqalevu, V., Varea, R., and Rollings, N. (2017). "Mangroves in small island development states in the Pacific: an overview of a highly important and seriously threatened resource," in *Participatory Mangrove Management in a Changing Climate,* eds R. DasGupta and S. Rajib (Tokyo: Springer), 303–327. doi: 10.1007/978-4-431-56481-2_19

Walley, C. J. (2010). Rough Waters*: Nature and Development in an East African Marine Park*. Princeton, NJ: Princeton University Press.

Webb, R. (2020). *The Law of Enhanced Weathering for Carbon Dioxide Removal*. New York, NY: Sabin Center for Climate Change Law, Columbia Law School.

Webb, R., Silverman-Roati, K., and Gerrard, M. (2021). *Removing Carbon Dioxide Through Ocean Alkalinity Enhancement and Seaweed Cultivation: Legal Challenges and Opportunities*. Sabin Center for Climate Change Law, Columbia Law School, Columbia Public Law Research Paper Forthcoming.

Wedding, L. M., Moritsch, M., Verutes, G., Arkema, K., Hartge, E., Reiblich, J., et al. (2021). Incorporating blue carbon sequestration benefits into sub-national climate policies. *Glob. Environ. Change* 2021:102206. doi: 10.1016/j.gloenvcha.2020.102206

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Incentivizing BECCS—A Swedish Case Study

Lars Zetterberg[1]*, *Filip Johnsson*[2] *and Kenneth Möllersten*[1]

[1] Department of Sustainable Society, IVL Swedish Environmental Research Institute, Stockholm, Sweden, [2] Department of Space, Energy, and Environment, Chalmers University of Technology, Göteborg, Sweden

Negative carbon dioxide (CO_2)-emissions are prevalent in most global emissions pathways that meet the Paris temperature targets and are a critical component for reaching net-zero emissions in Year 2050. However, economic incentives supporting commercialization and deployment of BioEnergy Carbon Capture and Storage (BECCS) are missing. This Policy and Practice Review discusses five different models for creating incentives and financing for BECCS, using Sweden as an example: (1) governmental guarantees for purchasing BECCS outcomes; (2) quota obligation on selected sectors to acquire BECCS outcomes; (3) allowing BECCS credits to compensate for hard-to-abate emissions within the EU ETS; (4) private entities for voluntary compensation; and (5) other states acting as buyers of BECCS outcomes to meet their mitigation targets under the Paris Agreement. We conclude that successful implementation of BECCS is likely to require a combination of several of the Policy Models, implemented in a sequential manner. The governmental guarantee model (Model 1) is likely to be required in the shorter term, so as to establish BECCS. Policy Models 2 and 3 may become more influential over time once BECCS has been established and accepted. Model 3 links BECCS to a large carbon-pricing regime with opportunities for cost-effectiveness and expanded financing. We conclude that Policy Models 4 and 5 are associated with high levels of uncertainty regarding the timing and volume of negative emissions that can be expected—Thus, they are unlikely to trigger BECCS implementation in the short term, although may have roles in the longer term. Based on this study, we recommend that policymakers carefully consider a policy sequencing approach that is predictable and sustainable over time, for which further analyses are required. It is not obvious how such sequencing can be arranged, as the capacities to implement the different Policy Models are vested in different organizations (national governments, EU, private firms). Furthermore, it is important that a BECCS policy is part of an integrated climate policy framework, in particular one that is in line with policies aimed at the mitigation of greenhouse gas (GHG) emissions and the creation of a circular economy. It will be important to ensure that BECCS and the associated biomass resource are not overexploited. A well-designed policy package should guarantee that BECCS is neither used to postpone the reduction of fossil fuel-based emissions nor overused in the short term as a niche business for "greenwashing" while not addressing fossil fuel emissions.

Keywords: bioenergy carbon capture and storage, negative emissions, incentives, policy instruments, policy sequencing, carbon dioxide removal

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Emily Cox,
Cardiff University, United Kingdom

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Javier Lezaun,
University of Oxford, United Kingdom
Felix Schenuit,
Center for Sustainable Society Research, Germany

***Correspondence:**
Lars Zetterberg
lars.zetterberg@ivl.se

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INTRODUCTION

Carbon Capture and Storage (CCS) has been analyzed extensively in the context of mitigating carbon dioxide (CO_2) emissions from fossil fuel-based processes. More recently, there has been growing interest in applying CCS to biogenic CO_2 emissions, i.e., so-called BioEnergy Carbon Capture and Storage (BECCS), although it had already started to be discussed as a concept in the late 1990s (Williams, 1998; Möllersten and Yan, 2001; Keith and Rhodes, 2002; Möllersten et al., 2003). BioEnergy Carbon Capture and Storage can serve to offset residual emissions in hard-to-abate sectors (e.g., agriculture, shipping, heavy road transport) and to contribute to net-negative emissions on a global level (Obersteiner et al., 2001). Both effects are likely to be required because emissions levels will probably exceed what is compatible with the Paris Agreement (Intergovernmental Panel on Climate Change (IPCC)., 2018). In fact, BECCS is the major technology for carbon dioxide removal (CDR) in the vast majority of scenarios that are considered to have a high likelihood of meeting the terms of the Paris Agreement (Rogelj et al., 2018). Thus, although other CDR technologies exist, such as direct air capture (DAC) and land use change and forestation, these are less-developed (DAC) or highly complex (land use change).

According to Sweden's climate target, greenhouse gas (GHG) emissions should be at a net-zero level by Year 2045 (Swedish Government, 2017). This translates into a reduction of domestic (production-based) emissions of at least 85% (relative to the level in Year 1990), and offsetting up to 15% of emissions, corresponding to approximately 11 $MtCO_2e$, through the use of so-called "supplementary measures." These measures include increased sequestration of carbon in forests and agricultural land, verified emission reductions ("offsets") in other countries, and BECCS.

Proposed BECCS Targets for Sweden

A recently conducted public inquiry in Sweden ("SOU2020:4") has examined the supplementary measures (Swedish Government, 2020) and has concluded that it will be more costly to reach the target of net-zero GHG emissions by Year 2045 without the supplementary measures, since it would require comprehensive transformation of the agricultural sector (e.g., to mitigate methane and nitrous oxide emissions). The governmental inquiry has identified BECCS as the most promising supplementary measure with the largest volume potential and has proposed targets for BECCS of up to 2 $MtCO_2$/year by Year 2030 and 3–10 $MtCO_2$/year by Year 2045. The wide range estimated for 2045 reflects the uncertainty regarding the need for supplementary measures in Year 2045, i.e., uncertainty related to the contributions from other GHG reduction measures.

The SOU2020:4 inquiry concludes that supplementary measures often involve investment-intensive projects that run for a long time. For such projects to be realized, the field of measures needs to be characterized for stable terms and conditions and clear targets, with the aim of reducing the project-associated risks for the involved actors. The inquiry further suggests that the volume of supplementary measures should be gradually increased, and that an early start in implementing these measures will provide flexibility in relation to mitigation options in the longer term.

The inquiry also notes that a policy for incentivizing BECCS should promote technological development and demonstration activities, while at the same time creating long-term economic conditions for full-scale BECCS projects. It concludes that Sweden should act to ensure that the EU develops a common long-term instrument to promote BECCS.

Swedish BECCS Potential

The total potential for BECCS in Sweden is substantial, as the country has many large-point sources of biogenic CO_2 emissions, mainly combined heat and power (CHP) plants burning wood waste from the forest industry and pulp and paper plants (Karlsson et al., 2017). The aforementioned SOU2020:4 governmental inquiry estimates the total biogenic CO_2 emissions from point sources larger than 0.1 Mt to amount to more than 30 $MtCO_2$ per year. Johnsson et al. (2020) have estimated that the total for the emissions that could be captured from the 28 industrial units (i.e., excluding the energy sector) with the highest levels of emissions (i.e., >0.5 Mt/year) is 23 $MtCO_2$ per year, of which around half is from biogenic emissions. This level of capture is linked to an estimated average cost of 80–140 €/tCO_2, including the costs for transport and storage (Johnsson et al., 2020). Karlsson et al. (2017) have estimated the total potential for BECCS as 23.7 Mt, applying a capture rate of 85%, which corresponds to the capture of 20.1 Mt of CO_2 of biogenic origin. If only considering technologies at a cost below 120 €/ton, the total potential would be 16.7 Mt/year (Karlsson et al., 2017).

In principle, there is little difference between technologies that capture fossil-origin emissions and biogenic emissions. There is a large body of literature on CCS (see for example the *International Journal of Greenhouse Gas Control Technologies*), investigating the various technological and cost aspects of such technologies (capture by means of pre-combustion, oxyfuel, post-combustion, chemical looping combustion, etc.), including the transport and storage of the captured CO_2. In addition, there are reports in the literature on the social acceptance of CCS (see Tcvetkov et al., 2019 for a review). A large part of this knowledge is applicable also to BECCS, although the aspects of the social acceptance of BECCS may differ from those of CCS applied to emissions from fossil fuels. The general public may perceive negative emissions technologies, including BECCS as a means to tamper with nature and Wolske et al. (2019) used this as an explanation for their finding that the support for BECCS (and DAC) was lower than support for afforestation and reforestation. Cox et al. (2020) performed a study on public perception on CDR technologies in the US and UK from which they conclude that the need for CDR is perceived as a too slow a response to climate change and interpreted as not addressing the root causes of climate change. Bellamy et al. (2019) conclude that that the type of policy instrument used to incentivize BECCS influence perceptions of the technology where the public may favor coercive instruments over price guarantees for producers selling BECCS derived energy.

The post-combustion capture technology is a commercially available technology that has been used in the chemical industry for several decades (Bui et al., 2018) and which is also applied in current CCS schemes. In Year 2020 there were 26 commercial CCS projects in operation around the world (Global CCS Institute, 2020), having a total capture capacity of around 40 $MtCO_2$/year, although most of them are concerned with Enhanced Oil Recovery (EOR), for which the CO_2 is used to extract more oil.

With respect to BECCS, there is a substantial body of literature on its potential roles in global emission scenarios, typically based on Integrated Assessment Models (IAMs), e.g., Rogelj et al. (2018), Bellamy and Geden (2019), Fuhrman et al. (2019), Gambhir et al. (2019), Gough and Mander (2019), Forster et al. (2020), and Laude (2020). However, there has been little actual implementation of BECCS—even less than for CCS. Fuss and Johnsson (2021) have concluded that there is an obvious gap between the need for BECCS as identified in global IAM scenarios and its actual implementation. This type of implementation gap is also evident in Sweden, where no BECCS has yet been implemented, despite the favorable conditions for BECCS.

Fridahl et al. (2020) have presented an overview of existing policy instruments (economic, regulatory, and informational) for BECCS with a Swedish focus, and they conclude that at present there are only supply-push incentives in the form of support for demonstration of BECCS, whereas demand-pull instruments are lacking. Although a survey among UN climate change conference delegates, showed low prioritization of BECCS relative to alternative technologies (Fridahl, 2017) there is an increased interest in BECCS among Swedish stakeholders in industry and in politics.

Considering the explicit targets proposed in the above mentioned public inquiry (Swedish Government, 2020), there is a need for prompt introduction of economic incentives, in the form of demand-pull incentives, to support the commercialization and deployment of BECCS (Fridahl et al., 2020, Fuss and Johnsson, 2021). However, it is not obvious how incentives for BECCS can and should be introduced and ramped up over time and Bellamy et al. (2019) concluded that that public support for BECCS is linked to attitudes toward the policies through which it is incentivized. Based on stakeholder interviews around four different scenarios, Bellamy et al. (2021) have discussed what these scenarios might mean for BECCS, and they argue that policies should account for diverse and geographically varying societal values and interests. Although these works all argue in favor of policies that incentivize BECCS, there is a gap in the literature with respect to studies that propose and dissect explicit policies for BECCS (and other CDR technologies for that matter) and how these can be ramped up over time. Therefore, the aim of the present paper is to discuss different models for creating incentives and financing for BECCS. For this, we use Sweden as an example, given its favorable conditions for BECCS.

Challenges for Incentivizing BECCS

Since BECCS will require substantial upfront investments and additional energy and will, thereby, increase the production cost (e.g., for heat and electricity and pulp and paper), it is important that the BECCS policy is sustainable in the long term in terms of the level of incentives, as well as predictability. This has been a general problem for several capital-intensive mitigation technologies, including fossil CCS for which the EU ETS system has, so far, given insufficient incentives for large-scale implementation. The price of emissions allowances has been too low and too unpredictable to trigger investments in CCS and other more-transformative technologies. Another characteristic of BECCS (and CCS) is that although BECCS is largely based on a commercially available technology [high technology readiness levels (TRLs) for post-combustion capture technologies], it cannot be ramped up in an incremental way (as is the case with wind and solar power) but instead requires large-scale units. Thus, any policy must be able to deal with this.

There are, at least, two explicit challenges associated with creating policies for incentivizing BECCS (or other CDR technologies), the first of which has previously been identified in the literature:

1. That the possibility for widespread deployment of BECCS later in the century may reduce the effort for deep near-term mitigation of fossil fuel emissions (Anderson and Peters, 2016), possibly locking Society into a high-temperature pathway if BECCS (or another CDR) fails to deliver at the required levels (e.g., Anderson and Peters, 2016; Obersteiner et al., 2018).
2. The creation of a near-term BECCS policy that is strong enough to trigger its implementation may require incentives that are higher than the cost of emitting fossil fuel carbon. This may result in inefficient use of biomass, which is a limited resource that is also needed for other purposes.

Regarding the first point above, recent publications by McLaren et al. (2019) and Geden and Schenuit (2020) have discussed the negative impacts that promises of negative emissions could have on emissions reduction, and they have proposed the development of separate targets for emission reductions and negative emissions, so as to minimize the risk that there will be less emphasis on fossil fuel mitigation due to the future availability of BECCS. Yet, the authors of the present work believe that, although the first point above is logical and may entail a risk of delaying near-term mitigation, it is somewhat theoretical in that, in practice, the present lack of a sufficiently strong climate policy does not seem to be due to the fact that actors in Society (firms or policymakers) are betting on future possibilities for negative emissions. This contrasts with the second point above, which is more or less already a reality in Sweden where energy, transport, and industrial actors all envision the use of biomass as an important mitigation measure, at the same time as there is a proposal to establish explicit target for BECCS for Year 2030 (Swedish Government, 2020). The proposed BECCS targets would require BECCS incentives of at least 100 €/tCO_2, or more likely 150–200 €/tCO_2 in the short term, before adequate experience is gained (cf. the costs given by Johnsson et al., 2020). This is far higher than the present cost to emit fossil fuel-derived CO_2, which at the time of writing is at 56 €/ton within the EU ETS (European Energy Exchange, 2021). Although this is the highest valuation so far, the future trajectory of allowance prices is uncertain (considering that allowance prices may decrease again). Thus, there is a risk that an asymmetry will be created between the cost of reducing fossil fuel emissions and the compensation assigned for negative emissions.

It can be concluded that there is a need for a climate policy that is sufficiently potent to trigger the required reduction in fossil fuel emissions at the same time as incentives for negative emissions are created that support the large-scale demonstration and development of BECCS. This is in line with Bednar et al. (2019), who have proposed that a mitigation strategy that includes CDR should build on the following two pillars: (i) earlier and more radical reductions in emissions than what most Paris Agreement-compliant mitigation scenarios suggest; and (ii) near-term development and ramping-up of CDR technologies to clarify their actual potentials and the scaling properties of specific technological options. The authors argue that CDR should primarily be regarded as a tool for hedging against climate-related uncertainties. Fuss and Johnsson (2021) have argued that a balance must be established between valuing negative emissions achieved through BECCS and the cost of fossil fuel-related emissions.

In summary, there is an urgent need to analyze how CDR can be incentivized. This paper is a first attempt to assess different Policy Models with the focus on BECCS in the Swedish context. We chose BECCS because this is the most-mature CDR technology for which—as indicated above—concrete targets have been proposed in a Swedish public inquiry.

ASSESSMENT OF BECCS POLICY MODELS

Choice of Policy Models

A common way to create incentives for reducing the environmental impact of emissions is the so-called Polluter Pays Principle, PPP (Organisation for Economic Co-operation and Development, 2021). *Polluter Pays Principle* includes the pricing of CO_2 emissions and other pollutants in the form of a tax or a trading system, such as the European Union Emissions Trading Scheme, EU ETS (European Commission, 2003). However, with negative emissions, PPP is not applicable, since there is no pollution, but instead a common benefit (or a *positive externality)*. Since carbon removal results in a common benefit, it can be argued that it should be taken from the state budget (although for a global common benefit there are no corresponding global "state budgets"). If one wants to formulate a principle analogous to PPP, this could be called the *Beneficiary Pays Principle* (BPP). This reasoning leads us to Policy Model 1, where the state procures a certain amount of BECCS. This model has also been proposed by the Swedish inquiry for supplementary measures (Swedish Government, 2020).

Although not strictly following the BPP, from a financing perspective, one could argue that those who emit fossil fuel emissions (or other GHGs) should contribute to financing BECCS. This could be implemented by imposing an obligation on those who emit to pay for carbon removal. Sectors that could be targeted for such obligations are those that account for significant emissions today and residual emissions in the future. This is our motivation for Policy Model 2 (quota obligation).

The Swedish BECCS potential is significantly larger than the estimated residual emissions in Sweden in Year 2045. Exploitation of the full potential of Swedish BECCS projects could be done by linking with international carbon markets. One way to do this is to allow the participants in the EU ETS to purchase BECCS credits as an alternative to emission allowances, which is the goal of Policy Model 3.

Policy Model 4 is based on offering BECCS credits to voluntary markets, which would be a way to broaden the funding of Swedish BECCS.

Based on these four models, the authors of this paper have participated in three workshops (12 February 2020 in Stockholm, 15 February 2021 online, 22 April 2021 online) to discuss the relevance and feasibility levels of the models. The participants in these workshops consisted of business representatives/potential BECCS operators, members of the Swedish parliament, government officials and academic experts. The workshops deemed the four models to be relevant and identified a fifth model (Policy Model 5: other states as buyers of BECCS credits).

In conclusion, we have identified the following five Policy Models for creating incentives and financing for BECCS in Sweden: (1) state guarantees; (2) quota obligations imposed on selected sectors; (3) EU ETS use of BECCS credits for compliance; (4) private entities for voluntary compensation; and (5) other states as buyers. These Policy Models, which are listed in **Table 1**, are analyzed and discussed regarding potential volumes, financing, governance, and stakeholder preferences.

Model 1: State Guarantees

With this Model, the state (i.e., the taxpayers) buys BECCS outcomes. This can be done through long-term agreements with BECCS producers, whereby the state guarantees to buy a certain level of carbon removal by BECCS over a certain time. To minimize costs to the state, the contracts can be auctioned off in lots to the lowest bidder. The previously mentioned Swedish public inquiry (Swedish Government, 2020) has proposed a system of Model 1 type in the form of a reversed auctioning system (reversed in the sense that there is one buyer of the credits—the Swedish state—and many potential sellers of negative emissions).

Potential Volumes and Financing

As an indicator of the required level of financing, the target of up to 2 Mt/year BECCS by Year 2030 for Sweden, proposed in the abovementioned government inquiry would entail a cost of 200 million € per year (Fuss and Johnsson, 2021), assuming a total BECCS cost of 100 €/tCO_2 (i.e., the costs estimated in Johnsson et al., 2020).

It is likely that the cost of the first full-scale capture projects will be higher than that for an N^{th}-of-its-kind plant (the bases for the costs given above). The first full-scale capture should be applied to large point sources of emissions, which are mainly

TABLE 1 | The five Policy Models for incentivizing BECCS investigated in this work.

Policy model	Primary financer	Motivation	Governance challenges drawn from the stakeholder workshops and identified in the related analysis
1. State guarantees	Swedish state	Favorable conditions can be created for ramping up BECCS facilities in accordance with near-term targets (e.g., to Year 2030).	Expensive for the state. Several firms expressed a strong interest in selling the credits to buyers on the voluntary market, which may be in conflict with the intention of the state to claim the outcome. Thus, the ownership of credits should be clarified prior to procurements. Risk for biomass resource depletion if applied in isolation from other policies. BECCS needs to be part of a broader strategy for the bioeconomy. May be challenging to reach acceptance for BECCS when using this model Bellamy et al. (2019)
2. Quota obligation	Sectors that emit GHGs, for instance transportation, waste, and agriculture	Broadens the financing basis. Reduced costs for the state compared to Model 1, which translates into increased public acceptability. Increased incentives for reducing fossil fuel use in transports, for reducing combustion of plastics and for reducing GHG emissions in the agricultural sector.	As transport-related emissions and plastics in waste are reduced over time (or from increased plastic recycling), so are the revenues to finance BECCS. As emissions from the transport sector are expected to be reduced, so will the revenues from the transport-based quota system. Thus, in the longer term, a quota obligation should target sectors with residual emissions, such as those from waste, agriculture, and aviation. Could facilitate public acceptance for BECCS in line with the findings of Bellamy et al. (2019)
3. Allowing participants in the EU ETS to use BECCS credits	EU ETS participants	Broadens the financing basis. Could lead to a significant demand for BECCS. Eventually will bring down costs for participants in the EU ETS.	Would require a major reform or amendment of the EU ETS Directive, since credits are not currently allowed in the EU ETS.
4. Private entities for voluntary compensation	Private companies, e.g., travel agencies	Can contribute to the deployment of BECCS. Expands the demand-base of the policy to include non-territorial carbon emissions, such as from international aviation and foreign companies. Would exert less pressure on governmental policies.	Although voluntary markets can contribute to early deployment, the Swedish state cannot count on this. Thus, if the state wants to support the development of BECCS other financing models will be needed. Voluntary markets could come on top of this. Need to address the risk for double claiming. Unless sold credits are subtracted from national mitigation targets there is a risk that global emissions may increase.
5. Other states as buyers	Other states		To prevent double counting, corresponding adjustments from national commitments need to be made.

The table also provides a summary of our analysis, presented in more detail in the following sections.

biomass-fired CHP units and pulp and paper plants. For such applications, the technology is new, and an initial learning phase will be required. Moreover, competition between technology providers is likely to be low and there may be costs related to uncertainty and internal risk. In addition, early transport and storage projects may have higher specific costs (€/ton stored-CO_2) than the subsequent, more-established transport and storage infrastructures, which may be shared between different users. In the Swedish case, initially, storage will most likely be purchased from Norway, and it is not obvious what the price will be in the longer run if there is competition for using this storage (i.e., the price for buying storage is not the same as the cost for storage). At present, Equinor (2020) estimates that the cost for transport and storage will be in the range of 30–55 €/tCO_2 referring to the cost given in IOGP (2019).

Governance

A major advantage of Policy Model 1 is that, in an initial stage, favorable conditions can be created to promote the establishment of the first BECCS facilities, given that long-term contracts with an agreed price per ton CO_2-sequestered create predictability for BECCS producers. Another advantage is that the state can have some control over how large a volume of negative emissions is produced through BECCS and when and for how long the state wants to support such production. Through long-term agreements, the state can decide in advance the volumes that it wants to buy, e.g., 2 Mt of BECCS reductions per year. Such predictability is most likely a prerequisite for operators to invest in BECCS. Long-term agreements in which the government undertakes to buy a large volume of negative emissions from one or more suppliers through auctions have the possible advantage that the price can be pressed downwards. However, one challenge will be whether or not the seller can deliver.

For BECCS (as for CCS), the option to start very small is unrealistic if the technology is to become implemented at the commercial scale. Thus, the first projects at commercial scale will require a high up-front investment and result in a higher operating cost (i.e., the product from the plant will be more expensive, albeit with no or negative carbon emissions). It will also be a challenge to ramp-up the technology in line with the Year 2030 target set in the public inquiry of supplementary measures (Swedish Government, 2020) as pointed out by Fuss and Johnsson (2021). In Sweden, projects are underway on biochar (char from the pyrolysis or gasification of biomass, which will be used as a soil additive), as well as initial projects using biomass waste fractions that are available for free (such as public gardening residues). These may offer carbon-negative outcomes at a lower cost than BECCS, albeit the potential in terms of volumes is low. Thus, the auctioning system should be designed to not only target such low-cost and low potential alternatives, but also to support the implementation of BECCS systems that have adequate duration and predictability. This is in line with the preliminary assessment of how an auctioning system could be designed, as issued by the Swedish Energy Agency (2021a). That report states that biochar should not be part of the auctioning system.

For Sweden to procure 2 Mt of BECCS per year will require 4–5 plants to be equipped with CCS, assuming typical plants with a size large enough to obtain the abovementioned specific cost for BECCS (i.e., emitting some 0.4–0.5 $MtCO_2$/year). There are pulp and paper plants that each emit more than 1 million ton of CO_2 and, thus, applying BECCS on those would only require two plants to reach the proposed 2 Mt BECCS target. However, it seems unlikely that the first BECCS applications would be on these plants. A key challenge for the government will be to match auction volumes with both the technical potential for BECCS in Sweden and the willingness of prospective BECCS operators to engage with auctions (Fridahl and Lundberg, 2021).

An alternative to auctioning is for the state to buy BECCS outcomes "per verified stored ton" at a fixed tariff. The main difference between this and auctioning is that the state decides the price per ton but then has limited control over how many ton will be purchased. The system can be compared to a negative tax, in the sense that the BECCS producer is paid for each ton of separated and stored CO_2. A fixed storage tariff, whereby the state pays per "verified stored ton," has the advantage that the state pays on delivery for the benefit performed, albeit with the disadvantage that it is difficult for the state to set an appropriate price level. With a too-low price, no volumes may be produced at all. Such a model will obviously rely on a sufficiently high price for carbon removal and that the high price is offered for long enough to establish sufficient predictability.

A state guarantee policy model may not be the best long term option for reaching acceptance for BECCS since Bellamy et al. (2019) concluded that the public may favor coercive instruments over price guarantees for producers selling BECCS derived energy.

Model 2: Quota Obligation on Selected Sectors With GHG Emissions

One can argue that sectors or activities for which it is difficult to mitigate GHG emissions should contribute to financing negative emissions, e.g., BECCS, if they cannot mitigate their own fossil fuel emissions. The state could impose an obligation on such GHG emitters to purchase BECCS credits corresponding to a share of their GHG emissions. In theory, such an obligation can be implemented on a one-for-one basis, meaning that 1 ton of emitted GHG requires the purchase of 1 ton of BECCS. However, a quota system on a one-to-one basis may constitute a significant cost for the participant. A more commonly used method—typically applied for renewable energy—is to apply a quota obligation starting at a level of 10% and thereafter ramp it up at a certain pace. The system is similar to the Swedish-Norwegian electricity certificates, which require electricity retailers to purchase renewable electricity certificates corresponding to a share of the sold electricity (Swedish Energy Agency, 2021b). It is not obvious for which sectors and emitters a quota obligation system would be an efficient policy instrument. Since BECCS offers negative emissions, it seems reasonable to assume that such a system could be an option for "hard-to-abate" sectors such as transportation (road, aviation, and maritime), waste and agriculture. It is not clear how these sectors should be defined. Thus, it may be that quota obligations will have to be offered to all emitters, and unless emitters can reduce emissions themselves, they will be obliged to purchase BECCS quotas.

Potential Volumes and Financing

Transportation is presently the largest emitter of GHG emissions in Sweden, with around 16 $MtCO_2e$ in 2019 (Swedish EPA, 2021). If, for example, this sector was to purchase quotas corresponding to 10% of their emissions, this would create a demand of 1.6 Mt of BECCS credits today. This corresponds approximately to the BECCS target proposed by the Swedish Government (2020) for Year 2030. This would increase the cost of gasoline by 2.9 eurocents (0.029 €) and the cost of diesel by 2.6 eurocents (0.026 €) (Zetterberg et al., 2019). As fossil fuels are phased out in the transport sector, the demand for BECCS credits should decrease.

A quota obligation fits well with the transport sector's challenge in meeting the Year 2030 target for emissions reductions, which is set at 70% relative to Year 2010. Although there is ongoing electrification of road transport, with several car manufacturers stating that they will stop producing vehicles (passenger cars) with internal combustion engines (typically around Year 2030) and with sales of new electric vehicles increasing, the replacement of the current car fleet will take time, which makes the goal of a 70% reduction a challenge. At present, the yearly reduction in emissions from the transport sector (excluding international aviation) is around 2%, which needs to increase to around 8% to meet the Year 2030 target (Swedish

EPA, 2021). Heavy road transportation represents the greatest challenge, since for this sector electrification is not obvious, with hydrogen/fuel cell vehicles and electric road systems emerging as alternatives to battery vehicles, even if the development of these options is slow and their future seems uncertain at present with TRL levels estimated to 5–6 (Gnann et al., 2017). While decarbonizing road transport is technically feasible, the aviation and maritime transport sectors imply significant challenges for fuel shifting (Nordic Council of Ministers, 2016; Horvath et al., 2018; Gray et al., 2021). These sectors may need to offset their emissions before the appropriate technologies are sufficiently advanced to allow direct and deep emissions cuts. It should be mentioned here that (domestic) aviation is not included in the aforementioned 70% reduction target.

In the longer term, e.g., coming up to Year 2045 when Swedish GHG emissions should be net zero, it should be possible for the road transport sector to meet the zero-emissions target provided that the present rate of technological development continues for light vehicles and new technologies are introduced for heavy road transport (e.g., electrification, hydrogen fuel cells, electric road systems) and that the related CO_2 emissions are close to zero, which would entail a low demand for BECCS credits. Nonetheless, a quota system for negative emissions that includes the transportation sector may help establish the BECCS technology, which should be beneficial for Society.

Combustion of domestic waste and non-toxic industrial waste in Sweden produces approximately 400 kg fossil CO_2 per ton waste (Year 2017), totaling approximately 3.4 Mt fossil CO_2-emissions due to the plastic content in the waste (Zetterberg et al., 2019). If a quota obligation was to be imposed on 50% of the plastic-related emissions this would create a demand for 1.7 Mt of BECCS credits (Zetterberg et al., 2019). Assuming a total BECCS cost of 100 €/tCO_2, this would correspond to approximately 20 € per ton combusted waste (0.4 t · 50% · 100€/t), or 50 €/tCO_2 emitted, which is less than the price on EU allowances of 56 €/tCO_2 when writing this in June 2021 (European Energy Exchange, 2021). As with the transportation sector, it can be expected that the plastic content of waste will decrease over time, which means that the demand for credits will decrease. Swedish waste combustion facilities are, unlike those in most other EU Member States, included in the EU ETS and need to purchase emission allowances corresponding to the emissions generated by the combustion of plastics. Therefore, if a quota obligation is to be placed on emissions from plastics processed in combustion facilities, one could argue that these facilities should be excluded from the EU ETS.

It should, however, be mentioned that there is ongoing research on developing "plastic refineries" for recycling plastic, whereby pyrolysis or gasification processes are used to process plastic waste back to its original components in the form of olefins (Thunman et al., 2019). Such processes can also be equipped with CCS which, if powered by renewable energy and assuming a sufficiently high recirculation rate, would result in negative emissions.

Agriculture accounts for approximately 6.9 MtCO_2e in Sweden (Swedish EPA, 2021). The governmental inquiry SOU2020:4 (Swedish Government, 2020) concludes that it would be costly to reduce GHG emissions to close to zero in the agricultural sector, as this would require a comprehensive transformation of this sector, including the mitigation of methane and nitrous oxide emissions. Therefore, we can expect that the agricultural sector will have residual emissions in Year 2045, which would make it a natural target for financing BECCS, for instance through a quota obligation, at least in the long term.

A quota obligation model (Model 2) may be a more favorable policy model than Model 1 for reaching acceptance of BECCS since it will not directly involve taxpayer's money, which is in line with the conclusions by Bellamy et al. (2019).

Governance

A challenge associated with using the road transport sector to finance BECCS is that the emissions from this sector are expected to decrease significantly in the next 10 years (Swedish Government, 2017), which will reduce the financial base for BECCS. This decrease can be compensated by increasing the quota obligation gradually from 10 to 100%. As the aviation sector is also likely to have residual emissions during the entire period up to Year 2045, it could provide a financing base for BECCS, together with other sectors, such as agriculture.

As with the state guarantee, it will be a challenge to design a quota system that can deal with the fact that BECCS must be initiated on a relatively large scale (and not incrementally, as discussed above). Quota obligations can be powerful drivers for the upscaling of CDR, although they can generate significant costs for the affected entities. Lobbyists are, therefore, likely to attempt to block the introduction of such mandates; experience from other mitigation technologies is that, in general, only profitable technologies are subjected to mandates (Honegger et al., 2021).

Model 3: Allowing Participants in the EU ETS to Use BECCS Credits

With the current rules, the EU ETS cap will reach zero in Year 2058, meaning that the last emission allowance will be issued in Year 2058 (Elkerbout and Zetterberg, 2020). However, in 2019, the European Council decided that the EU's GHG emissions should reach net zero by year 2050 (with a 55% reduction target for Year 2030, as compared with the Year 1990 levels, European Council, 2019). This necessitates a strengthening of the EU ETS and brings forward the time schedule for issuing the last allowance, for instance to Year 2050 or earlier. This raises the question as to what will happen when the EU ETS cap approaches zero. As we get closer to the year with zero emissions, it is likely that there will be residual emissions, for which abatement will be expensive and/or technically difficult. In addition, the application of CCS to emissions from fossil fuels, foreseen to be applied to mitigate process emissions from industries (e.g., the cement industry), will not fully eliminate emissions due to the capture rates being below 100%. Aviation—which is partially included in the EU ETS—may likewise continue to emit GHGs well into the future. If so, an emissions trading system with a zero cap could still be possible if there exist credits that represent negative emissions and that can be used to compensate for the residual emissions in the ETS.

One problem is that, under current rules, imports of credits are not allowed in the EU ETS (European Commission, 2013). It is noteworthy that the EU ETS already allows for the use of fossil CCS to reduce fossil fuel-related emissions. This could be an opening for allowing BECCS to be implemented in the future.

Potential Volumes and Financing

In the document *A Clean Planet for all*, issued by the European Commission, there are scenarios in which BECCS is responsible for a significant share of the emissions reductions, in some scenarios as much as 180 Mt/year in the Year 2050 (European Commission, 2018).

From the Swedish perspective, it is difficult to predict what the demand for BECSS credits would be if such credits could be used in the EU ETS. The demand would depend on the cost structure in Sweden compared to other types of emission reductions within the EU ETS, as well as on the prospects of other incentives for negative emissions. As pointed out previously, Sweden has favorable conditions for BECCS, so if the demand/price is high enough it is conceivable that the entire Swedish potential will be utilized, i.e., the abovementioned 17–20 Mt of BECCS credits per year (Karlsson et al., 2017).

A major advantage of including BECCS in the EU ETS is that BECCS would be included in a broader carbon pricing regime. This would provide participants an additional option to comply and contribute to bringing down costs for the participants in the EU ETS. This may also create a significant demand for BECCS and providing opportunities for scaling up BECCS. However, it will take time before BECCS credits will become an attractive alternative to emissions reductions or the buying of EU ETS allowances. With a cost for BECCS of 100 € or more, an allowance price in parity with that cost will be needed for BECCS to become an alternative in its own right for the participants. Yet, such an allowance price is also required for fossil fuel emissions sources if we are to abate emissions, including the use of CCS.

Governance

Allowing the use of BECCS credits for the purpose of compliance in the EU ETS would require significant revisions to the EU ETS, as well as to the effort sharing regulation (ESR) and the land use, land use changes, and forestry (LULUCF) Directive (Rickels et al., 2021). An obvious challenge is that the emissions factor for biomass is zero (European Commission, 2003). Emissions and uptake of biogenic CO_2 are accounted for under the LULUCF regulation and are expressed as carbon stock changes. However, this contrasts with fossil CCS, as the EU ETS allows the use of CCS for reducing fossil emissions. This asymmetry could be an opportunity to integrate BECCS into the EU ETS.

Discussions on the inclusion of BECCS in the EU ETS would raise questions as to whether or not the use of BECCS credits should be restricted. While unrestricted use might confer a higher level of effectiveness (Rickels et al., 2021), there are concerns that firms will buy BECCS credits instead of reducing their (fossil) emissions. However, as mentioned above, with a cost for BECCS of 100 € or more, it will take an allowance price of 100 € or higher before BECCS becomes a viable alternative to reducing emissions.

An alternative way to include BECCS in the EU ETS would be to create a separate market for BECCS (and potentially also other CDR technologies). Demand could initially be created through procurement (analogous to Model 1) or different types of investment support, for instance through the EU Innovation Fund or through national programs. Once the system has been operational for some time, it could be partially linked to the EU ETS. The transfer of credits could, for instance, be restricted.

There is currently no roadmap for modification of the existing EU ETS with regards to the integration of CDR (Rickels et al., 2021). Looking to the future, if the EU ETS is to have a zero cap in Year 2050, this will require the use of some sort of credit system for offsets. Given the complexity of the issue, with long lead times for investments and several EU regulations that need to be adjusted, the inevitable debate should start as soon as possible.

If Sweden wants to pursue the development of a regulatory framework at the EU level that creates incentives for negative emissions from BECCS, as suggested in SOU2020:4 (Swedish Government, 2020), one way forward would be to cooperate with other Nordic countries that show similar ambition. This may well-turn out to be the case given the significant bioenergy resources (Sweden, Finland, Norway) and CO_2 storage capacities in the region, primarily in the North Sea (Anthonsen et al., 2013).

Model 4: Private Entities for Voluntary Compensation

Voluntary carbon markets started to emerge in the early 2000's in parallel with the development of the regulated carbon market under the Kyoto Protocol (Hermwille and Kreibich, 2016). Demand for offsets on the voluntary market is created by companies and individuals that wish to offset all or part of their carbon footprint without having legal requirements (Leonard, 2009; Hyams and Fawcett, 2013). The voluntary markets demand for offsets peaked around 2010 and thereafter the demand dwindled. Estimates based on surveys indicate that globally between 2005 and 2016, approximately 1 billion ton of CO_2 were offset on a voluntary basis (Hamrick and Gallant, 2017). In later years, interest in carbon offsets on the voluntary market has increased again as corporations adopt net-zero GHG targets that will require offsetting to meet their climate targets (Hamrick and Gallant, 2017). The transacted volume on the voluntary market in 2019 was larger than that in the earlier record year of 2010, mainly driven by corporate net-zero targets, and preliminary figures indicate that the volume in Year 2020 will reach even higher levels (Donofrio et al., 2020). Voluntary carbon markets could play a significant role in mobilizing the necessary private climate financing. In 2019, renewable energy and forestry represented the two major project categories for carbon offsets, with 42 and 36% market shares, respectively (by ton of CO_2 transacted) (Donofrio et al., 2020). Voluntary carbon markets already include CDR project activities (Honegger et al., 2021). Carbon dioxide removal types that have so far been adopted include, inter alia, forestation activities, biochar as soil amendment, enhanced soil carbon sequestration, wooden building elements, DAC technologies, and enhanced weathering (Poralla et al., 2021; PuroEarth, 2021). Once BECCS is implemented, BECCS credits could be included.

Potential Volumes and Financing

In estimating the potential demand for voluntary BECCS credits in Sweden, it is useful to look at Sweden's contribution to international aviation. Swedish air travel has a climate impact that corresponds to approximately 10 Mt CO_2-equivalents per year, including international traveling (Kamb and Larsson, 2018). If 10% of these trips were to be compensated by BECCS, this would correspond to a demand of about 1 Mt/year. This constitutes a significant demand, albeit one that is uncertain. The willingness to pay is also uncertain, especially if cheaper alternatives for carbon offsetting are available. Yet, other means of offsetting emissions (e.g., afforestation projects in other countries) are debated and have an unclear climate benefit. BECCS is less expensive than DAC with costs ranging from 250 to 600 USD (Lebling et al., 2021). Another potential disadvantage with applying BECCS as an offset measure is that it requires high levels of cooperation and trust between different sectors/companies. Direct air capture constitutes a stand-alone measure that could be managed by an independent party.

In the international setting, large companies such as Microsoft, Stripe, and Shopify have committed to becoming carbon-neutral and they have expressed intentions to purchase significant amounts of carbon credits, largely based on negative emissions (Honegger et al., 2021). Furthermore, some recent proposals regarding standards for corporate net-zero targets imply an emerging preference for the use of offsets based on negative emissions rather than offsets based on avoided emissions (e.g., Allen et al., 2020). If the companies that are seeking to offset their emissions were to develop an appetite for BECCS credits, this could create a significant demand for BECCS in Sweden and in other countries.

Governance

Selling BECCS outcomes internationally raises concerns regarding double counting and additionality (Honegger et al., 2021). If a company such as Microsoft (USA) purchases BECCS credits from a Swedish BECCS producer to be used to offset their corporate carbon footprint, there must be a system in place that ensures that the same negative emissions are not accounted for in both the producing country (Sweden) and in the country of the purchasing company (USA), since double claiming would undermine the integrity of the Paris Agreement (Schneider et al., 2014).

Voluntary carbon offset markets provide the opportunity to create a demand based on non-territorial carbon emissions, such as those from international aviation and foreign companies. A clear disadvantage of the voluntary nature of the demand is that the "demand signal" is uncertain (volume and price) and is in itself probably not strong enough to incentivize BECCS investments. Moreover, carbon offsetting is a net-zero game that does not lead to overall mitigation of global emissions unless it is exclusively applied by companies to offset residual emissions, in addition to the most-stringent mitigation schemes for their value chain emissions.

To date, the providers of CDR credits on the voluntary markets have applied very diverse approaches with regard to the methodologies used for calculating the removal of emissions, as well as with respect to monitoring, reporting and verification (Poralla et al., 2021). This situation might damage the long-term prospects of the international market for CDR credits. Regulatory oversight on the national level with regards to claims made on removal credits could improve this situation. Such an oversight system should focus on issues related to permanence and the quality of Monitoring, Reporting, and Verification (MRV). It should prevent the emergence of low-quality removal credit providers and the multiple claiming of the same activities' mitigation results (Honegger et al., 2021).

Model 5: Other States as Buyers

The Paris Agreement recognizes that some Parties choose to pursue voluntary cooperation with regards to the implementation of their National Determined Contribution (NDC), so as to allow for a higher level of ambition in relation to their mitigation and adaptation actions and to promote sustainable development and environmental integrity (United Nations Framework Convention on Climate Change (UNFCCC), 2015). International cooperation toward achieving NDCs falls under Article 6 of the Paris Agreement, which enables cooperation through market and non-market approaches. Article 6 lays out the requirements for transfers between Parties, including the rules for their robust accounting, thereby enabling carbon markets to service the Paris Agreement. Furthermore, "internationally transferred mitigation outcomes" (ITMOs) are defined, which can be produced through any mitigation approach provided that there is consistency with both the principles listed in Article 6.2 and the guidance provided by the Parties (Asian Development Bank, 2018).

The rules of Article 6 may, therefore, be relevant to a situation in which Country A funds carbon removals (capture and/or storage) in Sweden and Country A wants to claim (all or part of) the associated removal toward its target. In order to avoid double counting, Article 6 requires that a "corresponding adjustment" be made, which means that when Parties transfer a mitigation outcome internationally to be counted toward another Party's mitigation pledge, this mitigation outcome must be "un-counted" by the Party that agreed to its transfer (Asian Development Bank, 2018). The detailed rules for Article 6 have not yet been agreed by the Parties to the Paris Agreement. While Parties have made progress in the various negotiation rounds, several crucial issues remain to be resolved, including the notion of "corresponding adjustments."

Potential Volumes and Financing

Since net-zero emissions need to be reached on a global level eventually and the potential for negative emissions (that can offset residual emissions) is unevenly distributed, other nations may wish to purchase Swedish negative emissions from BECCS in the long term. It is, however, currently difficult to estimate the magnitude of such demand. The prices achieved in such a market might for a long time remain insufficient as stand-alone incentives for BECCS (Honegger and Reiner, 2018).

Governance

Within the Paris Rulebook, CDR needs to be considered systematically alongside emission reduction measures. In the Article 6 work program, methodological issues related to baseline setting, additionality, and MRV need to be prioritized. In the negotiations on the operationalization of the Enhanced Transparency Framework (United Nations Framework Convention on Climate Change (UNFCCC), 2015), accounting rules for removals need to be sufficiently specified (Poralla et al., 2021).

Regarding the Paris Agreement Article 6 market mechanisms, Article 6.2 may serve as an entry point for bilateral or plurilateral piloting activities that would allow for pre-testing elements of the market instruments (Möllersten et al., 2021; Poralla et al., 2021) thereby providing a proof of concept of such international cooperation on CDR.

Accounting and Monitoring, Reporting, and Verification

Monitoring, Reporting, and Verification along the BECCS value chain is necessary to quantify the mitigation outcome. The geologic storage of CO_2 requires special attention in this respect. Requirements or guidelines for monitoring are a key component of governmental regulations for CO_2 sequestration projects (e.g., the EU CCS directive). Numerous pilot tests and commercial operations have demonstrated the value of a wide range of monitoring techniques (Bui et al., 2018).

Several GHG MRV and accounting protocols and guidelines currently exist for CCS activities, and various activities are ongoing in this area. Such guidelines exist at the project, entity, state, country, and international levels, and work is ongoing to develop common accounting approaches (IEAGHG, 2016).

Any scheme that provides for the issuance of BECCS credits that can be traded needs to ensure that the verified negative emissions are additional and that double counting is avoided. A baseline needs to be established, against which the emissions reduction outcome is measured.

Swedish Preferences for BECCS Policies

One of the main obstacles to BECCS implementation is the lack of incentives for mitigating biogenic CO_2 emissions. The existence of this barrier has been confirmed by Swedish industry and government representatives (Bellamy et al., 2021). Regarding state support, some government officials have expressed the opinion that initiatives should be technology-neutral and that options other than BECCS, for instance large-scale afforestation and biochar, should be considered (Bellamy et al., 2021). Regarding EU-level policies, several business representatives have opined that EUA price volatility makes investments uncertain and that EU ETS reforms will take too long. As an alternative, they suggest innovation support, for instance through the EU Innovation Fund, as a better source of financing. It should be noted that in March 2019—the time of the study conducted by Bellamy and colleagues—the EUA price had recently increased from 5 € to 20–25 € per tCO_2 (and which had at the time of writing in May 2021, further increased to more than € 50 per tCO_2, although this is—as pointed out previously—still lower than the cost for BECCS).

A more recent study on preferences, performed in late-2020 and early-2021 (Fridahl and Lundberg, 2021), reveals strong interest in BECCS among Swedish business and government representatives. Several Swedish companies have already, or are currently, performing preliminary studies and/or have applied to the EU Innovation Fund for financing for BECCS. Given the choice between a tariff-based system and a reversed auction system, the majority of the actors prefer reversed auctions (Fridahl and Lundberg, 2021).

A disadvantage of state-funded acquisitions is that the system is expensive for the state and for taxpayers. As mentioned above, the auctioning system proposed in SOU2020:4 (Swedish Government, 2020) aims to reach 1.8 $MtCO_2$ per year in Year 2030 (a maximum of 2 Mt), after which it will be evaluated. An estimated cost of 180 million € per year to the state exchequer is unlikely to be sustainable in the long run. Studies have indicated that the level of public acceptance of state-funded procurement could be low (Bellamy et al., 2019).

Indeed, Fridahl and Lundberg (2021) conclude that virtually all the actors took the view that such a system would falter in the longer term. An ambition to maintain a state-led support scheme to scale up BECCS was deemed unlikely to attract sufficient political or public support, since the cost would likely be seen as prohibitive.

Regarding the preferences expressed by Swedish businesses and governmental agencies, Fridahl and Lundberg (2021) found that in the longer term, almost all the actors were in agreement that an incentive for BECCS should ideally be generated at the EU level. In this context, the EU ETS is presented as one option, even if this would require substantial amendments to existing legal provisions.

According to Stockholm Exergi (the municipal energy company of Stockholm), they already have customers that are interested in buying negative emissions quotas (Levihn, Pers. Commun.). Other firms state that they are not likely to invest while the prospects for selling to the private entities remain uncertain, unless they can engage in direct long-term contracts with large buyers. Several prospective BECCS operators in Sweden have expressed strong interest in selling the carbon removal credits to voluntary markets, even if they have received state support through auctions or other avenues (Fridahl and Lundberg, 2021). This may conflict with the intentions of the Swedish state.

ACTIONABLE RECOMENDATIONS

Based on our analysis of the five selected Policy Models, it is possible to make some recommendations to policymakers. However, more work needs to be carried out and these recommendations should be regarded as a starting point for work on developing robust policy packages with the aim of avoiding negative side-effects.

Sweden requires a BECCS policy that is predictable and sustainable over time (Fridahl and Lundberg, 2021).

Uncertainties regarding the level of support, size, and duration of BECCS may deter prospective operators from engaging in the further development of BECCS. At the same time, it is important that the BECCS policy is part of an integrated climate policy framework, and in particular that it is in line with policies for the mitigation of fossil-fuel based emissions and the evolution toward a circular economy. This is necessary to avoid the over-exploitation of BECCS and associated biomass resources (see Section Challenges of Incentivizing BECCS). A well-designed policy package should ensure that BECCS is not just a way to postpone reducing fossil fuel-based emissions (Anderson and Peters, 2016) and that is not used for "greenwashing."

With Model 1, whereby the Swedish state buys BECCS outcomes through long-term agreements with BECCS producers, favorable conditions can be created for the realization of several full-scale BECCS facilities. These are required to meet the target proposed in the SOU2020:4 inquiry, i.e., 1.8 Mt/year of BECCS by Year 2030. Yet, it seems important that the Government of Sweden decides on the purpose of the procurement/support. Is it to establish a new market with several operators that can grow over time or is it designed to purchase removal credits at the lowest price?

To reach the proposed level of 1.8 $MtCO_2$ per year in Year 2030, a BECCS policy needs to be introduced immediately, considering the lead times required to establish BECCS on a sufficient scale. Reaching 1.8 Mt $MtCO_2$ per year will require 4–5 plants, depending on type of plant used and if full or partial capture. As a low number of plants and operators may fulfill the full demand, this may cause challenges for establishing a competitive market, and the government will need to design carefully the auctions regarding the timing and size of auctioned lots, in order to engage prospective BECCS operators.

Several prospective BECCS operators in Sweden have expressed strong interest in selling carbon removal credits, either to private entities for voluntary compensation or to the EU ETS (Fridahl and Lundberg, 2021). If the intention of the proposed state-supported system is to purchase negative emissions and use them to meet the Swedish climate mitigation target, this needs to be specified and the risks related to the potential double claiming of mitigation outcomes need to be addressed.

State-supported BECCS could be instrumental in implementing the first BECCS operations in Sweden, although the basis for financing such an endeavor needs to be broadened so as to ramp up BECCS over time and reduce the cost to Swedish taxpayers.

It remains to be seen how a sufficiently strong policy for ramping up BECCS can be combined with other financing models and policies that develop over time. Model 2, which involves the imposition of a quota obligation, has the advantage that the costs for financing BECCS are placed on GHG emitters, thereby creating incentives for emitters to reduce emissions, as well as providing financing for BECCS. A possible challenge linked to imposing a quota obligation on the road transport sector is that emissions are likely go down over time, thereby reducing the financial basis for BECCS. In the longer term, this can be mitigated by directing the quota obligation toward sectors that are expected to have residual emissions, i.e., the agricultural, waste, and aviation sectors. It seems unlikely that potential producers will invest in BECCS without first receiving guarantees from the state. Model 2 may, therefore, be realistic in the medium-to-long term. However, the government may well-introduce a quota obligation earlier to raise revenues for financing BECCS through Model 1.

The feasibility of Model 3, which entails linking with the EU ETS, depends on whether imports of credits to the EU ETS will be allowed. If so, this would be part of a broad carbon pricing regime that would provide cost-effectiveness for ETS participants and create a considerable demand for BECCS in the long term.

If Sweden intends to pursue the development of a regulatory framework at the EU level that creates incentives for negative emissions from BECCS (as suggested by the inquiry regarding negative GHG emissions Swedish Government, 2020), one way forward would be to cooperate with other Nordic countries that show similar ambition. This may well-turn out to be the case given their significant bioenergy resources (Sweden, Finland, Norway) and storage capacities (Norway).

In case the EU ETS strategy proves unfeasible, Sweden should also investigate alternative policies at the EU level that can create markets for BECCS. Another reason for doing this is that in the long term, residual emissions are likely to come from sectors that are not included in the EU ETS (waste and agriculture).

Regarding Model 4, which involves private entities purchasing BECCS credits to compensate voluntarily for emissions, voluntary buyers (corporations) may create a significant demand for BECCS outcomes in the short and medium terms, and possibly also in the long term. However, the market is uncertain regarding both volumes and price. In any case, the development of the willingness of companies to include BECCS as a voluntary measure (Model 4) to reduce their emissions along their value chains should be closely monitored by government, since such measures would ease the pressure on governmental policies and reduce the cost to taxpayers.

Model 5, in which other states act as buyers of BECCS credits, may become an option. However, the use of credits from CDR that are to be applied toward national mitigation targets of NDCs cannot take place unless Article 6 of the Paris Agreement becomes operational. Governments that wish to take part in international transfers of negative emission credits should, therefore, promote the establishment of adequate modalities and procedures for MRV and accounting of CDR in the Paris Rulebook.

Policy Sequencing

The five different Policy Models discussed in this work differ with respect to the degree of certainty that they will create a specific level of demand for BECCS and, thus, the volumes that can be expected. It is likely that a policy sequencing approach will be required for successful implementation of BECCS. From a Swedish regulator's point of view, a logical sequence for the policies would be to start with the state buying BECCS outcomes in auctions as soon as possible (Model 1), followed by a phase-in of quota obligations to increase volumes and broaden the basis for funding (Model 2). If the EU ETS will allow participants to use BECCS credits to compensate for hard-to-abate emissions, this could create a significant demand for Swedish BECCS outcomes in the long term (Model 3). In addition, private entities (Model 4) may purchase BECCS credits to compensate voluntarily for emissions. With Model 5, other states may buy BECCS outcomes to meet their mitigation targets under the Paris Agreement or to increase their own ambition regarding emissions. Yet, Models 3, 4, and 5 are highly uncertain regarding their timing and expected volumes. This creates a challenge in that unless these models are ramped up, it will be difficult to phase out Model 1 and, thus, the state may have to assume a long-term commitment to support BECCS. Not all models may be required for successful implementation of BECCS. Model 1 will not be (economically) sustainable in the long run, but mainly fitted for establishing BECCS. It should be important that a strategy on a sequencing of different policy models is developed at an early stage so that markets actors will now what will happen once Model 1 will be phased out.

Figure 1 presents a schematic illustration on the timing of the five Policy Models. The volume levels are indicated only in relation to each other, with the aim of showing the approximate levels proposed in SOU2020:4 (Model 1), the long-term potential (17–20 Mt/year), and the proposed ambition (3–10 Mt/year in SOU2020:4). Although a sequential policy approach appears to be necessary, it is not obvious how it should be established, given that the capacities to act for the different Policy Models presented in this work lie with different organizations (national government, EU, private firms).

There are several possible interactions between the five models that can potentially strengthen or weaken their implementation. For instance, if the state would support the establishment of the first BECCS operators, this would facilitate for voluntary markets to procure credits and would help establishing a market price for BECCS. However, international buyers of credits could also become competitors to the Swedish state in the sense that they may procure large quantities of credits, some of which Sweden needs to fulfill its climate objectives. The establishment of a system of government procurement (Model 1) would contribute to developing a CDR certification mechanism for use in the EU and beyond, thus supporting models 3, 4, and 5. Yet, more work is required to understand likely interactions between policy models.

DISCUSSION

Implications of Swedish BECCS in a Broader Context

This paper addresses Policy Models aimed at incentivizing BECCS in Sweden. In addition to enabling ambitious national targets through BECCS deployment, Sweden can make contributions to a faster and environmentally more-credible advancement of BECCS (and potentially other CDR technologies) outside of Sweden, through pioneering BECCS incentivization. This will provide valuable guidance on how to develop effective instruments for the development of BECCS in jurisdictions other than Sweden, for instance in the EU. This in turn will enable the EU to deploy and ramp up BECCS on a larger scale. Stakeholder acceptance from early Swedish projects will also provide valuable experience for the international context.

If Sweden acts as an early mover in the implementation of BECCS, its practical experiences can make important contributions to the European Commission's efforts to develop a CDR certification mechanism. It could, furthermore, inform as to the lessons learned, which could be useful for the establishment of a proper MRV system if and when BECCS credits can be used in the EU ETS.

The lessons learned while establishing an MRV and accounting frameworks for BECCS could also make valuable contributions beyond the EU, for example toward the development of robust MRV approaches for the creation of CDR credits for voluntary carbon markets, and to ensure that accounting in the context of the Paris Agreement's Enhanced Transparency Framework is sufficiently robust to address the challenges of CDR (Poralla et al., 2021).

If Sweden pursues Policy Models that involve engagement with private actors that acquire BECCS credits for voluntary emissions compensation it could be shown how compensation can build upon high-quality emissions removal credits. This would include the establishment of conservative baselines and quantification of mitigation results, appropriate consideration of permanence, robust MRV, and the avoidance of multiple claims regarding the same activities' mitigation results.

Potentially Adverse Effects and Need for a Policy Package Assessment

Assuming that the Swedish state, another state or private firms are prepared to pay the full cost for BECCS, estimated to be at least 100€/ton, this may trigger some unwanted effects. It is likely that in a world—including Sweden—that moves in line with the Paris Agreement, the value, and thereby the price of biomass will increase. Thus, there will most likely be increased competition for biomass between sectors. A policy that incentivizes BECCS is likely to further increase the competition for biomass. Since an incentive for BECCS must be applied at probably at least 100€/tCO_2 over a considerable period of time (say up to Year 2030), it is important that policymakers evaluate how any BECCS policy that includes such an incentive will influence the usage of other biomass types from the cost and resource efficiency perspectives. If this is not done, the BECCS policy could result in reduced biomass availability for other purposes, such as long-lived biomass products and increased forest cutting. It seems most likely that it will not be sustainable to use higher-quality and more expensive forest products, such as sawed timber, for BECCS.

An additional potential side-effect is that some actors (forest owners) may argue that if the state or a company pays for BECCS, such an incentive should, for cost-efficiency reasons, also include other policy measures that remove carbon from the atmosphere, i.e., there should be a CDR policy rather than a BECCS policy. This could, for instance, be large-scale production of biochar (charring biomass and burying it). The forest industry may also claim that the net carbon uptake by the forests should also be

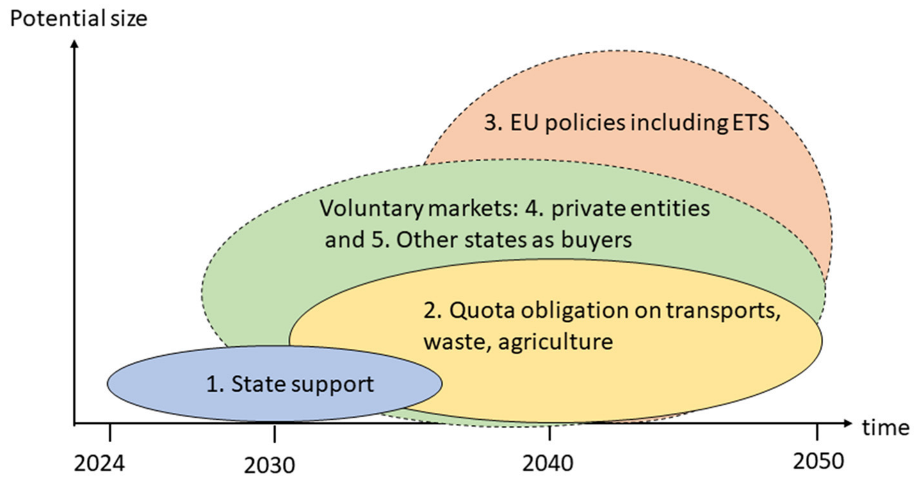

FIGURE 1 | Schematic illustration of the timing and potential volumes of the five Policy Models. The dotted lines correspond to markets that are not under the control of the Swedish state. As for the State support model (Model 1), there is a target of 1.8 Mt BECCS in Year 2030 (SOU2020:4 proposes to evaluate Model 1 in Year 2030, with no proposal as to what will happen after Year 2030); for Model 2, we assume that in the transport sector, from Year 2030 a quota obligation (for example, 10%) is imposed on fossil fuel use. The quota obligation increases steadily to reach 100% in Year 2045, to compensate for reduced emissions. In the waste and agricultural sectors, we assume that a quota obligation is also introduced, possibly later than that for the transport sector; and in Model 3, we assume that BECCS credits can be used in the EU emissions trading system from Year 2035 and onwards, although the demand for Swedish BECCS is uncertain. While voluntary markets (Model 4) and state buyers (Model 5) could create significant demand, this is difficult to assess in terms of volumes and timing.

subject to economic compensation. As part of routine forest management, thinning is performed two or three times during the forest life cycle to improve growth and provide feedstock for pulp and paper production. Typically, 25–30-year-old trees are cut down for these purposes (Swedish Forest Agency, 2008). If state or private companies would pay forest owners for producing biochar, they might use pulp wood for this purpose, which might result in a shortage of pulp wood, increased prices for paper and board, and reduced export revenues for Sweden. This calls for a policy package analysis that considers the expected values for different biomass products and feedstocks from the resource and cost-efficiency perspectives. This should also be important for gaining public acceptance for BECCS. Assigning a high price, in the vicinity of 100 € per ton, to stored biogenic carbon might release a powerful financial impetus to trigger actions that we cannot fully predict at the present time. Society needs to be cautious not to be caught up in a *Tyranny* of *Small Steps* behavior, where each incremental step is logical but where the eventual result is not what was intended in the first place. Thus, it should also be important that a BECCS policy be integrated with an overall policy for biomass, to avoid unwanted side-effects.

There should be a balance between the cost of emitting fossil carbon and the reward for providing negative emissions (Fuss and Johnsson, 2021). Thus, it is reasonable to propose that the incentive for implementing capture of fossil fuel emissions should be as strong as that for installing BECCS. Accordingly, in a situation for which a governmental policy for negative emissions is sufficiently strong to trigger negative emissions, say around 100 €/tCO_2, it would be problematic if the penalty (e.g., in the form of EU ETS) for emitting fossil CO_2 was considerably less-severe. This would result in an inefficient climate policy. Yet, a country such as Sweden with favorable conditions for BECCS may choose to incentivize the implementation and commercialization of BECCS over CCS in an initial phase, if it is regarded as contributing to technological developments of importance for the country and for the attainment of ambitious global climate targets.

Minx et al. (2018) have noted that a growing trend in the literature is drawing attention to the importance of understanding the difference between the technical potentials for CDR and their practical feasibility. Lenzi et al. (2018) have argued that uncertainties surrounding the potential side-effects of CDR at vast scales raises the question as to whether lower temperatures are obviously ethically preferable ("Keeping within 1.5°C could cause side-effects that are as bad as those in a world that is 2°C warmer," p. 304). They suggest that ethicists and social scientists should be more deeply involved in the elaboration of mitigation scenarios, in order to broaden the range of considerations included. On the other hand, it can be argued that a 2°C warming scenario will most likely require CDR to compensate for residual emissions in hard-to-abate sectors, as well as to compensate for an overshoot in emissions. Thus, the topic of the present paper—to discuss how negative emissions and BECCS in particular can be incentivized—should be of high importance, although there is an obvious need for further assessments of CDR and BECCS policies and how these can be part of a complete climate policy package.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

The original work on incentives and financing was led by LZ in collaboration with KM. In preparation of this paper, FJ added sections on BECCS technologies and potentially adverse effects of BECCS policies and provided new insights to previous work. The manuscript has been discussed and improved by all authors, including writing, reviewing, adding references, and in other ways improving the paper.

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REFERENCES

Allen, M., Axelsson, K., Caldecott, B., Hale, T., Hepburn, C., Hickey, C., et al. (2020). *The Oxford Principles for Net Zero Aligned Carbon Offsetting*. Smith School of Enterprise and the Environment, Oxford University.

Anderson, K., and Peters, G. (2016). The trouble with negative emissions. *Science* 354, 182–183. doi: 10.1126/science.aah4567

Anthonsen, K. L., Aagaard, P., Bergmo, P. E. S., Erlström, M., Fareide, J. I., Gislason, S. R., et al. (2013), CO_2 storage potential in the Nordic region. *Energy Proc.* 37, 5080–5092. doi: 10.1016/j.egypro.2013.06.421

Asian Development Bank (2018). *Article 6 of the Paris Agreement*. Manila: Asian Development Bank. doi: 10.22617/TIM189647-2

Bednar, J., Obersteiner, M., and Wagner, F. (2019). On the financial viability of negative emissions. *Nat. Commun.* 10:1783. doi: 10.1038/s41467-019-09782-x

Bellamy, R., Fridahl, M., Lezaun, J., Palmer, J., Rodriguez, E., Lefvert, A., et al. (2021). Incentivising bioenergy with carbon capture and storage (BECCS) responsibly: comparing stakeholder policy preferences in the United Kingdom and Sweden. *Environ. Sci. Policy* 16, 47–55. doi: 10.1016/j.envsci.2020.09.022

Bellamy, R., and Geden, O. (2019). Govern CO_2 removal from the ground up. *Nat. Geosci.* 12, 874–876. doi: 10.1038/s41561-019-0475-7

Bellamy, R., Lezaun, J., and Palmer, J. (2019). Perceptions of bioenergy with carbon capture and storage in different policy scenarios. *Nat. Commun.* (2019) 10:743. doi: 10.1038/s41467-019-08592-5

Bui, M., Adjiman, C., Bardow, A., Anthony, E., Boston, A., Brown, S., et al. (2018). Carbon capture and storage (CCS): the way forward. *Energy Environ. Sci.* 11, 1062–1176. doi: 10.1039/C7EE02342A

Cox, E., Spence, E., and Pidgeon, N. (2020) Public perceptions of carbon dioxide removal in the United, States and the United Kingdom. *Nat. Clim. Change* 10, 744–749. doi: 10.1038/s41558-020-0823-z

Donofrio, S., Maguire, P., Zwick, S., and Merry, W. (2020). *Voluntary Carbon and the Post-Pandemic Recovery*. Washington DC: Ecosystem Marketplace.

Elkerbout, M., and Zetterberg, L. (2020). *EU ETS - Reform Needs in the Light of National Policies*. book for European Liberal Forum. Available online at: fores.se. (accessed August 9, 2021).

Equinor (2020). Northern Lights - A European CO_2 *Transport* and *Storage Network*. presentation by Per Sandberg.

European Commission (2003). *Directive 2003/87/EC of the European Union and of the Council of 13 October 2009 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading Within the Community and Amending Council Directive 96/61/EC*.

European Commission (2013). Decision No 529/2013/EU of the European Parliament and of the Council of 21 May 2013 on *Accounting Rules* on *Greenhouse Gas Emissions* and *Removals Resulting From Activities Relating* to *Land Use, Land-Use Change and Forestry and on Information Concerning Actions Relating to Those Activities.*

European Commission (2018). *In-Depth Analysis* in *Support* of the *Commission Communication* COM (2018) 773 - A Clean Planet for *All. A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy.*

European Council (2019). *EUCO 29/19 Note from General Secretariat of the Council to Delegations on European Council Meeting 12 December 2019 - Conclusions.*

European Energy Exchange (2021). *Spot price on EUA:s*. Available online at: https://www.eex.com/en/market-data/environmental-markets/spot-market (accessed June 28, 2021).

Forster, J., Vaughan, N. E., Gough, C., Lorenzoni, I., and Chilvers, J. (2020). Mapping feasibilities of greenhouse gas removal: key issues, gaps and opening up assessments. *Glob. Environ. Chang.* 63:102073. doi: 10.1016/j.gloenvcha.2020.102073

Fridahl, M. (2017). Socio-political prioritization of bioenergy with carbon capture and storage. *Energy Policy* 104, 89–99. doi: 10.1016/j.enpol.2017.01.050

Fridahl, M., Bellamy, R., Hansson, A., and Haikola, S. (2020). Mapping multi-level policy incentives for bioenergy with carbon capture and storage in Sweden. *Front. Clim.* 2:604787. doi: 10.3389/fclim.2020.604787

Fridahl, M., and Lundberg, L. (2021). Actor Preferences in the *Design* of a *Support Scheme* for *Bioenergy* with *Carbon Capture* and *Storage* (BECCS). *(Aktörspreferenser i Design av ett Stödsystem för bio-CCS).* In Swedish.

Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W., and Clarens, A. F. (2019). From zero to hero?: why integrated assessment modeling of negative emissions technologies is hard and how we can do better. *Front. Clim.* 1:11. doi: 10.3389/fclim.2019.00011

Fuss, S., and Johnsson, F. (2021). The BECCS implementation gap-a Swedish case study. *Front. Energy Res.* 8:553400. doi: 10.3389/fenrg.2020.553400

Gambhir, A., Butnar, I., Li, P. H., Smith, P., and Strachan, N. (2019). A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCs. *Energies* 12, 1–21. doi: 10.3390/en12091747

Geden, O., and Schenuit, F. (2020). *Unconventional Mitigation - CDR as a New Approach in EU Climate Policy*. Berlin: German institute for International and Security Affairs.

Global CCS Institute (2020). *Global Status of CCS 2020, the Global CCS Institute*. available online at: https://www.globalccsinstitute.com/ (accessed August 9, 2021).

Gnann, T., Plötz, P., Wietschel, M., and Kühn, A. (2017). "What is the best alternative drive train for heavy road transport?," *EVS 2017 - 30th International Electric Vehicle Symposium and Exhibition* (Stuttgart).

Gough, C., and Mander, S. (2019). Beyond social acceptability: applying lessons from CCS social science to support deployment of BECCS. *Curr. Sustain. Energy Reports* 6, 116–123. doi: 10.1007/s40518-019-00137-0

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., and Murphy, J. D. (2021). Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Adv. Appl. Energy* 1:100008. doi: 10.1016/j.adapen.2021.100008

Hamrick, K., and Gallant, M. (2017). *Unlocking Potential - State of the Voluntary Carbon Markets 2017*. Washington, DC: Forest Trends' Ecosystem Marketplace. Available online at: https://www.cbd.int/financial/2017docs/carbonmarket2017.pdf (accessed May 22, 2019).

Hermwille, L. and Kreibich, N. (2016). *Identity Crisis? - Voluntary Carbon Crediting and the Paris Agreement. Report No. 02/2016*. Wupperthal: Wupperthal Institute for Climate, Environment and Energy.

Honegger, M., Poralla, M., Michaelowa, A., and Ahonen, H. (2021). Who is paying for carbon dioxide removal? Designing policy instruments for mobilizing negative emissions technologies. *Front. Clim.* 3:672996. doi: 10.3389/fclim.2021.672996

Honegger, M., and Reiner, D. (2018). The political economy of negative emissions technologies: consequences for international policy design. *Clim. Policy*. 18, 306–321. doi: 10.1080/14693062.2017.1413322

Horvath, S., Fasihi, M., and Breer, C. (2018). Techno-economic analysis of a decarbonized shipping sector: technology suggestions for a fleet in 2030 and 2040. *Energy Convers. Manag.* 164, 230–241. doi: 10.1016/j.enconman.2018.02.098

Hyams, K., and Fawcett, T. (2013). The ethics of carbon offsetting. *WIREs Clim. Change* 4, 91–98. doi: 10.1002/wcc.207

IEAGHG (2016). *Review of GHG Accounting Rules for CCS. 2016/TR3.*

Intergovernmental Panel on Climate Change (IPCC). (2018). *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

IOGP (2019). "The potential for CCS and CCU in Europe," *Report to the Thirty-Second Meeting of the European Gas Regulatory Forum 5–6 June, 2019* (Madraid: International Association of Oil and Gas Producers).

Johnsson, F., Normann, F., Svensson, E. (2020). Marginal abatement cost curve of industrial CO_2 capture and storage - a swedish case study. *Front. Energy Res.* 8:175. doi: 10.3389/fenrg.2020.00175

Kamb, A., and Larsson, J. (2018). *Klimatpåverkan Från Svenska Befolkningens Flygresor 1990-2017*. Chalmers Tekniska Högskola, Avdelningen för Fysisk Resursteori.

Karlsson, H., Delahaye, T., Johnsson, F., Kjärstad, J., and Rootzén, J. (2017). Immediate deployment opportunities for negative emissions with Bio-CCS: a Swedish case study. *arXiv Preprint.* arXiv:1705.07894.

Keith, D. W., and Rhodes, J. S. (2002). Bury, burn or both: a two-for-one deal on biomass carbon and energy - Reply. *Clim. Change*. 54, 375–377. doi: 10.1023/A:1016187420442

Laude, A. (2020). Bioenergy with carbon capture and storage: are short-term issues set aside? *Mitig. Adapt. Strateg. Glob. Chang.* 25, 185–203. doi: 10.1007/s11027-019-09856-7

Lebling, K., McQueen, N., Pisciotta, M., and Wilcox, J. (2021). *Direct Air Capture: Resource Considerations and Costs for Removal*. World Resources Institute.

Lenzi, D., Lamb, W., and Hilaire, J. (2018). Weigh the ethics of plans to mop up carbon dioxide. *Nature* 561, 303–305. doi: 10.1038/d41586-018-06695-5

Leonard, K. (2009). *Quality Enhancement in Voluntary Carbon Markets: Opening up for Mainstream*. Hamburg: Diploma Verlag.

McLaren, D., Tyfield, D., Willis, R., Szerszynski, B., and Markusson, N. (2019). Beyond "Net-Zero": a case for separate targets for emissions reduction and negative emissions. *Fron. Clim.* 1:4. doi: 10.3389/fclim.2019.00004

Minx, J., Lamb, W., Callaghan, M., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions part 1: - research landscape and synthesis. *Env. Res. Lett.* 13:063001. doi: 10.1088/1748-9326/aabf9b

Möllersten, K., and Yan, J. (2001). Economic evaluation of biomass-based energy systems with CO_2 capture and sequestration in kraft pulp mills - the influence of the price of CO_2 emission quota. *World Resour. Rev.* 13, 509–525. Available online at: https://www.researchgate.net/publication/270893240_Economic_evaluation_of_biomass-based_energy_systems_with_CO2_capture_and_sequestration_in_kraft_pulp_mills_-_The_influence_of_the_price_of_CO2_emission_quota (accessed August 9, 2021).

Möllersten, K., Yan, J., and Moreira, J. R. (2003). Potential market niches for biomass energy with CO_2 capture and storage - opportunities for energy supply with negative CO_2 emissions. *Biomass Bioenerg.* 25, 273–285. doi: 10.1016/S0961-9534(03)00013-8

Möllersten, K., Zetterberg, L., Torvanger, A., Siikavirta, H., and Kujanpää, L. (2021). *Policies for the Promotion of BECCS in the Nordic Countries*. Nordic Council of Ministers.

Nordic Council of Ministers (2016). *Sustainable Jet Fuel for Aviation - Nordic Perspectives on the Use of Advanced Sustainable Jet Fuel for Aviation.* Report TemaNord 2016:538. Available online at: https://www.nordicenergy.org

Obersteiner, M., Azar, C., Kauppi, P., Möllersten, K., Moreira, J., Nilsson, S., et al. (2001). Managing climate risk. *Science* 294, 786–787. doi: 10.1126/science.294.5543.786b

Obersteiner, M., Bednar, J., Wagner, F., Gasser, T., Ciais, P., Forsell, N., et al. (2018). How to spend a dwindling greenhouse gas budget. *Nat. Clim. Chang.* 8, 2–12. doi: 10.1038/s41558-017-0045-1

Organisation for Economic Co-operation and Development (OECD) (2021). *Recommendation of the Council on Guiding Principles concerning International Economic Aspects of Environmental Policies*, OECD/LEGAL/0102.

Poralla, M., Honegger, M., Ahonen, H., and Michaelowa, A. (2021). *Sewage Treatment for the Skies: Mobilising Carbon Dioxide Removal Through Public Policies and Private Financing.* Freiburg: Perspectives Climate Research.

PuroEarth (2021). *Carbon Removal Methods*. Available online at: https://puro.earth/services/ (accessed June 28, 2021).

Rickels, W., Proel,β, A., Geden, O., Burhenne, J., and Fridahl, M. (2021). Integrating carbon dioxide removal into european emissions trading. *Front. Clim.* 3:690023. doi: 10.3389/fclim.2021.690023

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., et al. (2018). "Mitigation pathways compatible with 1.5°C in the context of sustainable development," In: *Global warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

Schneider, L., Kollmuss, A., and Lazarus, M. (2014). *Addressing the Risk of Double Counting Emission Reductions Under the UNFCCC*. Stockholm Environment Institute. doi: 10.1007/s10584-015-1398-y

Swedish Energy Agency (2021a). *Förslag på Utformning av ett System för Driftstöd, i Form av Omvänd Auktionering eller Fast Lagringspeng, för Avskiljning, Infångning och Lagring av Koldioxid Från Förnybara Källor (bio-CCS), dnr-2020-23877, April 15, 2021* (in Swedish).

Swedish Energy Agency (2021b). *The Electricity Certificate System*. Available online at: www.energimyndigheten.se/en/sustainability/the-electricity-certificate-system/ (accessed June 24, 2021).

Swedish EPA (2021). *Sweden's Territorial Emissions and Uptake of Greenhouse Gases*. Available online at: http://www.naturvardsverket.se/klimatutslapp (accessed March 19, 2021).

Swedish Forest Agency (2008). *Skogliga Konsekvensanalyser 2008 - SKA-VB 08*. Skogsstyrelsen Report 25-2008. In Swedish.

Swedish Government (2017). *Regeringens Proposition 2016/17:146 "Ett Klimatpolitiskt Ramverk för Sverige"* (in Swedish). Available online at: regeringen.se (accessed August 9, 2021).

Swedish Government (2020). *SOU 2020:4. Vägen till en Klimatpositiv Framtid - Betänkande av Klimatpolitiska Vägvalsutredningen, 2020*. Stockholm: Norstedts Juridik.

Tcvetkov, P., Cherepovitsyn, A., and Fedoseev, S. (2019). Public perception of carbon capture and storage: a state-of-the-art overview. *Heliyon* 5:e02845. doi: 10.1016/j.heliyon.2019.e02845

Thunman, H., Berdugo Vilches, T., Seemann, M., Maric, J., Cañete Vela, I., Pissot, S., et al. (2019). Circular use of plastics-transformation of existing petrochemical clusters into thermochemical recycling plants with 100% plastics recovery. *Sustain. Mater. Technol.* 22:e00124. doi: 10.1016/j.susmat.2019.e00124

United Nations Framework Convention on Climate Change (UNFCCC) (2015). *The Paris Agreement*. Available online at: https://unfccc.int/process-andmeetings/ the-paris-agreement/the-paris-agreement (accessed June 24, 2021).

Williams, R. (1998). "Fuel decarbonisation for fuel cell applications and sequestration of the separated CO_2," in *Eco-Restructuring: Implications for*

Sustainable Development, ed R. Ayres (Tokyo, New York, NY: United Nations University Press), 180–222.

Wolske, K. S., Raimi, K. T., Campbell-Arvai, V., and Hart, P. S. (2019). Public support for carbon dioxide removal strategies: the role of tampering with nature perceptions. *Clim. Change* 152, 345–361. doi: 10.1007/s10584-019-02375-z

Zetterberg, L., Källmark, L., and Möllersten, K. (2019). *Incentives and Financing of Bio-CCS in Sweden (Incitament och Finansiering av Bio-CCS i Sverige).* IVL Report C417. Stockholm: IVL Swedish Environmental Research Institute (In Swedish).

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Exploring Narratives on Negative Emissions Technologies in the Post-Paris Era

Danny Otto[1], Terese Thoni[2], Felix Wittstock[2] and Silke Beck[2]*

[1] *Department of Urban and Environmental Sociology, Helmholtz Centre for Environmental Research-UFZ (Helmholtz Zentrum für Umweltforschung), Leipzig, Germany,* [2] *Department of Environmental Politics, Helmholtz Centre for Environmental Research-UFZ (Helmholtz Zentrum für Umweltforschung), Leipzig, Germany*

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****Correspondence:***
Danny Otto
danny.otto@ufz.de

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The 2015 Paris Agreement specified that the goal of international climate policy is to strengthen the global response to climate change by restricting the average global warming this century to "well below" 2°C above pre-industrial levels and to pursue efforts to limit it to 1.5°C. In this context, "Negative Emissions Technologies" (NETs)—technologies that remove additional greenhouse gases (GHGs) from the atmosphere—are receiving greater political attention. They are introduced as a backstop method for achieving temperature targets. A focal point in the discussions on NETs are the emission and mitigation pathways assessed by the Intergovernmental Panel on Climate Change (IPCC). Drawing on perspectives from Science & Technology Studies (STS) and discourse analysis, the paper explores the emergence of narratives about NETs and reconstructs how the treatment of NETs within IPCC assessments became politicized terrain of configuration for essentially conflicting interests concerning long-term developments in the post-Paris regime. NETs are—critics claim—not the silver bullet solution to finally fix the climate, they are a Trojan horse; serving to delay decarbonization efforts by offering apparent climate solutions that allow GHGs emissions to continue and foster misplaced hope in future GHG removal technologies. In order to explore the emerging controversies, we conduct a literature review to identify NETs narratives in the scientific literature. Based on this, we reevaluate expert interviews to reconstruct narratives emerging from German environmental non-governmental organizations (eNGOs). We find a spectrum of narratives on NETs in the literature review and the eNGO interviews. The most prominent stories within this spectrum frame NETs either as a moral hazard or as a matter of necessity to achieve temperature targets.

Keywords: negative emissions technologies, carbon dioxide removal, environmental NGO, IPCC, climate politics and policy, future making, narratives

INTRODUCTION: SETTING THE STAGE FOR ANTICIPATING CLIMATE FUTURES

Narratives play a central role in mobilizing knowledge for climate action (e.g., Hulme, 2008; Jackson, 2015). Recently, Hajer and Pelzer (2018, p. 222) argue that narratives have become even more important as climate "politics is no longer about raising awareness but about shaping the sustainability transition itself." More specifically, they indicate that "desirable climate futures" cannot be persuasively represented only in scientific terms of "CO_2 levels," "parts per million" or in sole reliance on integrated assessment models (IAMs). While scientific evidence provided by authoritative institutions such as the IPCC is an important resource for justifying and enacting climate politics (Beck and Oomen, 2021), scientific evidence alone does not seem sufficient to catalyze political action to meet the climate policy goals.

Narratives are understood as stories that define a problem, elaborate its consequences, and outline solutions (Roe, 1991; Leach et al., 2010). They play an important role as they can translate *matters of fact*—such as projected temperature—into *matters of concern* (Latour, 2004; Krauß and Bremer, 2020) because they spell out what futures are desirable (to what end) and what policy option are feasible and legitimate to achieve them. As climate politics shifts toward sustainability transformations, such narratives of desirable futures and ways to achieve them become more important in motivating and catalyzing political action on the ground (Hajer and Pelzer, 2018, p. 222). Following this line of argument, we explore emerging narratives around so-called Negative Emissions Technologies (NETs)—technologies, such as afforestation, bio-energy and carbon capture and storage or enhanced weathering, that remove CO_2 from the atmosphere—and how they are enacted in climate discourses.

The paper seeks to illuminate how the study of narratives can open up a fruitful discussion on desirable futures in a post-Paris era. While there is an emerging social scientific literature on IAMs and IPCC pathways (e.g., van Beek et al., 2020), there is a lack of empirical studies on how narratives are mobilized and challenged by environmental non-governmental organizations (eNGOs) on the ground (Oomen et al., 2021). To address this gap in the literature, we explore how the treatment of NETs within recent IPCC assessments and reports turned into a politicized terrain of configuration for essentially conflicting interests concerning long-term developments in the post-Paris regime.

We draw on perspectives from Science & Technology Studies (STS) and discourse analysis to explore the emerging narratives on NETs and gain first insights into their role in enacting climate politics. We conduct a review to reconstruct NETs narratives identified in the scientific literature. Additionally, we reanalyze expert interviews with eNGOs to explore how they respond to the role of NETs in IPCC reports. We focus on how NETs are embedded in narratives of desirable futures and study how they are justified.

The paper is structured as follows. The next section illustrates the conceptual framework and introduces an understanding of narratives from a co-productionist perspective. Data and Methods section gives a detailed account of the methods used in our analysis. We present the results of the literature review and the secondary analysis of the expert interviews in Role of NETs in Climate Governance—Insights From the Scholarly Literature and German eNGO narratives on NETs sections. Discussion section discusses the results in light of previous investigations and marks out promising avenues for further research.

CONCEPTUAL FRAMEWORK

In this section, we will introduce the conceptual framework of this study by defining narratives and addressing their role in climate governance from a co-productionist viewpoint (see also Longhurst and Chilvers, 2019). Furthermore, we introduce research on climate policy discourses (Bäckstrand and Lövbrand, 2019) as a reference point for our analysis of NETs narratives.

There are many different ways of characterizing and analyzing narratives (e.g., Abbott, 2008; Cobley, 2014; Amerian and Jofi, 2015). Bremer et al. (2017, p. 671) summarize narratives as follows: "narratives set a sequence and order to events occurring in a defined place and time, often structured as beginning–middle–end." More specifically, we consider narratives as stories that define a problem (beginning), elaborate on its consequences (middle) and outline solutions (end) (Roe, 1991; Leach et al., 2010). Similarly, Felt et al. (2007, p. 73) note, narratives "define the horizons of possible and acceptable action, project and impose classifications, distinguish issues from non-issues, actors from non-actors." Concerning climate policy, narratives influence the way societal groups and actors understand the problem and have a strong impact on how solutions are perceived, communicated, and legitimated. Thus, they play an important role in assembling and integrating actors around a particular kind of vision of desirable futures (cf. Hajer and Pelzer, 2018; Longhurst and Chilvers, 2019, p. 975).

Our understanding of narratives is rooted in a co-productionist perspective, which is based on the assumption that there are intrinsic links between ways of knowing a phenomenon on the one hand, and ways of acting upon it to transform it on the other (Jasanoff, 2004; Longhurst and Chilvers, 2019). This approach offers an interpretive lens to explore underlying normative, but often hidden rationales and justifications of policy choices for governing emerging technologies and distributing their risks and benefits (Beck et al., 2021). From a co-productionist perspective, even narratives of plausible futures that are seemingly descriptive or exploratory (such as the IPCC pathways), are prescriptive in that they put forward particular visions of what counts as a desirable future (Andersson and Westholm, 2019).

To contextualize the discussion on NETs narratives in climate politics, we draw on Bäckstrand and Lövbrand (2006, 2019) classification of climate policy discourses. In line with Hajer (1995, p. 45), they understand discourses as "specific ensembles of ideas, concepts and categorization that are produced, reproduced and transformed in a particular set of practices." Climate policy discourses and their role in climate governance are conceptualized as follows: "By defining problems of government, determining desirable codes of conduct and canvassing areas of political intervention, they produce the governed reality and hereby delimit the realm of the possible for climate politics" (Bäckstrand and Lövbrand, 2019, p. 520). In order to relate climate policy discourses and narratives, we understand narratives as embedded in discourses and emerging in discursive practices (cf. Urhammer and Røpke, 2013). Narratives are one mode of sense making within discourses. They draw upon different discursive elements in order to connect to preceding discussions and organize them into comprehensible plots. For the case at hand, we follow the rationale that narratives on NETs emerge as part of climate policy discourses. This enables us to relate the definitions of problems and solutions in NETs narratives to those outlined in climate policy discourses.

Bäckstrand and Lövbrand identify three climate policy discourses in forest plantation projects: ecological modernization, green governmentality and civic environmentalism (Bäckstrand and Lövbrand, 2006, p. 52 et sqq.).

- The **ecological modernist discourse** combines cost-efficient climate mitigation with sustainable forest management in a "win-win rhetoric." From this point of view climate change can be solved by technological innovation and markets.
- The **green governmentality discourse** stresses planetary carbon control by scientific precision (highlighting, amongst others, the IPCC report on IPCC (2000a) and "professionalized resource management, environmental target-setting and monitoring" (Bäckstrand and Lövbrand, 2019, p. 523).
- In contrast to the other discourses, the heterogeneous and critical **civic environmentalism** discourse moves beyond global markets and standardized science and top-down management in favor of local, bottom-up participation in forest sequestration projects. From this perspective climate change requires fundamental transformations of consumption patterns and institutions.

More than a decade later, Bäckstrand and Lövbrand (2019) return to their typology of policy discourses and examine to what extent they still shape climate politics. They consider the UN climate conferences in Durban (2011), Warsaw (2013), Lima (2014), and Paris (2015) as "active political sites where particular ways of thinking about and acting upon climate change take form, stabilize and enable more or less systematic forms of government" (Bäckstrand and Lövbrand, 2019, p. 521). While there are some "subtle shifts in the discursive landscape," the overall framework of Bäckstrand and Lövbrand has proven to be helpful for mapping climate discourses on the international level over time (Bäckstrand and Lövbrand, 2019, p. 528).

We will employ this framework in our analysis by discussing how the identified narratives relate to the three historically established climate policy discourses. This enables us to distinguish between novel emerging narratives on NETs. It, also allows for future comparisons of narratives on other climate related technology or policy issues.

DATA AND METHODS

In this section, we provide information on methods used for our exploration of NETs narratives. We combine literature reviews and secondary analysis of interviews with eNGO experts in order to reconstruct emerging NETs narratives. This approach enables us to explore the range of NETs narratives and to gain insights into ongoing controversies by paying particular attention to the perspectives of eNGOs.

Literature Review

We conducted a topic search in the journal database Web of Science to identify relevant literature for our review (see **Table 1**). The focus of the literature review is to better understand narratives on the governance of NETs that either build on or differ from the role of NETs in pathways presented by the IPCC, especially the Special Report on 1.5°C global warming (from now on IPCC SR15). Given that this is still a nascent field of research, we adopted a broad approach to gathering relevant literature, using two search strands targeting two mutually overlapping bodies of literature. We complemented this formalized approach by identifying additional literature from, for instance, reference lists and quotations.

We used a total of five keyword groups (search strings). For the two search strands, we combined a total of four keyword groups (**Table 1**). Three keyword groups (1–3) were the same in each search strand. We designed keyword groups 1–3 to capture papers that deal with a post-Paris world (1), ways of knowing or imagining the future (e.g., scenarios) (2), and ways of governing (3), respectively. In addition to these three keyword groups, we added one keyword group focusing on the IPCC (4), and another one focusing on NETs (5). To form our two search strands, we then combined keyword groups 1–4 for the first one, and 1–3 plus 5 for the second one. We chose to focus on these keyword groups and search strands as they are apt to provide articles that develop NETs narratives (for instance by legitimizing NETs as promising climate change mitigation option).

We designed the keyword groups to capture a broad range of papers and one by one, these keyword groups generate a very large number of papers, but combined, they generate a more manageable and targeted batch of papers. The aspiration was not to cover all literature. The aim of this search approach was instead to (1) present a transparent strategy that can be extended, and (2) inductively examine the available literature that falls within our inclusion criteria.

The two search strands generated a total of 102 papers after removing duplicates. All abstracts were screened and 47 papers selected for full review. The main reasons for excluding papers based on the screening of abstracts were: (1) the paper did not focus on politics, governance or the like but on rather technical and scientific issues outside the scope of the current paper, (2) the paper engaged with ways of knowing the future rather than governing the future. In cases of doubt regarding relevance, the paper was included in the full paper screening.

We reviewed the literature for recurring themes and analyzed how NETs are represented as a climate change mitigation option. We paid particular attention to the problems (e.g., average global temperature rise, delaying decarbonisation) and solutions (e.g., the deployment of NETs) and how they are justified.

Expert Interviews

We conducted a secondary analysis of seven semi-structured expert interviews with German environmental NGO representatives to complement the literature review and to

TABLE 1 | Sampling steps literature review.

Search in web of science

Language: English | Time span: 2015–2020 | Results from all databases | Topic Search

Keyword groups			**Results**
#1: (Paris Agreement OR post-Paris OR "COP 21" OR COP21 OR "conference of the parties")	AND	**#4:** (IPCC OR "Intergovernmental Panel on Climate Change")	38
AND		**#5:** ("carbon dioxide removal" OR "negative emission" OR "bioenergy with carbon capture" OR "direct air capture" OR afforestation OR reforestation OR "blue carbon" OR "ocean fertilization" OR "ocean alkalinity" OR "enhanced weathering" OR "soil carbon sequestration")	72
#2: (imaginary OR future OR narrative OR discourse OR storyline OR pathway OR scenario)			
AND			
#3: (governance OR policy OR policies OR political)			
Total			110
After merging duplicates			102
After content screening			47

We used '' as truncation operator to capture variations of a word e.g., govern* where appropriate.*

reconstruct emerging narratives on NETs. We chose these interviews for a secondary analysis of NETs narratives as each of them featured extensive discussions on the role of NETs in climate change mitigation. The interviews thus provide a valuable basis for this exploratory analysis of the narratives emerging around NETs in the German eNGO community.

The interviews were carried out in two different research projects and at different times. Four face-to-face interviews took place in 2018, shortly after the publication of IPCC SR15 (2018). They focused on the role of climate engineering including CDR in scientific assessments. A second batch of three interviews was conducted in 2020. The main concern of these interviews was the perceptions of carbon capture and storage technologies (CCS).

Both research projects followed a parallel sampling strategy to select interview partners. Environmental NGOs were defined in reference to the UNFCCC list of admitted NGOs (UNFCCC, 2021), and we considered those that are listed as part of the "environmental CAN" (climate action network) constituency as relevant for our purposes. A two-step theoretical sampling strategy was applied (Glaser and Strauss, 1970; Dimbath et al., 2018). We selected eNGOs from the UNFCCC list in order to capture the perspectives of the main actors of the German eNGO field (Foljanty-Jost, 2005), and according to an initial analysis of eNGO position papers on NETs. In a second step, we identified and approached specific interview partners based on their thematic work (energy and/or climate policy) within the eNGO. In order to ensure confidentiality and enable an open interview atmosphere, we agreed to keep the institutions and interview partners anonymous. While there is an overlap between the eNGOs interviewed in the two projects, we did not interview the same representatives twice. All interviews were recorded and transcribed.

We employed qualitative content analysis (Schreier, 2012) to code the interviews and to identify NETs narratives. We developed a coding frame to collect all segments of the interviews concerning NETs. These sections were analyzed for narratives that justify, assess or contest the climate change mitigation potential of NETs.

ROLE OF NETs IN CLIMATE GOVERNANCE—INSIGHTS FROM THE SCHOLARLY LITERATURE

In this section, we review the state of research and identify narratives around the role of NETs in climate policy. We conclude the section by drawing linkages between the narratives we outline and broader climate policy discourses (Bäckstrand and Lövbrand, 2019).

NETs Narratives in Climate Policy—A Spectrum of Ideas

Carbon sinks—understood as "natural or man-made systems that absorb CO_2 from the atmosphere and store them" (IPCC, 2000b)—feature in the IPCC assessments since the early 1990s (e.g., IPCC, 1990, p. 12), and have been a part of the UNFCCC since its inception (United Nations, 1992). The large scale removal of additional CO_2 from the atmosphere has more recently gained attention as component of climate change mitigation pathways (cf. Carton et al., 2020, p. 2). In its fifth assessment cycle, the IPCC introduced bioenergy with carbon capture and storage (BECCS) as a mitigation option aimed at keeping global warming below 2°C (IPCC, 2014, p. 89). SR15 clearly states: "All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the twenty-first century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak" (IPCC, 2018, p. 17).

Recent IPCC assessments have been widely interpreted in the scholarly literature to show that the global temperature goals cannot be met without NETs (Lin, 2018; Minx et al., 2018; Rogelj et al., 2018; Stavrakas et al., 2018; Doelman et al., 2019;

Fajardy et al., 2019; Mundaca et al., 2019; Rickels et al., 2019; Honegger et al., 2020). In other words, **NETs are framed as a matter of necessity** (solution) to reach the long-term global temperature goal (problem) (see United Nations, 2015). They are taken as an integrative part of climate governance. Bellamy and Healey (2018, p. 1) state: "It is increasingly recognized that meeting the obligations set out in the Paris Agreement on climate change will not be physically possible without deploying large-scale techniques for either removing greenhouse gases already in the atmosphere or reflecting sunlight away from the Earth."

A recurring argument against the inclusion of NETs in emission and mitigation pathways is that NETs risk slowing down mitigation action today, leaving unanswered the important question of what happens if NETs do not deliver at scale (e.g., Larkin et al., 2018; Carton, 2019; Waller et al., 2020). This is also known as mitigation deterrence or, as we will call it henceforth, **moral hazard** (e.g., Low and Schäfer, 2020; McLaren, 2020). In this narrative, NETs are not framed as a solution to the problem of achieving temperature targets rather they risk distracting vital attention from mitigation efforts.

In the literature reviewed, the narrative that NETs are necessary to reach temperature targets relates to other narratives about the role of NETs in climate policy. Some present NETs as unwanted but without alternatives (Haikola et al., 2019), others specific NETs as options to optimize climate mitigation (see e.g., Herr et al., 2017 on Blue Carbon; Marcucci et al., 2017 on direct air capture with CCS; Fernandez and Daigneault, 2020 on afforestation). Consequently, these narratives form a spectrum, ranging from NETs as a feasible and effective option to reach temperature targets, through NETs as necessary option to reach temperature targets (but not necessarily positive), to NETs as a risky option for reaching temperature targets. To better understand the differences and overlaps between these narratives, we now explore their overarching rationales related to climate policy, and associated risks.

Exploring the Rationales Underpinning NETs' Narratives

In the **"NETs are necessary" narrative,** the rational for the deployment of NETs is to reach the long-term global temperature goals. NETs take time, the argument goes, to develop. Hence, if we want them to deliver as assumed in the pathways, we need to act now in terms of, for instance, research funding and institutional compatibility (Minx et al., 2017; e.g., Bataille et al., 2018; Bellamy and Healey, 2018; Nemet et al., 2018; Stavrakas et al., 2018; Brack and King, 2020; Jones and Albanito, 2020). It is generally acknowledged that there are uncertainties regarding the large-scale deployment of NETs (e.g., IPCC, 2018). However, without NETs, the chances of reaching the long-term global goal are even lower (e.g., Lin, 2018; Daggash and Mac Dowell, 2019; Haikola et al., 2019).

In contrast, a main concern for the narrative that portrays **NETs as a moral hazard** is that including NETs in pathways and strategies changes political priorities today in ways that affect possibilities in the future (cf. Low and Honegger, 2020; Woroniecki et al., 2020). In this case, the promise of capturing and removing carbon in the future is delaying action today (e.g., Shue, 2018; Asayama and Hulme, 2019). As phrased by Carton (2019, p. 765): "The political economy of delay, a constellation of economic, political, cultural and everyday practices that in numerous ways serve to postpone the necessary devaluation of fixed fossil fuel capital." Moreover, even though uncertainties around large-scale deployment of NETs are clearly outlined in the literature (e.g., IPCC, 2018), the fact that NETs are nevertheless included in pathways could lead actors to take their effectivity for granted and make it difficult to understand the urgency to act on climate change today (e.g., Larkin et al., 2018).

The concern that the promise of NETs could slow down mitigation action is partly addressed in the literature where the role of NETs is seen as necessary. The essential contribution of NETs is to compensate for hard-to-abate emissions—for instance from aviation or shipping (e.g., IPCC, 2018; Minx et al., 2018). In other words, NETs should complement other efforts, not be the only game in town. In the scholarly literature, there are numerous examples for combining rapid societal change with future technological solutions such as the use of NETs (Grigoroudis et al., 2017; Marcucci et al., 2017; Aengenheyster et al., 2018; Brack and King, 2020).

Reducing Uncertainties and Exploring Alternative Approaches

One key concern that emerges from the scholarly literature related to governance of NETs is the uncertainties of the future, large-scale deployment. There seem to be two main suggestions on how to address these uncertainties in the literature. Following the **NETs are necessary narrative**, the main focus is on reducing uncertainties, not least by providing more resources to research and development (e.g., Nemet et al., 2018; cf. Low and Honegger, 2020). They are based on the rational that uncertainties are manageable by more and better research.

There is also a strand of literature that focuses on assessing uncertainties regarding the feasibility of NETs deployment that, instead of looking at the feasibility of reaching specific temperature targets, starts with today's conditions and asks what seems feasible, given current conditions (cf. Thoni et al., 2020). These types of analyses often break down ideas of maximum potential to more modest expectations for the use of NETs (Boysen et al., 2017; Geden et al., 2018; Vaughan et al., 2018; Asayama and Hulme, 2019; Wachsmuth and Duscha, 2019; Brack and King, 2020; Wieding et al., 2020). As such, this literature can be understood as a an attempt to address the risk of mitigation deterrence by taking current conditions rather than distant goals and theoretical possibilities as a starting point. For instance, as phrased by Geden et al. (2018, p. 1): "While policymakers, in accepting the IPCC's assessments, appear to have implicitly accepted that CDR is necessary to meet the Paris Agreement's targets, they have avoided asking (or answering) the next obvious question:'Who exactly is going to do it'."

Following the **moral hazard narrative**, the focus is instead on exploring alternative ways of imagining the future than modeling in general and IAMs specifically. Opening up the imagination of climate futures does not reduce uncertainties related to the deployment of NETs as such, but reduces the risk that the political imaginary is reduced to a narrow spectrum (Beck and Mahony, 2018; Beck and Oomen, 2021).

There is a growing body of literature that argues to the importance of creating spaces in which a broader range of actors (not just experts and government representatives) are given the opportunity and the means to imagine climate futures (Lawrence et al., 2018; Forster et al., 2020; Low and Honegger, 2020; Markusson et al., 2020). One aim of broadening the debate is to ensure that political and normative choices do not remain hidden in technical practices such as IAM scenarios and to ensure that a range of futures can be explored rather than just a narrow set of pathways (e.g., Beck and Oomen, 2021). For example, in their analysis of views on and ways of assessing the feasibility of NETs deployment, Forster et al. (2020) highlight a range of existing approaches that could complement IAMs by attending to complex socio-political issues, including future options beyond those explored by IAMs. Examples include participatory integrated assessments, transparent communication around assumptions, and responsible and reflexive assessment, innovation, and governance (Forster et al., 2020; see also Beck and Mahony, 2017; Berg and Lidskog, 2018).

Link to Climate Governance Discourses

In our review, we identified two important narratives on the role of NETs in climate policy - one proposing that the deployment of NETs will be necessary and thus should be considered a part of climate governance to reach temperature targets, and another one suggesting that including NETs as part of climate governance can lead to mitigation deterrence and make it more difficult to mitigate climate change. We also saw alternatives or hybrids, such as focusing on feasibility of deployment on the ground rather than feasibility of meeting temperature targets, less easily placed in either one of these narratives. Hence, while there are clearly deep differences between the key narratives we have identified, the scholarly literature on NETs cannot only be understood as a rigid dichotomy between these two narratives. It is probably more accurate to think of the literature as representing a spectrum of findings and arguments that are deeply supportive of NETs deployment, necessary or not, to deeply against it. To better understand the differences and similarities between the two main narratives discussed in this section and to place them in a broader context, we now turn to the literature on climate policy discourse, more specifically the discourses of green governmentality, ecological modernization, and civic environmentalism (Bäckstrand and Lövbrand, 2006, 2019).

The discussion about NETs in general carries important characteristics both from green governmentality such as the focus on staying below a global temperature target, and the idea about carbon sinks (see e.g., Carton et al., 2020) and ecological modernization with technological solutions, win-win between climate action and economic development, and cost efficiency (Fujimori et al., 2018; Honegger and Reiner, 2018; Ueckerdt et al., 2019; Donnison et al., 2020). Previous literature has also suggested that ideals associated with the ecological modernization discourse, such as techno-fixes and market solutions, could, in the context of NETs, slow-down the phasing out of "carbon infrastructures" (cf. Low and Boettcher, 2020, p. 9), in line with the moral hazard narrative. In terms of mobilization of actors, a recurring theme in the literature on NETs is the role of science and expertise, as well as large bodies like the IPCC (see e.g., van Beek et al., 2020; Waller et al., 2020). To address the risk of NETs as a moral hazard and the closing down of alternative climate futures, scholars have suggested the need to open up the process of knowledge-making (e.g., more disciplines) and decision-making, especially related to marginalized groups and intergenerational justice, a theme in line with the civic environmentalism discourse (cf. Carton, 2019; Carton et al., 2020; Markusson et al., 2020; Paterson, 2020).

Comparing rationales behind NETs as a climate policy option, we see that in general, literature on NETs commonly highlights the urgency of climate change as a global problem, which is typically associated with the green governmentality discourse (Bäckstrand and Lövbrand, 2019), and the need for rapid emission reductions combined with the deployment of NETs (Grigoroudis et al., 2017; Marcucci et al., 2017; Aengenheyster et al., 2018; Rogelj et al., 2018; Brack and King, 2020). However, assuming large-scale future deployment of NETs could provide justifications for incremental change and slower decarbonisation, as cautioned by the moral hazard narrative (cf. Holz et al., 2018; Butnar et al., 2020). Consequently, taking into account the risk that NETs are not deployed at large scale in the future means that even more rapid transformation is needed (Larkin et al., 2018; Lawrence et al., 2018; Asayama and Hulme, 2019; Harwatt, 2019; Anderson et al., 2020; Wieding et al., 2020) is more in line with the civic environmentalism discourse. Hence, a key feature of NETs' narratives is that they outline ideas for change, but may differ in their understanding of the plausible and desirable pace and magnitude of change, partly corresponding with differences between the NETs are necessary and the moral hazard narratives (cf. Ueckerdt et al., 2019 about the "economically optimal warming limit" and NETs deployment; Larkin et al., 2018; see also Linnér and Wibeck, 2020).

That being said, the literature on NETs is not black and white in terms of links to overarching climate policy discourses. This becomes clear not least when considering individual NETs rather than all NETs as a group. Some NETs that focus on enhancement of natural sinks, including restoration of ecosystems, are sometimes called nature-based solutions. The literature on such technologies includes discursive elements that have clear links to ecological modernization, such as a win-win narrative, market-based approaches, and cost-efficiency (see e.g., Needelman et al., 2019; Pascoe et al., 2019; Carton et al., 2020; Fernandez and Daigneault, 2020). However, there are also some similarities to the civic environmentalist discourse, with a narrative around community-based, bottom-up approaches (e.g., Sutton-Grier and Moore, 2016; Herr et al., 2017).

GERMAN eNGO NARRATIVES ON NETs

NETs and carbon dioxide removal overall have not been prominent topics in German climate policy and they do not feature in the German climate law (Federal Law Gazette, 2019). With the IPCC SR15 carbon dioxide removal entered policy debates but it is approached with restraint (Schenuit et al., 2021). Especially NETs connected to CCS are discussed with much reluctance because of earlier public and political opposition against CCS projects and the persisting legal barriers for the deployment of this technology (e.g., Fischer, 2015; Dütschke et al., 2016; Krämer, 2018; see also Federal Law Gazette, 2012). As Schenuit et al. (2021) argue, this results, inter alia, in a differentiation into "natural" (e.g., afforestation) and "technical/geochemical-based" NETs (e.g., BECCS) in the German discussion. Recently, dynamics in German eNGO positions on NETs were observable. Some either expressed support for "natural" carbon removal (Deutscher Naturschutz Ring, 2020) or acknowledged the need for geochemical-based NETs (e.g., Wuppertal Institut für Klima, 2018; Prognos, 2020). To further investigate these dynamics we analyze expert interviews with German eNGO representatives.

We identify three different narratives with regard to a potential future role for NETs, each engaging with NETs in a different way. Two of these narratives map on the most prominent stories we found in our literature review and resemble the moral hazard and NETs are necessary narratives. In addition, we find a variation of the NETs are necessary story that centers on the thought that NETs are unwanted but seemingly unavoidable. Our aim in describing the narratives is to add to the stories outlined in the literature review and the literature on eNGO perception of NETs (e.g., Corry and Riesch, 2012; Corry and Reiner, 2020). In addition, we discuss how the IPCC is called upon as a resource of legitimation for these narratives.

NETs as a Moral Hazard

NETs as a moral hazard was the dominant narrative in the first set of expert interviews in 2018 and recurs in the second set conducted in 2020. It rejects NETs completely as a technical means of offsetting emissions. "End-of-pipe" technologies such as carbon capture and storage (CCS) and NETs connected to CCS (like BECCS or direct air carbon capture and storage - DACCS) are not regarded as viable options for achieving climate targets. On the contrary, they are considered as moral hazard for the following two rationals:

1. They distract from CO_2 reduction efforts in the present by promising the extraction of atmospheric CO_2 in the future by "wishful thinking" and "science fiction." Betting on NETs is neither economic nor realistic. DACCS especially is perceived as inefficient because of the low concentration of CO_2 in the atmosphere and the high amount of energy it would take to capture, transport and store it. Hence, avoiding emissions from the start is much more useful while efforts expended on NETs are a "waste of time" that could be spent on more pressing issues.
2. Especially those NETs connected to the geological storage of CO_2 entail risks. Framed as "waste disposal," CCS is seen as a "risk technology" due to the uncertainties arising from potential leakages, migration of the CO_2 plume or induced seismic activity. Beyond the risks of geological storage, environmental concerns are raised for BECCS on account of the "excessive land use" required for biomass production, resulting in biodiversity loss (due to monocultural biomass plantations) and negative impacts on natural CO_2 sinks (e.g. deforestation to extend agricultural land).

In this sense, the moral hazard narrative identified in the eNGO interviews positions NETs as a problem for climate change mitigation and strongly critiques any reliances on CCS based NETs. Following this line of argument, some interviewees raised the question why ambitious temperature goals are maintained if they are not achievable without NETs. Other eNGO representatives questioned the inclusion of BECCS in IPCC assessments. Despite their vocal criticism of NETs, however, the interviewees were careful in raising concerns about the IPCC, as the following statement illustrates:

> "I have doubts about the process [of drafting the IPCC SR15]. I have named [energy company] before as a substantial supporter of CCS technology in Germany. It really raises questions about the independence of research, when [an energy company] sponsors a professorship for sustainability and this professor, who is an advocate of CCS, arouses false hope and is involved in the writing of the IPCC report. While I hold the IPCC in high, high esteem I am critical of the process [that led to the inclusion of large amounts of BECCS in the scenarios]."

External influence—namely company lobbying—is viewed to have a negative impact on the IPCCs assessment and as responsible for the inclusion of BECCS.

In this narrative, that rejects NETs completely, all efforts for climate change mitigation should focus on the expansion of renewable energy production, the reduction of overall energy consumption and behavioral changes (e.g., mobility). If there should still be a future need for negative emissions, this should be addressed by strengthening natural carbon sinks (e.g., rewetting of peatlands or eco-system restoration) and "revitalizing the environment" in the process.

NETs Are Unwanted but Seemingly Unavoidable

This second narrative seeks to adopt a "realistic position," as one of the interviewees put it, by engaging in a differentiated discussion of NETs. This position still prioritizes energy system transformation and behavioral change for sustainability, but centers much more on the question of what kind of NETs might play a role in the future, not whether NETs should play a role at all. The interviewees refer to the IPCC in order to make the case that presumably some form of NETs will be necessary in the future. They stress that the IPCC makes the trade-off between NETs and emissions reduction explicit as the scale of NETs will heavily depend on the amount of emissions cut. A reliance on NETs is still unwanted and everything should be done to avoid the need for such measures. Parallel to the first narrative, the feasibility of BECCS is called into question due to the "unrealistic" amount of land that would be required for the production of biomass to achieve the bioenergy estimated in the IPCC pathways in SR15. The inefficiency and high costs associated with DACCS are raised as barriers to deployment, and the safety issues of geological CO_2 storage (intrusion into groundwater, plume movement) are pointed out. It is not possible, however, to dismiss NETs altogether, as a sufficient reduction of greenhouse gas emissions might not be achieved in time. This conflictual position becomes apparent in the following statement:

> "But it is also clear to me that, if we seriously consider the Paris climate goals and simultaneously do not move away from the path on which we are moving now, that of course things like direct air capture will be necessary. But I don't know how. And right now I don't see the time to focus on that, but rather to initiate the transformation while we still can. Direct air capture is perhaps for the time when we know for sure: we are too late and cannot change it anymore."

If the removal of CO_2 becomes unavoidable then "nature-based solutions" (rewetting peatland, soil carbon sequestration, and afforestation) are favored in this narrative because of their beneficial effects on nature conservation, even if the problems associated with such solutions—including the international coordination of measures and the scale and security of CO_2 storage—are apparent. The interviewees who mobilize this narrative are "hopeful" given that not all the IPCC's pathway scenarios include a high amount of NETs based on CCS; they state their support for "those pathways without or with limited BECCS [in IPCC SR15]." This establishes a link to the IPCC scenarios and an option to highlight the aspects of the report that fit the narrative while still being critical of others. Their strongest criticism is directed at the "enormous" amounts of BECCS in some scenarios.

NETs Are Necessary

This narrative became apparent in the second set of interviews conducted in 2020. It states clearly that, in the interviewee's opinion, the IPCC has shown that NETs will be necessary to achieve net zero carbon emissions and there is no way around them. This is taken as the "word of science" on the "goal of climate neutrality." It is, therefore, crucial to have climate models that "really calculate climate neutrality" and outline the capacity of NETs needed to achieve it. A "100 percent renewables" approach does not appear feasible in the light of the scenarios and is incompatible with the Paris temperature goals and the net zero target. In consequence, the interviewee who mobilizes this narrative is puzzled by the debate on BECCS:

> "I see the goals for climate neutrality, for the CO_2 budgets. I take them as the word of science and the same scientific report names BECCS. And should I now say I reject BECCS? For me this is one paper and if its first core message is—the CO_2 budget is this—and its second message is—BECCS potential is this—then I cannot take the one and ignore the other. That would be unscientific."

The selective reception of scientific assessments might be done with political intention but, in the interviewee's opinion, this is not "science-based" and the IPCC report needs to be "appreciated in its entirety." A rapid transformation of the energy system and of society as a whole toward sustainability still has the highest priority, but if negative emissions are an inevitable addition, than it is "unproductive and potentially damaging" to view natural and technical carbon removal as competing with each other. "All peatlands and all rainforests will be necessary to reach net zero and technical sinks will still be required as well."

Considering the diversity of narratives around NETs, our results are in line with previous studies of eNGO positions on NETs and CDR (Corry and Reiner, 2020), which also found competing evaluations of the issue. Comparing the eNGO narratives to the spectrum of stories we found in the literature review, we see that the narratives 1 and 3 fit the moral hazard and NETs are necessary narratives. The second eNGO narrative can be seen as a variation of the NETs are necessary narrative. It acknowledges that some NETs will most likely be needed to achieve temperature targets but emphasizes the strong preference for a rapid reduction of carbon emissions.

We see that the prominent role of NETs in IPCC assessed pathways is controversial among German eNGOs. Consequently, references to the IPCC (most prominently to SR15) may express various attitudes (approval, rejection, building upon etc.). For eNGOs that oppose NETs this can mean questioning the IPCC on the grounds of influence exerted by industry or politicians, unrealistic assumptions, or the selectivity of the scientific literature assessed (e.g., dominance of IAMs). Those who see NETs as "unwanted but seemingly unavoidable" may stress the existence of scenarios without or with small amounts of BECCS in the IPCC assessment and point to "nature-based solutions" to achieve negative emissions. Those who see NETs as necessary draw on the IPCC report and accuse other eNGO views of being selective by neglecting NETs.

When we relate the narratives to the climate policy discourses discussed by Bäckstrand and Lövbrand (2019), it is not possible to pinpoint the narratives in one particular discourse. While we find that the first narrative, NETs as moral hazard, can be conceptualized as part of the civic environmentalism discourse (as it advocates fundamental transformations instead of future NETs), it also contains some of the logic of an ecological modernization discourse and green governmentality in its discussion of natural sinks for carbon removal. The third narrative might stress the need for NETs in an ecological modernist fashion but it also contains elements of civic environmentalist discourse, with a strong emphasis on the necessity of combining all available climate change mitigation options and the need for "fundamental transformations of our consumption patterns and institutions" (Bäckstrand and Lövbrand, 2006, p. 56). The second narrative (NETs are unwanted but seemingly unavoidable) is positioned between the ecological modernization and civic environmentalism discourses and displays characteristics of both. With their strong reliance on the authoritative role of "big science" and "scientific expert advisors" (such as the IPCC) in the construction of eco-knowledges along with the shared idea that "sound science" is a legitimate resource with which to measure, predict and manage environmental risks (cf. Bäckstrand and Lövbrand, 2006), we find elements of a green governmentality discourse ingrained in all three eNGO narratives. Thus, rather than attributing eNGO narratives on NETs to clear-cut positions in climate policy discourses, we find that the lines between discourses blur in discussions on the necessity of NETs.

Taking a closer look at the interpretational power ascribed to the IPCC by the interviewees, we find that there is a general agreement on its position within the climate change discourse. All interviewees stress the relevance of the IPCC and perceive it as a "political actor" and a "global reference" with epistemic authority on issues of sustainability and climate change. IPCC reports are described as "political initiators" for sustainability and even "vehicles for enhancing political pressure." The narratives we have identified in this exploratory study all relate to the IPCC's conclusions around NETs, suggesting that eNGOs are currently confronted with a situation where IPCC reports can be referred to by various actors to either legitimize or delegitimize proposals for NETs. It will be a task for future studies to investigate this further.

In addition to referring to the IPCC in a certain fashion, the eNGO narratives on NETs display further characteristics we wish to point out. The first of these is a positivist perception of science that is embedded within the narratives. This is most apparent in the third narrative where scientific evidence ("the word of science") is the main argument for a climate future with NETs while diverging narratives are accused of not "appreciating" the IPCC report in its entirety and not being "science based" but "political." To a lesser degree, this also holds true for the second narrative, in which the existence of a scenario without BECCS or DACCS is seen as providing "hope" for a positive climate future. Even though the IPCC is criticized in the first narrative for including large amounts of BECCS, this critique is ultimately directed either at an external actor—namely, an energy company illegitimately advocating CCS—or at organizational issues rather than at the scientific procedures. Corry and Reiner (2020) note a similar emphasis on "the science" and "truth" in recent climate protests. This perception of science portrays a narrowed down version of the relation between scientific expertise and political processes, with the former guiding the latter.

A second characteristic of the narratives is their positioning of actors within the stories. So far, we have discussed the representation of the IPCC as a scientific authority, but other actors are also mobilized in them. One example of this are energy companies. They appear in the narratives as adversaries and represent a counter-position to the eNGOs. In the moral hazard narrative this becomes clear when a push for NETs and a negative influence on the IPCC are identified as stemming from an energy company "meddling" in scientific research. Technologies like BECCS and "nature-based solutions" are also mobilized in the narratives. These technologies are, depending on the narrative, either represented as opposition or alliance—"villains" or "heroes" of desirable futures. Such dichotomies reduce the complexity of these carbon removal options and obscure what counts as a "nature-based solution"—lost in the simplification are the paradoxes and unintended consequences (e.g., Bellamy and Osaka, 2020; Bertram and Merk, 2020; Woroniecki et al., 2020).

DISCUSSION

Our study begins with the search for NETs narratives and the question how the IPCC's assessments of NETs turned into a terrain of configuration for essentially conflicting interests. In an explorative approach, we reconstruct emerging NETs narratives in the scientific literature and in a secondary analysis of expert interviews with environmental NGO representatives.

We find a spectrum of narratives in the literature review, ranging from the view that NETs can play a positive role to achieve climate targets, to the perspective that there is a risk that NETs delay climate action. Our analysis identified two especially prominent narratives. The first falls in the middle of the outlined spectrum and frames NETs as a matter of necessity by building upon IPCC assessments. The second positions NETs as a moral hazard because they delay decarbonization and their feasibility is uncertain.

In a new phase of climate politics, eNGOs have to respond to the novel role of the IPCC as venue for anticipating sustainability transformations (e.g., Beck and Mahony, 2018; Hajer and Pelzer, 2018). Our findings indicate that the inclusion of NETs into the climate portfolio results into controversies among eNGOs and, like in the literature review, we find a spectrum of positions on NET. We find the prominent "moral hazard" and "NETs are necessary" narratives but also some variation of the latter. This further stresses the point that these narratives should not be seen as a strict dichotomy since they do not account for all positions within the debate. In line with existing literature (e.g., Corry and Reiner, 2020), we find that eNGO representatives integrate the IPCC assessments into their argumentative positions on NETs in different ways. Those promoting NETs as a viable option for mitigating climate change count on the IPCC. Those more skeptical or averse to NETs mobilize alternative resources (for instance scenarios not included in IPCC reports) or focus on pathways with "nature based" NETs in the IPCC assessments in order to legitimize their narratives. We observe that those critical of NETs (and of the IPCC for including them in their assessments) are also reluctant to challenge the IPCC's epistemic authority openly. The eNGOs in our small sample still seek a scientific legitimation for their narrative.

Our study contributes to a better understanding of the role of narratives: we show how different actors draw upon various elements to support their visions of desirable climate futures and to position themselves in responses to NETs and their potential or risks. "Nature-based solutions" offer a good example of this. In order to present these options as alternative to "high-tech" options such as BECCS or DACCS, eNGOs framed them as less invasive and in alignment with nature. In agreement with previous studies (e.g., Woroniecki et al., 2020), we argue that this does not only rely on assumptions taken for granted about "nature" but that it neglects the complexities and entanglements of so-called "nature-based solutions" in their natural and societal contexts. It would be worthwhile to study the rhetoric and metaphors of this debate in more detail in future research (Corry and Riesch, 2012, p. 92; see for instance, Castree, 2020).

The prevailing NETs and alternative narratives can be connected to the climate discourses identified by Bäckstrand

and Lövbrand (2019). Their framework is helpful for analyzing conflicting lines of argument in the field of climate politics emerging around NETs. We find that the "NETs are necessary" narrative is partly linked to the discourse on ecological modernization with its technological focus and emphasis on eco-friendly capitalism. For the moral hazards narrative, we find linkages with civic environmentalism (Bäckstrand and Lövbrand, 2019, p. 529), because it calls for (intergenerational) climate justice and fundamental transformations as alternative to technological fixes. However, we also observe that the discourses overlap when NETs narratives are concerned. In the literature review and the interviews with eNGOs, we find that the argumentative structures of ecological modernization, green governmentality and civic environmentalism discourses are (in varying degree) present in the narratives and counter-narratives on NETs whenever the issue of reaching temperature targets is discussed. The strong influence of climate science is also evident: calculations of CO_2 budgets available to achieve temperature goals have become seemingly unavoidable points of reference in discourses on shaping and achieving desirable climate futures.

It remains a task for further research to map a broader range of narratives on NETs and other climate futures. Continued work on mapping visions, stories and imaginaries is needed in order to study their "respective partialities, exclusions and sociopolitical dimensions" and to "offer a more humble, reflexive, and responsible foundation for practices of future-making and sociotechnical transformations" (Longhurst and Chilvers, 2019, p. 973; see also Chilvers et al., 2021). Our study contributes to this objective by exploring narratives on NETs. Nevertheless, we recognize the limitations of our approach, which have mainly to do with the small number of interviews and the narrow focus on German eNGOs. Furthermore, the specific settings of our interviews are likely to have exerted some effects on our analysis since they come from different projects (one addressing climate engineering including CDR and the other focused on the perception of CCS).

This exploratory analysis can be a starting point for more empirical research in this direction. Further research could also strive to respond to global inequalities and take marginalized voices into account when considering narratives on NETs (e.g., Biermann and Möller, 2019). Methodologically, such endeavors can be fruitfully augmented by content analysis of policy documents and press releases as well as explicit comparisons of different socio-historical settings (such as narrative repertoires pre- and post-Paris). We also suggest that future investigations zoom in on particular NETs as our analysis indicates that there are marked differences in narratives between different kinds of technologies that could provide negative emissions.

Furthermore, power relations need to be addressed in a more encompassing fashion. The capacity and agency available to different actors for making the future an object of representation should be taken into account. This does include reflections upon the narratives that research items are transporting and this article (while aiming for a meta-perspective) is certainly no exception to this. Finally, the questions "who gets to envision the future" and who is entitled to speak on behalf of whom (Markusson et al., 2020) need to be discussed beyond the scope of this article. It will be a task for further research to study the mobilization of multiple human and non-human actors (e.g., Latour, 2005; Whatmore, 2009) in the making and stabilization of desirable climate futures.

CONCLUSION

In this paper, we explored narratives emerging around NETs and investigated the roles that are ascribed by different actors to the IPCC as discursive source of legitimation within these stories. Theoretically, we introduced narratives from a co-productionist perspective and highlighted how they might potentially influence climate governance by defining environmental problems, elaborating consequences and outlining potential solutions. Narratives thereby strongly affect how climate policy options are perceived, communicated and legitimated. Based on a literature review of scientific articles and a complementary secondary analysis of expert interviews with German eNGOs, we find narratives that frame NETs as either a matter of necessity or a moral hazard to be most prominent in our exploratory analysis. Consequently, we focused on understanding their respective foundations, complexities, and overlaps. The IPCC is a highly important reference for these narratives, either as legitimation or as point of contention. Our results indicate that the increasingly open and explicit discussion of NETs in IPCC reports results in controversy among eNGOs that struggle to position themselves toward IPCC assessments, especially when advocating against the use of NETs. We analyzed how this spectrum of narratives links to climate policy discourses (Bäckstrand and Lövbrand, 2019). While we find that the narratives can be viewed as materializations of ecological modernization or civic environmentalism, we also see that the dividing lines between climate policy discourses blur when the role of NETs in climate change mitigation is concerned. Mapping further narratives on NETs and the visions of desirable climate futures that accompany them remains a task for future research with a broader empirical basis.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because due to privacy and ethical concerns, neither the data nor the source of the data can be made available. Requests to access the datasets should be directed to danny.otto@ufz.de.

AUTHOR CONTRIBUTIONS

DO, TT, FW, and SB contributed to conception and design of the study. DO and FW organized and conducted the expert interviews and performed the qualitative content analysis. TT did the literature review. DO wrote the first draft of the manuscript. TT and SB wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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REFERENCES

Abbott, H. P. (2008). *The Cambridge Introduction to Narrative*. *2nd ed*. Cambridge, New York, NY: Cambridge University Press.

Aengenheyster, M., Feng, Q. Y., van der Ploeg, F., and Dijkstra, H. A. (2018). The point of no return for climate action: effects of climate uncertainty and risk tolerance. *Earth Syst. Dyn.* 9, 1085–1095. doi: 10.5194/esd-9-1085-2018

Amerian, M., and Jofi, L. (2015). Key concepts and basic notes on narratology and narrative. *Sci. J. Rev.* 4, 182–192. doi: 10.14196/sjr.v4i10.1927

Anderson, K., Broderick, J. F., and Stoddard, I. (2020). A factor of two: how the mitigation plans of 'climate progressive' nations fall far short of Paris-compliant pathways. *Clim. Policy* 20, 1290–1304. doi: 10.1080/14693062.2020.1728209

Andersson, J., and Westholm, E. (2019). Closing the future: environmental research and the management of conflicting future value orders. *Sci. Technol. Hum. Values* 44, 237–262. doi: 10.1177/0162243918791263

Asayama, S., and Hulme, M. (2019). Engineering climate debt: temperature overshoot and peak-shaving as risky subprime mortgage lending. *Clim. Policy* 19, 937–946. doi: 10.1080/14693062.2019.1623165

Bäckstrand, K., and Lövbrand, E. (2006). Planting trees to mitigate climate change: contested discourses of ecological modernization, green governmentality and civic environmentalism. *Glob. Environ. Polit.* 6, 50–75. doi: 10.1162/152638006775991911

Bäckstrand, K., and Lövbrand, E. (2019). The road to paris: contending climate governance discourses in the post-copenhagen era. *J. Environ. Policy Plan.* 21, 519–532. doi: 10.1080/1523908X.2016.1150777

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., and Fischedick, M., Lechtenböhmer, S., et al. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *J. Clean. Prod.* 187, 960–973. doi: 10.1016/j.jclepro.2018.03.107

Beck, S., Jasanoff, S., Stirling, A., and Polzin, C. (2021). The governance of sociotechnical transformations to sustainability. *Curr. Opin. Environ. Sustain.* 49, 143–152. doi: 10.1016/j.cosust.2021.04.010

Beck, S., and Mahony, M. (2017). The IPCC and the politics of anticipation. *Nat. Clim. Change* 7, 311–313. doi: 10.1038/nclimate3264

Beck, S., and Mahony, M. (2018). The politics of anticipation: the IPCC and the negative emissions technologies experience. *Glob. Sustain.* 1:e8. doi: 10.1017/sus.2018.7

Beck, S., and Oomen, J. (2021). Imagining the corridor of climate mitigation ? what is at stake in IPCC's politics of anticipation? *Environ. Sci. Policy* 123, 169–178.

Bellamy, R., and Healey, P. (2018). 'Slippery slope' or 'uphill struggle'? Broadening out expert scenarios of climate engineering research and development. *Environ. Sci. Policy* 83, 1–10. doi: 10.1016/j.envsci.2018.01.021

Bellamy, R., and Osaka, S. (2020). Unnatural climate solutions? *Nat. Clim. Change* 10, 98–99. doi: 10.1038/s41558-019-0661-z

Berg, M., and Lidskog, R. (2018). Pathways to deliberative capacity: the role of the IPCC. *Clim. Change* 148, 11–24. doi: 10.1007/s10584-018-2180-8

Bertram, C., and Merk, C. (2020). Public perceptions of ocean-based carbon dioxide removal: the nature-engineering divide? *Front. Clim.* 2:594194. doi: 10.3389/fclim.2020.594194

Biermann, F., and Möller, I. (2019). Rich man's solution? Climate engineering discourses and the marginalization of the Global South. *Int. Environ. Agreem. Polit. Law Econ.* 19, 151–167. doi: 10.1007/s10784-019-09431-0

Boysen, L. R., Lucht, W., Gerten, D., Heck, V., Lenton, T. M., and Schellnhuber, H. J. (2017). The limits to global-warming mitigation by terrestrial carbon removal. *Earths Fut.* 5, 463–474. doi: 10.1002/2016EF000469

Brack, D., and King, R. (2020). Managing land-based CDR: BECCS, forests and carbon sequestration: managing land-based CDR. *Glob. Policy*. 12, 45–56. doi: 10.1111/1758-5899.12827

Bremer, S., Blanchard, A., Mamnun, N., Stiller-Reeve, M., Haque M. M., and Tvinnereim, E. (2017). Narrative as a method for eliciting tacit knowledge of climate variability in Bangladesh. *Weather Clim. Soc.* 9, 669–686. doi: 10.1175/WCAS-D-17-0007.1

Butnar, I., Broad, O., Rodriguez, B. S., and Dodds, P. E. (2020). The role of bioenergy for global deep decarbonization: CO_2 removal or low-carbon energy? *GCB Bioenergy* 12, 198–212. doi: 10.1111/gcbb.12666

Carton, W. (2019). "Fixing" climate change by mortgaging the future: negative emissions, spatiotemporal fixes, and the political economy of delay. *Antipode* 51, 750–769. doi: 10.1111/anti.12532

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *WIREs Clim. Change*. 11:e671. doi: 10.1002/wcc.671

Castree, N. (2020). The discourse and reality of carbon dioxide removal: toward the responsible use of metaphors in post-normal times. *Front. Clim.* 2:614014. doi: 10.3389/fclim.2020.614014

Chilvers, J., Bellamy, R., Pallett, H., and Hargreaves, T. (2021). A systemic approach to mapping participation with energy transitions. *Nat. Energy* 6, 250–259. doi: 10.1038/s41560-020-00762-w

Cobley, P. (2014). *Narrative*. *Second edition*. London, New York: Routledge, Taylor and Francis Group

Corry, O., and Reiner, D. (2020). Protests and policies: how radical social movement activists engage with climate policy dilemmas. *Sociology* 55, 197–217. doi: 10.1177/0038038520943107

Corry, O., and Riesch, H. (2012). "Beyond 'for or against'. Environmental NGO-evaluations of CCS as a climate change solution," in *The Social Dynamics of Carbon Capture and Storage. Understanding CCS Representations, Governance and Innovation*, eds. N. Markusson, S. Shackley, and B. Evar (London; New York: Routledge, Taylor and Francis Group), 91–108

Daggash, H. A., and Mac Dowell, N. (2019). Higher carbon prices on emissions alone will not deliver the Paris agreement. *Joule* 3, 2120–2133. doi: 10.1016/j.joule.2019.08.008

Deutscher Naturschutz Ring (2020). *Von Worten zu Taten: Für ein Paris-kompatibles EU-Klimaschutzgesetz*. Available online at: https://www.dnr.de/fileadmin/Positionen/2020-05-05-EU-Klimaschutzgesetz-Verbaendeposition.pdf (accessed February 21, 2021).

Dimbath, O., Ernst-Heidenreich, M., and Roche, M. (2018). The practice and theory of theoretical sampling. Methodological considerations on the progression of sampling decisions. *Forum Qual. Sozialforschung Forum Qual. Soc. Res.* 19:26. doi: 10.17169/fqs-19.3.2810

Doelman, J. C., Stehfest, E., Tabeau, A., and van Meijl, H. (2019). Making the Paris agreement climate targets consistent with food security objectives. *Glob. Food Secur.* 23, 93–103. doi: 10.1016/j.gfs.2019.04.003

Donnison, C., Holland, R. A., Hastings, A., Armstrong, L.-M., Eigenbrod, F., and Taylor, G. (2020). Bioenergy with Carbon Capture and Storage (BECCS): finding the win-wins for energy, negative emissions and ecosystem services—size matters. *GCB Bioenergy* 12, 586–604. doi: 10.1111/gcbb.12695

Dütschke, E., Wohlfarth, K., Höller, S., Viebahn, P., Schumann, D., and Pietzner, K. (2016). Differences in the public perception of CCS in Germany depending on CO_2 source, transport option and storage location. *Int. J. Greenh. Gas Control* 53, 149–159. doi: 10.1016/j.ijggc.2016.07.043

Fajardy, M., Patrizio, P., Daggash, H. A., and Mac Dowell, N. (2019). Negative emissions: priorities for research and policy design. *Front. Clim.* 1:6. doi: 10.3389/fclim.2019.00006

Federal Law Gazette (2012). *Gesetz zur Demonstration und Anwendung von Technologien zur Abscheidung, zum Transport und zur dauerhaften Speicherung von Kohlendioxid. Bundesgesetzblatt Nr.* 38

Federal Law Gazette (2019). *Gesetz zur Einführung eines Bundes-Klimaschutzgesetzes und zur Änderung weiterer Vorschriften*.

Felt, U., Wynne, B., Callon, M., Goncalves, M. E., Jasanoff, S., Jepsen, M., et al. (2007). *Taking European knowledge society seriously: report of the Expert Group on Science and Governance to the Science, Economy and Society Directorate, Directorate-General for Research, European Commission*. Luxembourg: Off. for Official Publ. of the European Communities.

Fernandez, M. A., and Daigneault, A. J. (2020). A double win: new pathways to reduce greenhouse gas emissions and improve water quality in New Zealand. *Environ. Res. Lett.* 15:074004. doi: 10.1088/1748-9326/ab8255

Fischer, W. (2015). "No CCS in Germany despite the CCS act?," in *Carbon Capture, Storage and Use: Technical, Economic, Environmental and Societal Perspectives* (Berlin: Springer International Publishing), 255–286. doi: 10.1007/978-3-319-11943-4_12

Foljanty-Jost, G. (2005). NGOs in environmental networks in Germany and Japan: the question of power and influence. *Soc. Sci. Jpn. J.* 8, 103–117. doi: 10.1093/ssjj/jyi019

Forster, J., Vaughan, N. E., Gough, C., Lorenzoni, I., and Chilvers, J. (2020). Mapping feasibilities of greenhouse gas removal: Key issues, gaps and opening up assessments. *Glob. Environ. Change* 63:102073. doi: 10.1016/j.gloenvcha.2020.102073

Fujimori, S., Hasegawa, T., Rogelj, J., Su, X., Havlik, P., Krey, V., et al. (2018). Inclusive climate change mitigation and food security policy under 1.5°C climate goal. *Environ. Res. Lett.* 13:074033. doi: 10.1088/1748-9326/aad0f7

Geden, O., Scott, V., and Palmer, J. (2018). Integrating carbon dioxide removal into EU climate policy: prospects for a paradigm shift. *WIREs Clim. Change* 9:e521. doi: 10.1002/wcc.521

Glaser, B. G., and Strauss, A. L. (1970). "Theoretical sampling," in *Sociological Methods. A Sourcebook*, ed. N. K. Denzin (Chicago, IL: Aldine), 105–114

Grigoroudis, E., Kanellos, F., Kouikoglou, V. S., and Phillis, Y. A. (2017). The challenge of the Paris agreement to contain climate change. *Intell. Autom. Soft Comput.*, 1–12. doi: 10.1080/10798587.2017.1292716

Haikola, S., Hansson, A., and Anshelm, J. (2019). From polarization to reluctant acceptance–bioenergy with carbon capture and storage (BECCS) and the post-normalization of the climate debate. *J. Integr. Environ. Sci.* 16, 45–69. doi: 10.1080/1943815X.2019.1579740

Hajer, M. A. (1995). *The Politics of Environmental Discourse: Ecological Modernization and the Policy Process*. Oxford, New York: Clarendon Press, Oxford University Press

Hajer, M. A., and Pelzer, P. (2018). 2050—An energetic Odyssey: understanding 'Techniques of Futuring' in the transition towards renewable energy. *Energy Res. Soc. Sci.* 44, 222–231. doi: 10.1016/j.erss.2018.01.013

Harwatt, H. (2019). Including animal to plant protein shifts in climate change mitigation policy: a proposed three-step strategy. *Clim. Policy* 19, 533–541. doi: 10.1080/14693062.2018.1528965

Herr, D., Unger, M., Laffoley, D., and McGivern, A. (2017). Pathways for implementation of blue carbon initiatives. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 27, 116–129. doi: 10.1002/aqc.2793

Holz, C., Siegel, L. S., Johnston, E., Jones, A. P., and Sterman, J. (2018). Ratcheting ambition to limit warming to 1.5°C–trade-offs between emission reductions and carbon dioxide removal. *Environ. Res. Lett.* 13, 064028. doi: 10.1088/1748-9326/aac0c1

Honegger, M., Michaelowa, A., and Roy, J. (2020). Potential implications of carbon dioxide removal for the sustainable development goals. *Clim. Policy* 21, 678–698. doi: 10.1080/14693062.2020.1843388

Honegger, M., and Reiner, D. (2018). The political economy of negative emissions technologies: consequences for international policy design. *Clim. Policy* 18, 306–321. doi: 10.1080/14693062.2017.1413322

Hulme, M. (2008). The conquering of climate: discourses of fear and their dissolution. *Geogr. J.* 174, 5–16. doi: 10.1111/j.1475-4959.2008.00266.x

IPCC (2000a). *Land Use, Land-Use Change, and Forestry: Summary for Policymakers: a Special Report of the Intergovernmental Panel on Climate Change*. Geneva: WMO (World Meteorological Organization): UNEP (United Nations Environment Programme).

IPCC (2018). *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Geneva: Intergovernmental Panel on Climate Change.

IPCC (ed.) (1990). *Climate Change: the IPCC Scientific Assessment*. Cambridge; New York: Cambridge University Press.

IPCC (ed.) (2000b). *Special Report on Emissions Scenarios: a Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge; New York: Cambridge University Press.

IPCC (ed.) (2014). *Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York, NY: Cambridge University Press.

Jackson, M. (2015). Glaciers and climate change: narratives of ruined futures. *WIREs Clim. Change* 6, 479–492. doi: 10.1002/wcc.351

Jasanoff, S. (2004). *States of Knowledge the Co-production of Science and Social Order*. Available online at: https://www.taylorfrancis.com/books/9780203413845 (accessed February 23, 2021).

Jones, M. B., and Albanito, F. (2020). Can biomass supply meet the demands of bioenergy with carbon capture and storage (BECCS)? *Glob. Change Biol.* 26, 5358–5364. doi: 10.1111/gcb.15296

Krämer, L. (2018). "Germany: a country without CCS," in *Carbon Capture and Storage. Emerging Legal and Regulatory Issues*, eds. I. Havercroft, R. Macrory, and R. Stewart (Oxford/Portland, Oregon: Hart Publishing), 59–74.

Krauß, W., and Bremer, S. (2020). The role of place-based narratives of change in climate risk governance. *Clim. Risk Manag.* 28:100221. doi: 10.1016/j.crm.2020.100221

Larkin, A., Kuriakose, J., Sharmina, M., and Anderson, K. (2018). What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. *Clim. Policy* 18, 690–714. doi: 10.1080/14693062.2017.1346498

Latour, B. (2004). Why has critique run out of steam? From matters of fact to matters of concern. *Crit. Inq.* 30, 225–248. doi: 10.1086/421123

Latour, B. (2005). *Reassembling the Social: an Introduction to Actor-Network-Theory*. Oxford; New York: Oxford University Press.

Lawrence, M. G., Schäfer, S., Muri, H., Scott, V., Oschlies, A., Vaughan, N. E., et al. (2018). Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals. *Nat. Commun.* 9:3734. doi: 10.1038/s41467-018-05938-3

Leach, M., Scoones, I., and Stirling, A. (2010). Governing epidemics in an age of complexity: Narratives, politics and pathways to sustainability. *Glob. Environ. Change* 20, 369–377. doi: 10.1016/j.gloenvcha.2009.11.008

Lin, A. (2018). *Carbon Dioxide Removal After Paris*. Rochester, NY: Social Science Research Network. Available online at: https://papers.ssrn.com/abstract=3152076 (accessed June 25, 2021).

Linnér, B.-O., and Wibeck, V. (2020). Conceptualising variations in societal transformations towards sustainability. *Environ. Sci. Policy* 106, 221–227. doi: 10.1016/j.envsci.2020.01.007

Longhurst, N., and Chilvers, J. (2019). Mapping diverse visions of energy transitions: co-producing sociotechnical imaginaries. *Sustain. Sci.* 14, 973–990. doi: 10.1007/s11625-019-00702-y

Low, S., and Boettcher, M. (2020). Delaying decarbonization: climate governmentalities and sociotechnical strategies from Copenhagen to Paris. *Earth Syst. Gov.* 5:100073. doi: 10.1016/j.esg.2020.100073

Low, S., and Honegger, M. (2020). A precautionary assessment of systemic projections and promises from sunlight reflection and carbon removal modeling. *Risk Anal.* 2020:risa.13565. doi: 10.1111/risa.13565

Low, S., and Schäfer, S. (2020). Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling. *Energy Res. Soc. Sci.* 60:101326. doi: 10.1016/j.erss.2019.101326

Marcucci, A., Kypreos, S., and Panos, E. (2017). The road to achieving the long-term Paris targets: energy transition and the role of direct air capture. *Clim. Change* 144, 181–193. doi: 10.1007/s10584-017-2051-8

Markusson, N., Balta-Ozkan, N., Chilvers, J., Healey, P., Reiner, D., and McLaren, D. (2020). Social Science Sequestered. *Front. Clim.* 2, 1–6. doi: 10.3389/fclim.2020.00002

McLaren, D. (2020). Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. *Clim. Change.* doi: 10.1007/s10584-020-02732-3

Minx, J. C., Callaghan, M., Lamb, W. F., Garard, J., and Edenhofer, O. (2017). Learning about climate change solutions in the IPCC and beyond. *Environ. Sci. Policy* 77, 252–259. doi: 10.1016/j.envsci.2017.05.014

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environ. Res. Lett.* 13:063001. doi: 10.1088/1748-9326/aabf9b

Mundaca, L., Ürge-Vorsatz, D., and Wilson, C. (2019). Demand-side approaches for limiting global warming to 1.5°C. *Energy Effic.* 12, 343–362. doi: 10.1007/s12053-018-9722-9

Needelman, B. A., Emmer, I. M., Oreska, M. P. J., and Megonigal, J. P. (2019). "Blue Carbon Accounting for Carbon Markets," in *A Blue Carbon Primer: The State of Coastal Wetland Carbon Science, Practice*, eds. L. Windham-Myers, S. Crooks, and T. G. Troxle, 283–293.

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., et al. (2018). Negative emissions—Part 3: Innovation and upscaling. *Environ. Res. Lett.* 13:063003. doi: 10.1088/1748-9326/aabff4

Oomen, J., Hoffman, J., and Hajer, M. A. (2021). Techniques of futuring: on how imagined futures become socially performative. *Eur. J. Soc. Theory* 1368431020988826. doi: 10.1177/1368431020988826

Pascoe, S., Brincat, S., and Croucher, A. (2019). The discourses of climate change science: scientific reporting, climate negotiations and the case of Papua New Guinea. *Glob. Environ. Change* 54, 78–87. doi: 10.1016/j.gloenvcha.2018.11.010

Paterson, M. (2020). 'The end of the fossil fuel age'? discourse politics and climate change political economy. *New Polit. Econ.* 2020:1–14. doi: 10.1080/13563467.2020.1810218

Prognos, Öko-Institut and Wuppertal Institut für Klima Umwelt Energie (2020). *Towards a Climate-Neutral Germany: Three Steps for Achieving Climate Neutrality by 2050 and an Intermediate Target of—65% in 2030 as Part of the EU Green Deal*. Available online at: https://static.agora-energiewende.de/fileadmin/Projekte/2020/2020_10_KNDE/A-EW_193_KNDE_Executive-Summary_EN_WEB_V111.pdf (accessed May 4, 2021).

Rickels, W., Merk, C., Reith, F., Keller, D. P., and Oschlies, A. (2019). (Mis)conceptions about modeling of negative emissions technologies. *Environ. Res. Lett.* 14:104004. doi: 10.1088/1748-9326/ab3ab4

Roe, E. M. (1991). Development narratives, or making the best of blueprint development. *World Dev.* 19, 287–300. doi: 10.1016/0305-750X(91)90177-J

Rogelj, J., Shindell, D. T., Jiang, K., Fifita, S., Ginzburg, V., Handa, C., et al. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. *Glob. Warm. 15°C IPCC Spec. Rep. Impacts Glob. Warm. 15°C Pre-Ind. Levels Relat. Glob. Greenh. Gas Emiss. Pathw. Context Strength. Glob. Response Threat Clim. Change Sustain. Dev. Efforts Eradicate Poverty*. Available online at: https://paper/Mitigation-pathways-compatible-with-1.5%C2%B0C-in-the-of-Rogelj-Shindell/4d222655d8f9cc642dafdceb3ddae9633b989765 (accessed March 16, 2021).

Schenuit, F., Colvin, R., Fridahl, M., McMullin, B., Reisinger, A., Sanchez, D. L., et al. (2021). Carbon dioxide removal policy in the making: assessing developments in 9 OECD cases. *Front. Clim.* 3:638805. doi: 10.3389/fclim.2021.638805

Schreier, M. (2012). *Qualitative Content Analysis in Practice*. Los Angeles: SAGE.

Shue, H. (2018). Mitigation gambles: uncertainty, urgency and the last gamble possible. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* 376:20170105. doi: 10.1098/rsta.2017.0105

Stavrakas, V., Spyridaki, N.-A., and Flamos, A. (2018). Striving towards the deployment of bio-energy with carbon capture and storage (BECCS): a review of research priorities and assessment needs. *Sustainability* 10:2206. doi: 10.3390/su10072206

Sutton-Grier, A. E., and Moore, A. (2016). Leveraging carbon services of coastal ecosystems for habitat protection and restoration. *Coast. Manag.* 44, 259–277. doi: 10.1080/08920753.2016.1160206

Thoni, T., Beck, S., Borchers, M., Förster, J., Görl, K., Hahn, A., et al. (2020). Deployment of negative emissions technologies at the national level: a need for holistic feasibility assessments. *Front. Clim.* 2:590305. doi: 10.3389/fclim.2020.590305

Ueckerdt, F., Frieler, K., Lange, S., Wenz, L., Luderer, G., and Levermann, A. (2019). The economically optimal warming limit of the planet. *Earth Syst. Dyn.* 10, 741–763. doi: 10.5194/esd-10-741-2019

UNFCCC (2021). *Admitted NGOs*. Available online at: https://unfccc.int/process/parties-non-party-stakeholders/non-party-stakeholders/admitted-ngos/list-of-admitted-ngos (accessed March 16, 2021).

United Nations (1992). *United Nations Framework Convention on Climate Change.* UNFCCC. Available online at: https://unfccc.int/process-and-meetings/the-convention/history-of-the-convention/convention-documents (accessed May 4, 2021).

United Nations (2015). *Paris Agreement*. Available online at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed June 1, 2021).

Urhammer, E., and Røpke, I. (2013). Macroeconomic narratives in a world of crises: an analysis of stories about solving the system crisis. *Ecol. Econ.* 96, 62–70. doi: 10.1016/j.ecolecon.2013.10.002

van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D., and Cassen, C. (2020). Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970. *Glob. Environ. Change* 65:102191. doi: 10.1016/j.gloenvcha.2020.102191

Vaughan, N. E., Gough, C., Mander, S., Littleton, E. W., Welfle, A., Gernaat, D., et al. (2018). Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios. *Environ. Res. Lett.* 13:044014. doi: 10.1088/1748-9326/aaaa02

Wachsmuth, J., and Duscha, V. (2019). Achievability of the Paris targets in the EU—the role of demand-side-driven mitigation in different types of scenarios. *Energy Effic.* 12, 403–421. doi: 10.1007/s12053-018-9670-4

Waller, L., Rayner, T., Chilvers, J., Gough, C. A., Lorenzoni, I., Jordan, A., et al. (2020). Contested framings of greenhouse gas removal and its feasibility: social and political dimensions. *WIREs Clim. Change* 11:e649. doi: 10.1002/wcc.649

Whatmore, S. J. (2009). Mapping knowledge controversies: science, democracy and the redistribution of expertise. *Prog. Hum. Geogr.* 33, 587–598. doi: 10.1177/0309132509339841

Wieding, J., Stubenrauch, J., and Ekardt, F. (2020). Human rights and precautionary principle: limits to geoengineering, SRM, and IPCC scenarios. *Sustainability* 12:8858. doi: 10.3390/su12218858

Woroniecki, S., Wendo, H., Brink, E., Islar, M., Krause, T., Vargas, A.-M., et al. (2020). Nature unsettled: How knowledge and power shape 'nature-based' approaches to societal challenges. *Glob. Environ. Change* 65:102132. doi: 10.1016/j.gloenvcha.2020.102132

Wuppertal Institut für Klima, Umwelt, Energie (2018). *Strategien für eine naturverträgliche Energiewende*. Available online at: https://www.nabu.de/imperia/md/content/nabude/energie/190514_strategien_energiewende_nabu.pdf.

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Permission to Say "Capitalism": Principles for Critical Social Science Engagement With GGR Research

Stephen Hall[1]* *and Mark Davis*[2]

[1] School of Earth and Environment, University of Leeds, Leeds, United Kingdom, [2] School of Sociology and Social Policy, University of Leeds, Leeds, United Kingdom

The grand scale of GGR deployment now necessary to avoid dangerous climate change warrants the use of grand interpretive theories of how the global economy operates. We argue that critical social science should be able to name the global economy as "capitalism"; and instead of speaking about "transforming the global economy" as a necessary precondition for limiting climate change, instead speak about transforming, or even transcending, *capitalism*. We propose three principles are helpful for critical social science researchers willing to name and analyse the structural features of capitalism and their relation to greenhouse gas removal technology, policy, and governance. These principles are: (1) *Greenhouse Gas Removal technologies are likely to emerge within capitalism, which is crisis prone, growth dependent, market expanding,* We use a broad Marxist corpus to justify this principle. (2) *There are different varieties of capitalism and this will affect the feasibility of different GGR policies and supports in different nations.* We draw on varieties of capitalism and comparative political economy literature to justify this principle. (3) *Capitalism is more than an economic system, it is ideologically and culturally maintained.* Globally-significant issues such as fundamentalism, institutional mistrust, precarity, and populism, cannot be divorced from our thinking about globally significant deployment of greenhouse gas removal technologies. We use a broad Critical Theory body of work to explore the ideational project of maintaining capitalism and its relation to GGR governance and policy.

Keywords: capitalism—varieties of, critical political economy, negative emission technologies, greenhouse gas removal, critical theory

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Correspondence:
Stephen Hall
s.hall@leeds.ac.uk

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INTRODUCTION

In a recent analysis of limiting global mean temperature increase below 1.5°C, Rogelj et al. (2018) find that all scenarios "achieving pronounced emission reductions require a transformation of the *global economy*." We agree that greenhouse gas emissions mitigation and emissions removals of the scale required to limit climate change to 1.5°C requires a "transformation of the global economy," but we also find a substantial lack of critical engagement from the humanities and social sciences (HASS) in what this *"global economy"* actually is, what assumptions we are making when we engage with more "instrumental" GGR research (Castree et al., 2014; Markusson et al., 2020), and how "we" as critical scholars can both maintain a healthy critical appraisal of the development of GGR in this global economy, while not disappearing from the debate because we question some of its founding premises. As Rose et al. (2012, p. 3) argue "The environmental humanities is necessarily [...] an effort to inhabit a *difficult space* of simultaneous critique and action." Perhaps the fastest route into this "difficult space" is to name and analyse the *global economy* as "Capitalism."

Approaching the global economy as "Capitalism" is a bold move. It detaches the discussion from a generalized term ("the global economy") and allows us to analyse a specific mode of production, as well as the cultural, social, and ecological relations that come along with it. In much of the world GGR will likely not emerge in feudalism, theocracy, socialism, or communism. Notwithstanding a revolution, it will emerge in capitalism. The "difficult space" we enter when we "say capitalism" is summarized by Žižek (2008). This difficult space exists because:

> *"liberal-democratic capitalism is accepted as the finally-found formula of the best possible society; all one can do is to render it more just, tolerant, etc. The only true question today is: do we endorse this "naturalization" of capitalism, or does today's global capitalism contain strong enough antagonisms that will prevent its indefinite reproduction?"* (Žižek, 2008, p. 37–38).

The tension is a real concern in calling for more critical engagement with GGR research, because this means there are two pathways for individual scholars. First, one accepts, or at the very least tolerates and works with, this naturalization of capitalism (see Jacobs and Mazzucato, 2016). One then goes on to apply a critical HASS lens to discrete elements of the problem at hand, such as securing public acceptance, securing state innovation resources, and/or rendering climate policies more just (Lamb et al., 2020). Here, social science has the primary role of mediating between policy, technology, and "the public" (Bellamy and Healey, 2018; Forster et al., 2020). New cultural and constructivist approaches are also emerging that explore the diverse publics and discourse surrounding GGR technologies, exposing the contested and multiple discourses, and framings of experts and/or publics and their perspectives on GGR technologies (Rose et al., 2012, Dowd et al., 2015; Lenzi et al., 2018; Waller et al., 2020).

Waller et al. (2020) identify three framings we can use to distinguish the different positions adopted by HASS researchers exploring the social and political dimensions of greenhouse gas removal: (1) a techno-economic framing; (2) a social and political acceptability framing; and (3) a responsible development framing. Both "techno-economic" and "social and political" framings are compatible with HASS researchers following the first path, naturalizing these studies within capitalism, albeit for many, with a specific aim of changing capitalism's course, rendering it more just or ecologically reproducible. Only in the "responsible development" framing do Waller et al., detect opportunities for challenging existing social orders, although Waller et al., leave these "social orders" undefined[1].

Cox et al. (2020a) explore a range of perceptions of risk and desirability of GGR technologies. They find that, for some, a barrier to acceptance of GGR technologies, is how they serve to perpetuate the current societal order, that is how GGR technologies justify a "non-transition" to a sustainable future society. In another contribution, Cox et al. (2020b, p. 211) re-interpret this dataset to infer that the "non-transitions" mean, in fact, a transition from "incumbent *capitalist* systems." For our analysis, we draw a line between those contributions that allude to some form of broader social order, and those that name *capitalism* as that social order.

To name capitalism in GGR research is to echo Žižek (2008) by not endorsing capitalism by omission, but to tackle what it means to grow the GGR "sector" within this specific mode of production. This second pathway, "saying capitalism" does not need to end in a rejection of capitalism *in toto*. It means exploring its structural contours, the social, and cultural features of capitalism that affect our study of the greenhouse gas removal field. It should lead us to take our own position on what role GGR plays in reproducing capitalism, and whether or not this is desirable. ŽiŽek has already drawn the conclusion that capitalism's relation to nature is one of four antagonisms strong enough to warrant a search for a new social order, a new means of production (Žižek, 2017). Humanities and social sciences researchers in GGR may or may not reach this conclusion, but to date there has been very little debate or scholarship to guide that journey despite some recent work beginning to make progress.

For example, Markusson et al. (2017, 2018) adopt an explicit cultural political economy analysis of carbon capture and storage (Markusson et al., 2017) and negative emission technologies (Markusson et al., 2018). In the CCS research (Markusson et al., 2017), they find that neoliberal political economies utilize CCS as a legitimating socio-temporal *"fix"* to the tensions between fossil capitalism and nature. CCS is found to be also a key discursive element in legitimating neoliberal political economics. In the Negative Emissions piece, Markusson et al. (2018) deploy the same analytical register, a "cultural political economy" to identify neoliberalism as a somewhat hegemonic cultural political economy, which is *invisible* to instrumental, managerial, realist social science. Similarly, whilst cultural and constructivist approaches invite us to explore more contested framings, they rarely name and analyse those framings within a dominant capitalist political economy.

In describing greenhouse gas removal technologies as a possible "spatio-temporal fix," Markusson et al. (2017, 2018) introduce a key term familiar to critical geographers but to date somewhat absent from the GGR debate. A "fix" is a way to maintain existing capital accumulation regimes using institutional and technological innovation, often by mobilizing state power (Jessop, 2006). Markusson et al. (2018) predominant concern, is the legitimization of mitigation deterrence at a policy level. They argue that moving to a cultural political economy register allows us to see and to critique how carbon capture and storage and greenhouse gas removal technologies can "fix" the problems climate change poses for capitalism by resolving the conflict between economic growth and emissions from hard to decarbonize sectors.

Within Markusson et al. (2017, 2018) contributions we see the beginning of a rich and productive debate. Within HASS scholarship and across the GGR community more broadly,

[1]Let us be clear this is not an accusation of "omitting" capitalism, there is more than one term that can pass for a social order.

however, we note a particular dearth of anchoring concepts or principles by which to conduct [cultural] political economy analysis. Why does capitalism need "fixing?" What are the structural features of capitalism which create the need for fixing and maintenance? Why do we persist with a system with such well-documented flaws? We intervene here to suggest some of these anchoring concepts and to explore what it means to see capitalism as in need of *both material and ideational* maintenance (Markusson et al.). In what follows, we explore where the need for "material" maintenance of capitalism, namely its interlinked tendencies toward crises, growth dependency, and market expansion.

THE MATERIAL MAINTENANCE OF CONTEMPORARY CAPITALISM

Materially maintaining capitalism means explicitly creating institutions, policies, regulations, or strategies to deal with the economic problems capitalism creates for itself. The three main problems we submit for analysis are intertwined and form Principle 1*;*

> *"Greenhouse Gas Removal technologies are likely to emerge within capitalism, which is crisis prone, growth dependent, market expanding."*

CAPITALISM AS CRISIS PRONE

Capitalism is crisis prone. Deep and "unpredictable" recessions occur where capital is not invested, unemployment mushrooms and productivity dramatically reduces. The need to "fix" capitalism, materially to maintain it, arises because capitalism is riven with contradictions and tensions that produce these crises (Harvey, 2017). The most obvious examples are the "Great Depression" of the 1930's and the recent 2008 Global Financial Crisis, though many more exist (Harvey, 2010). While it is clearly the case that economies often enter crises, dominant economic theory, namely the neo-classical school (Earle et al., 2016), at least until 2008 did not pay much attention to the systemic risk of crises. Instead, economists viewed the history of economic crises as a result of government intervention in otherwise perfect markets, or as generated by some exogenous interference in markets for capital, labor, and commodities that, if left to themselves, would stabilize over time (Bonizzi and Powell, 2020).

Beyond the neo-classical school, Marxist and Keynesian approaches instead argue that crises are inherent features of capitalism, with Keynesians arguing that periodic crises of capitalism are a result of mismatched periods of under-consumption (low effective demand) and under-investment (Bonizzi and Powell, 2020). Marxist analyses, notably Sweezy (1942), argue that crises are hardwired into the nature of capitalism, driven by its tendency to expand and speed up its capacity to produce consumer goods faster than the ability of consumers to purchase those goods. Both of these analyses center on the demand side or "consumption." Conversely, Marxist analysis also argues that crises can arise in the supply side of the economy, where the rate of profit reduces as competition in a sector intensifies. This eventually leads to an investment strike, as productive returns on further capital investment become difficult to find (Harvey, 2017). Marxist scholars also link the 2008 crisis to financial deregulation and easing of credit conditions, which was designed to allow wages to fall as output and associated consumption continued to increase. This indiscriminate extension of credit to cover consumer expenditures (particularly mortgages) was a "fix," which only postponed an inevitable crisis as wages stagnated while the productive capacity of economies continued to grow (Giacché, 2011; Shaikh, 2016).

Marxist analysis therefore sees crises as purgative, inevitable, even *necessary* events that resolve the pressure that builds up as a result of the contradictions inherent within capital accumulation. Indeed, it is these crises that make space for further rounds of productive investment (Harvey, 2014; also Schumpeter, 1934). The move to a Marxist or Keynesian approach, then, accepts crises as inherent to capitalism and, instead of blaming the state as the cause of crises, recommend either state intervention *a la* Keynes, or following a Marxist tradition, explore how state intervention serves to regulate and reproduce capitalism (Jessop and Sum, 2006) often moving contradictions and crises around in time and space (Harvey, 2010).

The key insight for HASS scholars working on GGR is what this means for public policy and the role of the state at different levels. Humanities and social sciences scholars can build upon Marx and, particularly through Harvey (2010, 2014), analyse the state as a necessary manager of these crises. They may explore how this management drives the state to enable spatio-temporal "fixes" that manage, at least for some time, the crisis-tendencies inherent in accumulation (Jessop, 2006, p.146).

One such fix is a "switch" of capital from the circuits of production and consumption into other "circuits" of capital, such as large urban or infrastructural projects. Here, the stated objectives of urban projects are often secondary to the primary imperative of finding *something* for capital to invest in. Critical urban scholars have found the spatio-temporal fix argument extremely powerful in understanding the "real" drivers behind urban projects, uncovering the causal factors and power coalitions that emerge to secure such "fixes" and to explain why urban projects are successful if they achieve this objective, as opposed to any number of the local socio-economic improvements the projects promise to deliver (Apostolopoulou, 2021). Harvey's thesis is that urbanization or infrastructure investment is a particularly useful spatio-temporal fix, yet Markusson et al. and others (Carton, 2019) note climate policy and climate-facing investments can act as a "*Socio-ecological* fix" for the other contradictions of capitalism, namely relations to nature (also Ekers and Prudham, 2018).

There are two critical elements here that inform HASS GGR research. The first is that crises are not exogenous shocks that nobody can predict, but inherent features of capitalism that drive the state, as the regulating agent of capitalism, to enable spatio-temporal or socio-ecological fixes. Second, these climate policies are only legitimate in the eyes of state actors *if* they temporarily resolve crises. This resolution leads many to argue that this fix, be it material (i.e., the actual deployment of negative emissions) or discursive (i.e., the inclusion of negative emissions) in IPCC scenarios and models (see Carton, 2019) is temporal, in that it delays and dilutes the urgency of mitigation measures whilst at the same time legitimizing the continuation of fossil capitalism in the same way geo-engineering has served to do (Sapinski et al., 2020).

Seeing the state as key to the construction of both spatio-temporal and socio-ecological fixes is important because it gives us access to the real motivation behind so much climate policy. We can also use the notion of the socio-ecological fix *and* the spatial-temporal fix to question individual types of GGR deployment, to "see" proposals such as Zero Carbon Humber[2] and the Northern Forest[3] (to take two examples proximate to the authors) not as the result of an optimal decision for GGR deployment, but as attempts to re-produce capitalism in a given region.

Zero Carbon Humber is a consortium of industry partners in the economically disadvantaged Humber region in the UK. The region is home to multiple "difficult to decarbonize" industries which, in order to be compatible with a Net Zero economy, require carbon capture and storage to remain competitive in global markets. The consortium has mobilized state and private capital to construct CCS infrastructure which can be used by companies in the region to transport captured carbon dioxide from fossil fuelled processes into geological storage in the North Sea[4].

If we view such proposals as a spatio-temporal fix or a socio-ecological fix we can then *analyse them on this basis*, how effective are they likely to be at achieving climate goals *and* protecting good industrial jobs in struggling regions? In the case of Zero Carbon Humber, maintaining both the labor and capital relations around port-based chemical and industrial production. What alternatives do they occlude if tackling climate change were the goal instead of safeguarding existing power relations and regimes?

By understanding crises as inherent to capitalism, and seeing state action as often a fix to such crises, GGR scholars can better appreciate that the most palatable projects and policies are going to be those that can postpone or displace these crises. Analyzed on this basis, "optimal" GGR deployment may look very different to scenarios based upon top-down techno-economic models.

CAPITALISM AS MARKET EXPANDING

In "The Origin of Capitalism," Wood (2002) explores how markets existed long before capitalism became the dominant mode of production and how the distinct feature of capitalism is how deeply it depends on markets, how the means of production, labor, and commodities are *all* offered for exchange in a market, instead of only the final commodity, with labor, machinery, land, etc., held by a feudal lord, a theocratic institution etc. (Polanyi and MacIver, 1944). Markets, particularly for money and finance, are critical because they allow capital to *change forms* and to be invested elsewhere when the market for a given commodity becomes unprofitable (Harvey, 1978).

One source of crises is an inability to sell that which is produced, a crisis of realization where a market is saturated, obsolete, or there is no more effective demand. This is an interesting point for the capitalist who sells, for example lipstick. Because the cosmetics capitalist has reached a point where investing in more lipstick production is futile, they have a choice of where to invest next. If all other consumer goods markets are saturated they are not out of options. They can "switch" their capital into another circuit of production, those for example producing public goods such as infrastructure (Torrance, 2009). Again this is an example of a spatio-temporal fix, where capital that once produced cosmetics is now invested in bridges to avoid devaluation and perhaps structural crisis. There is a feat of financial engineering that is needed, however, to switch between circuits of capital. Castree and Christophers (2015) refer to this feat, stating how capital is made liquid by finance, how finance capital "melts present solidities into air to create different futures."

In order to achieve this switch there needs to be a form of "market making" that results in a reasonable expectation of profit. There must be the application of capital *and* a direct or indirect means of revenue capture to realize that profit. This has led to a burgeoning literature on the financialization of urban infrastructures (O'Neill, 2019), wherein the construction and protection of these revenue mechanisms by state and non-state actors is often prioritized in project planning to the exclusion of social, ecological, or even local economic benefit. Similarly, financialization and market making is needed for carbon trading, where a "market mechanism" is constructed to value and to trade carbon credits, artificial commodities constructed from the absence of emissions (Knox-Hayes, 2013).

For some time, the construction and promotion of market mechanisms to solve environmental problems have been legitimized through a broad Environmental Economics corpus that seeks to value and price nature and to construct markets for their protection (Groom and Talevi, 2020). This pricing and trading of nature to produce a "greener capitalism" (Böhm et al., 2012) gives rise to an intellectual divide between those who seek to internalize externalities with a price and market mechanism (see for a landmark example, The Stern Review, Stern, 2006), and those for whom ongoing trends of ecological commodification and expropriation, drive familiar processes of uneven and crisis-prone development (Böhm et al., 2012), or worse are empirically-blind to the non-substitutability of nature and unable to contend with hard "planetary boundaries" (Barbier and Burgess, 2017).

If we recognize that capitalism must expand the terrain for market exchange to avoid crises, then we should also be able to recognize that much of the debate over whether or not pricing nature is economically optimal is a moot point. It *has to be legitimized* because the space of market provision needs to expand to avoid crises. Developing social science around the marketization of previously non-market relations under capitalism is not a new phenomenon (Polanyi and MacIver,

[2]https://www.zerocarbonhumber.co.uk/
[3]https://thenorthernforest.org.uk/
[4]https://www.zerocarbonhumber.co.uk/the-vision

1944). For critical GGR scholars, we need to see the process of policy formation as an implicit search for market expansion, not an informed process of economic research that simply happens to diagnose competition and markets as the solution *all the time* (Bowman et al., 2014). A GGR policy is likely to be legitimate and desirable in the eyes of a capitalist state, only if it is easily linked to finance capital and a stable market mechanism can be found. We can recognize the market making tendency of capitalism in isolation, or we can see it as part of a wider "growth dependency" that forms the final pillar of Principle 1.

CAPITALISM AS GROWTH DEPENDENT

> *Economic growth in capitalism is inevitable, since this economic system is oriented towards unlimited and short term valorisation, quantitative and geographic expansion, circularity and reversibility* (Büchs and Koch, 2017, p.9).

There is a wealth of debate about where growth comes from in an economy, which is beyond the scope of this paper to unpack. The neo-classical school focuses analysis upon expanding productive capacity from technological innovation. Marxian analysis argues that ever more capital has to be invested into the productive process due to the forces of competition. Keynesian analysis explores the role of aggregate demand (how much is spent on consumption). And, evolutionary economics details the role of entrepreneurs and "creative destruction" that makes way for new rounds of accumulation or growth (Bourayou and Van Waeyenberge, 2020).

The question of how growth happens is important to HASS scholars because where a HASS scholar lands in that debate will inform what types of economic stimulus are seen as legitimate. Yet there are still deeper and more critical questions about economic growth that need to be asked: Why is growth necessary in capitalism? Is growth necessary for human wellbeing? Is growth necessary for negative emission technologies?

To summarize "why" growth instead of "how" growth, we return to Harvey's (2014) Marxian analysis. Harvey explores how capital will only be invested if "it" (capitalists) believes there will be more money available at the end of an investment cycle than at the beginning. If there was no such belief investment of new capital in new rounds of production would cease, again causing crises, and a search for a "fix," such as a return to aggregate growth (Jackson, 2009). For this belief to exist, somewhere around a 3% compound growth rate is commonly regarded as "healthy" (Harvey, 2017). This means that new productive investments must be found for an exponentially-increasing volume of capital.

In our current climate science it is unthinkable that a period of no growth or "de" -growth can exist under capitalism. Even in the "transformation of the global economy" envisioned by Rogelj et al. (2018) an average GDP growth of 231% is envisaged across the global economy between 2020 and 2050 within pathways "consistent" with meeting the 1.5° target (IIASA, 2020). IPCC growth scenarios notwithstanding, there remain serious questions over the assumed ability truly to decouple GDP and GHG emissions (Hickel and Kallis, 2020; Wiedenhofer et al., 2020).

There is now a substantial scholarship questioning whether "more growth is good" and whether a growing economy is healthy (Jackson, 2009, 2021; Raworth, 2017). This debate explores what structural changes are needed to bring a "post-growth" economy about (Hardt et al., 2021) and how different economies or alternative economic models might leave growth behind (O'Neill et al., 2018; Hickel and Kallis, 2020). This attachment to growth is critical because it frames how climate change mitigation and negative emissions technologies are legitimized and communicated at the IPCC level. Within the IAM models there is a percentage of future GDP that must be allocated to each technology, the smaller the percentage the easier the political narrative (Livingston and Rummukainen, 2020). At the same time, however, that growth demands that we mine, extract, create, or consume our way to an economy 231% bigger than it is today, and during a moment when growth is extremely sluggish in OECD nations and previous drivers of growth—such as financial engineering, money creation, incorporation of women into the workforce and the privatization and marketization of previously public and common goods—is fast running low on new options (Hardt and Negri, 2009; Harvey, 2014).

Humanities and social sciences scholarship on GGR will have to contend with the notion that GGR options in capitalism are primarily evaluated relative to their deployment cost as a proportion of GDP. While GDP is a poor measure of human well-being, it is quite a good measure of how well-capitalism is doing because rising GDP means that, when one sector is exhausted, finance capital can switch capital into another sector. This is what Castree and Christophers (2015) have in mind when they explore options for liquid financial capital to find new, ecologically-positive spatial fixes, including possibly negative emissions. The challenge for different GGR technologies may be less the actual ability to sequester carbon in a sustainable form, and more to be compatible with a monitoring, reporting, and evaluating function that is easily marketized, financed, and traded as a commodity.

The sections above have summarized a set of substantial debates that deserve greater attention by HASS scholars in the GGR debates. The tendencies of capitalism to crises, marketization, and the attendant necessity of long run GDP growth, all mean that HASS scholars of GGR deployment within capitalism have a challenging research agenda ahead, but one in which principle 1 has provided a useful starting point.

> Principle 1: *Greenhouse Gas Removal technologies are likely to emerge within capitalism, which is crisis prone, growth dependent, market expanding.*

Before progressing further, we contend with the various expressions of capital across space and time to ground our analysis in actually-existing "capitalisms."

VARIETIES OF CAPITALISM

Given the various points in time and space where capitalism became established, it is no surprise that there are different expressions of capitalism in different geographic regions. While the generalities of principle 1 still hold, they do find multiple expressions. Our second principle therefore calls for GGR scholars in the social sciences to explore the different forms capitalism takes in a given space and time. Hall and Soskice (2001) "varieties of capitalism" contribution is key here. Their initial purpose was to explore how different institutional formations bred different social relations of capital accumulation and circulation across nations and regions. This included explorations of the different welfare state regimes (Mares, 2002), labor market policies (Wood, 2001), industrial strategies (Hancké, 2001), and Corporate Governance models (Vitolis, 2001) amongst others. In turn this led to broad characterizations of states into Liberal Market Economies (LMEs), exemplified by the Anglophone states where competition between firms, formal contracting, low unionization, and fluid labor and capital markets exist; and Coordinated Market Economies (CMEs), exemplified by Germany and comprising thicker corporate networks, patient, and stable capital relations between firms and finance, and a more formal relation with organized [skilled] labor (Schneider and Paunescu, 2012).

While the initial varieties of capitalism literature focussed on OECD nations, more recent work has expanded to include varieties of: Asian capitalism (Zhang and Whitley, 2013), post-communist countries (Lane and Myant, 2007), and emerging economies (Schedelik et al., 2021). Accepting that capitalism comes in varieties is a foundational principle of comparative political economy (Hay, 2020). Much of the literature is concerned with the correct institutional mix to promote and sustain growth and economic performance. In this way the comparative political economy literature using the "varieties" approach is less critical, and is an example of our claim that HASS scholars can very well "say capitalism" without concluding, *a la* ŽiŽek, that its indefinite reproduction is impossible.

Climate change mitigation research using the "varieties of capitalism" school has explored: how different financial institutions across countries affect the deployment of renewable energy systems (Hall et al., 2016); how co-ordinated market economies can lead to a deeper lock-in of high carbon assets (Rentier et al., 2019); and how important institutional relations are in efforts to green the passenger car industry (Mikler, 2009). With recent examples beginning to explore how comparative political economy can be a powerful explanatory device for understanding which nations are likely to support carbon sink technologies and potentially negative emission technologies (Røttereng, 2018).

For HASS scholars looking to develop the debate around GGR *in* capitalism, the "varieties of capitalism" school, along with wider comparative political economy of climate mitigation, is a key body of work to synthesize. To proceed with such an endeavor principle 2 is necessary:

> *Principle 2: There are different varieties of capitalism and this will affect the feasibility of different GGR policies and supports in different nations.*

By starting a journey using principles 1 and 2, we attend primarily to the *material* maintenance of capitalism, including state economic, labor, and financial policy, the construction of markets, and various economic diagnoses of poor or lagging performance. Markusson et al. (2018), however, also call us to attend to the *ideational* maintenance of capitalism. Whilst a more interpretive and less empirical endeavor, it is one that is nonetheless important to how HASS scholars bold enough to "say" capitalism can engage with GGR research. In the following section, we depart from drawing direct lines of enquiry to GGR research, for a time, to introduce the school of Critical Theory, which we find powerful for understanding the "public" challenge of GGR research.

CAPITALISM AS IDEOLOGICALLY MAINTAINED

"Critical Theory" is used as a shorthand to capture the critique of capitalism that was first developed by a group of German-Jewish scholars at the University of Frankfurt am Main in the 1930s, before their exile to the United States to escape the rising tide of fascism. If there is one principal idea that animates the work of the Frankfurt School theorists it is how capitalism as a total social system is able to suppress movements for genuine change by encouraging cultural, political, and economic freedoms, rather than through brute repression by state apparatus (Bottomore, 2002). It is through the *idea* that individuals are free—free to vote, free to shop, free to think—that capitalism is able to reproduce itself despite its crisis tendencies and the human/ecological damage it causes. The proponents of Critical Theory argue that the freedoms currently on offer are simply not capable of threatening the stability of the capitalist system and those who benefit from it.

In the 1930s, two prominent figures in Critical Theory—Max Horkheimer and Theodor Adorno—were trying to explain the crisis in Marx's theory of social change. In the period immediately after the First World War, there had been widespread social unrest in Europe. In particular, the 1917 Russian Revolution and the subsequent formation of the Soviet Union acted as a focal-point for left-wing Marxist ambitions and widespread hope that the capitalist system could be overthrown on the world stage (Kellner, 1990). As early as the mid-1920s, however, this dream was in rapid retreat. Intense battles were being fought inside left-wing socialist groups across Europe and, at the same time, powerful right-wing conservative responses were beginning to show that the possibility of a universal working class revolution—as Marx expected to happen—was becoming far less likely, especially in Germany. It was in this context that Adorno and Horkheimer founded their Institute for Social Theory at Frankfurt am Main, to protect the legacy of Marx's ideas from their apparent refutation by world events and, more generally, to prevent the wholesale elimination of left-wing ideas in Europe (Jay, 1996).

The Frankfurt School set about expanding Marx's ideas in a new direction, via Max Weber and Sigmund Freud, by shifting the focus away from political economy (material maintenance) and instead toward the themes of culture and ideology (ideational maintenance). Underpinning their approach was the hugely controversial claim that a Marxist social revolution could not happen precisely because the working class were now being incorporated into the capitalist system via what they called "Mass Culture" (Swingewood, 1977; Naremore, 1991). The working class were becoming a willing part of the capitalist system by embracing the "false freedoms" and "illusory individualism" handed out by the consumer market. More controversially still, Adorno and Horkheimer proposed that the working class, in becoming seduced by the consumer dreamworlds of Mass Culture, were increasingly *responsible* for the ability of capitalism to go on reproducing itself.

"Mass Society" thus refers to a large-scale, impersonal, and highly-rationalized set of social institutions. The idea is useful because it draws our attention to the ways in which daily life in complex modern societies, with their increasingly distant forms of power, can also become highly anonymous and appear not to care about or wish to support the important social relations that exist between the individual and their community. Mass Societies are rendered possible, so their argument goes, thanks to the technological advances of modern communications and electronic media. Culture in a Mass Society is therefore one that is *transmitted to* individuals for the purposes of consumption, rather than something that arises organically from the creative labors of daily life (Adorno and Horkheimer, 1944).

As fascism took hold in Germany, Adorno, and Horkheimer found refuge in the USA where rampant consumerism at that time dramatically shaped their thinking. The rise of the mass media, and specifically the leisure and entertainment industries, were understood in terms of their capacity to exploit this radical new category of individuals, namely the "consumer." Film, TV, and radio, were all seen as brutal evidence in the rise of what they called a "totally commodified culture," one in which everything was valued solely for its economic qualities (Adorno, 2001). As a result, individuals, especially when lacking the resources necessary to participate fully in a consumer culture, become further disempowered and lose a sense of their agency to drive forward meaningful change in their own lives and the wider world. As the sociologist Bauman (1999) has argued, there is an important distinction to be made between *individuals de jure* (those who are powerless over their own lives, but whom are nevertheless declared to be individuals by the social systems with which they interact) and *individuals de facto* (those who truly have influence to shape their own destiny and to make free choices).

The ability to promote individual freedoms through cultural choices without any real traction over the construction and maintenance of capitalist systems of production was seen by Adorno and Horkheimer as a new and highly-effective form of social control. Increasingly overworked, exploited, and alienated workers in the mass factories of the USA were not rebelling or forming into collective groups of unionized resistance in order to fight capitalism, which is what Marx had predicted. Instead, those workers were kept passive through the emergence of mass advertising and new media technologies, such that individuals were fast becoming passive consumers of mass-produced goods.

For Adorno and Horkheimer—and this is the second big idea in their whole argument—it was an "illusory sense of difference" created by advertisers and marketing professional that masked a more fundamental principle of similarity, namely the reproduction of capitalism, and the power of its ruling elite. The logic behind their complex argument is simple. The never-ending and rapid development of the capitalist economy in pursuit of greater profit creates more and more commodities that are then marketed to the consumer by evermore sophisticated new media technologies in such a way as to give the illusion of difference. In this way, market relations expand by manufacturing new "wants, needs, and desires" in order to stave-off material crises (Principle 1).

Adorno and Horkheimer argue that, whereas once "culture" had been a space for men and women to think and to act freely, it was now instead a sphere of almost total domination, one designed to complement and legitimize a crisis prone, growth-addicted, and commodifying mode of production (Principle 1). That is to say: with the emergence of advertising, "who we are" as individuals becomes synonymous with "what we buy." A sense of self is far less reliant on where we work, our values, and what roles we may have in our communities, and is rather communicated through the consumption and display of mass-produced products.

According to Marx, capitalism is perpetually in a state of potential crisis (Principle 1) and to prevent those contradictions from reaching the point of actual crisis, capitalism produces ideology to construct reality in such a way that the underlying contradictions are not fully transparent. Ideology is rendered naturalistic or opaque through the deployment of culture as a system of cognitive repression enacted by ostensibly freely choosing consumers, but whose varied choices serve only to reinforce the system and stave off the crisis for another day. Through consumer goods and organized mass entertainment, ideology penetrates into the cultural sphere and ceases to be an illusion or a "false consciousness." One of the central arguments of the Frankfurt School was that the effectiveness of ideology as a system of control lies not so much in its false messages, but in its sheer ability to be able to remove the desire for change from society through its negation of critical thinking.

It is this idea, more recently expressed by Zygmunt Bauman as the "TINA syndrome" —i.e., "there is no alternative" —that has come to exemplify our current neoliberal stage of capitalist development. Across all of his work, from the early 1960s through to his last book *Retrotopia* (Bauman, 2017), Bauman invites us to see the world through the eyes of society's weakest members, and then to tell anyone honestly that capitalist societies are good, civilized, advanced, free. Today, such counter-cultural instincts seem as important as ever. Bauman became famous for his concept of "liquid modernity" (Bauman, 2013), a sense that once reliable forms of labor or obdurate social institutions were no longer solid or fixed.

There is a key resonance here with Principle 2, since the different varieties of capitalism literatures are concerned with re-ordering state involvement in the economy, labor, and financial relations. In order to ensure economic performance, old institutions and relations are "melted away" in order to produce comparative advantage, with little thought to the social damage such uncertainty causes for the communities it affects. Similarly, Bauman's notion of the liquidity of modern life resonates with

Castree and Christophers' (2015) description of finance capital's ability to "melt present solidities into air."

Bauman attends to the human and cultural consequences of such rapid and consistent re-ordering of social institutions, where individuals are shorn of reliable life strategies and the institutions or social relations that surround them. The *individual de jure* becomes a precarious state, where once relevant and valuable skills are rendered obsolete and there is no guarantee that the acquisition of new skills, life strategies, or social institutions/relations will be successful, endure, or reproduce the freedom to consume for very long.

In parallel, real power becomes remote and inaccessible. Recall from principle 1 the effect of infrastructure financialization, where local autonomy is subordinated to the needs of finance capital (O'Neill, 2019). The cultural effects of this "liquid society" and removal of *de facto* individual agency render public concerns moot and futile to engage with. Bauman notes a retreat from the *agora*, from public decision-making over collective futures, fuelled by a sense that these public decisions are no-longer meaningful, and that distant others are preventing any real change.

A key feature of Bauman's analysis of "liquid modernity", as Davis M. (2020) has argued, is an apparent divorce of power from politics, leading to the leaking away of trust from political leaders on all sides. The divorce of power from politics—such a repeated argument in the latter part of Bauman's career, understood as the emancipation of capital from the territorially-fixed controls of states—means that national politicians are no longer able to fulfill their traditional functions amidst the stupefying pace of (technologically-enabled) change. This political impotence creates a new legitimation crisis (Habermas, 1988), which sees that same modern impulse to perfect society directed toward the only "imagined community" (Anderson, 2006) left available to it— "the past." If the future is only to be feared, because we have become so removed from the idea of genuine societal transformation and the possibility of "life after capitalism," then let us only face backwards and revel in a nostalgic recreation by daring to utilize various degrees of palingenesis to see the nation "*re*born," to "take *back* control," to become "great *again*." This is how what Bauman (2017) called the retrotopic imaginary seeks safety, in the comfort of perceived certainties long since gone.

The ramifications of a Mass Culture of consuming individuals, with a very precarious and uncertain sense of themselves, fuelled by a suspicion that real power is far away from them, is of critical importance to greenhouse gas removal scholars. The work of Cox, outlined above, demonstrated there is a clear suspicion that GGR technologies do nothing other than justify a "non-transition" and, under the surface of these stated concerns of "mitigation delay" and other rational responses, resides a recognition that what currently "is" is not very satisfying. However, inchoate that sentiment may be, it is worth further research to excavate, and in particular should be linked to popular but similarly inchoate calls to "build back better" from the Covid-19 pandemic, a slogan striking a similar note to those mentioned above given its retrotopic chord. Conversely, calls for a "Green New Deal" exist because a new deal is needed, since what we have now is quite simply "not fair" (Hampden-Turner and Trompenaars, 2021).

Leveraging and exploring where GGR fits in these "mass culture" narratives is a productive avenue of research and links back to ways in which different publics and constituencies are formed around GGR issues (Bellamy and Healey, 2018). Adopting a Critical Theory register arms us with a controversial, and somewhat "darker" notion (Pollock and Davis, 2020), that some publics are operating with a sense of precarity and uncertainty, completely at odds with the "mass culture" around them and likely to comprise a rather messy and angry ideological soup that is a direct product of the realities of "market force" meeting the unreality of mass culture (Hopkin, 2017; Davis A. E., 2020; Davis M., 2020). Making space for this confusion, anger, and sense of precarity that is produced by the ideational maintenance of capitalism *will* be important.

Consider the following from the perspective of different "publics" in the Humber region: what "we" are asking for, if we want to treat proposals like "Zero Carbon Humber" seriously, is the creation of a *fictitious* market for an *invisible* gas to be taken from the air, and then for that *invisible* gas to be sent through *invisible* pipes, subsidized by public money, into *invisible* caverns, to mitigate a problem which will become apparent in decades. "We" are proposing this in a region of long-term economic stress where *immediate* need is apparent in schools and public services that are suffering from multiple years of austerity and slow growth. "We" are doing so in a cultural climate of precarity, uncertainty, and extreme mistrust in the possibility of a stable future (Bauman, 2013). For these reasons, we argue it is important to pay far closer attention to the ideological maintenance of capitalism and the cultural mileux we as social scientists are entering when we try to think through problems of social legitimacy and consent. As such, we ask HASS GGR scholars to proceed with principle 3.

Principle 3: *Capitalism is more than an economic system, it is ideologically and culturally maintained.*

CONCLUSION

This article has explored the ways in which HASS scholars coming to the field of greenhouse gas removal can do so in ways which recognize and contend with capitalism. We began with establishing a dividing line between contributions which name and contend with "capitalism" explicitly and those which gesture toward an unnamed "global economy." We then set out the difficult space one is invited to inhabit when capitalism is named, which begins a journey toward ŽiŽeks "ultimatum" to either endorse capitalism's naturalization by endeavoring to make it more just, or conclude that its contradictions and tensions are too great for it to be sustained. We do not invite HASS GGR researchers to declare their conclusions just yet; instead, we present three guiding principles that we think could be used to shape the social science of greenhouse gas removal. Principles that go beyond "instrumental" service to techno economic modeling and invite a more critical position.

The first principle recognizes GGR technologies will emerge within capitalism. Even if state delivered, they will be delivered by a capitalist state, and capitalism, wherever it is found is crisis prone, growth dependent and market expanding. There are several productive avenues of research available to those focusing on Principle 1, not least the ways in which GGR projects and deployment can be approached as a spatio-temporal or socio-ecological "fix" to the crisis tendencies of capital, and how a GGR economy might arise in a non-capitalist "growth agnostic" political economy.

The second principle recognizes that capitalism finds different expressions in place and time and while Principle 1 holds, its individual expressions will be necessarily diverse. GGR policy that will work in Germany will not work in Brazil, or at least not in the same ways. This is due to different institutional structures and balances of state involvement in the economy, financial institutions, and labor bargaining power to name just a few. Recognizing the "Varieties of Capitalism" literature is broadly oriented toward improving national economic performance should also strengthen our claim that HASS scholars "saying" capitalism, need not be in the process of rejecting it.

Finally, principle 3 draws our attention to the ways in which critical social theory can be used to explore how capitalism is not only maintained through material political means but also has an ideational and ideological dimension that is transmitted through mass culture, and that breaking down old institutional certainties produces real tensions and precarity which will be operating in any sphere of public discourse. These tensions are unlikely to be explicit and will need deeper interpretation and analysis than instrumental and empirical social science is able to provide.

Our hope is that this contribution will spark debate on greenhouse gas removal *in* capitalism and lead to a set of critical reflections at the very early stages of GGR development and deployment. We expect a healthy debate on the suitability of the three principles proposed and welcome any attempt to operationalize them in future GGR research.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

SH and MD developed the manuscript, principles, and concepts of the article in tandem. Both authors contributed to the article and approved the submitted version.

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REFERENCES

Adorno, T. (2001). *The Culture Industry: Selected Writings on Mass Culture, 2nd Edn*. London: Routledge Classics.

Adorno, T., and Horkheimer, M. (1944). *Dialectic of Enlightenment*. New York: Continuum.

Anderson, B. (2006). *Imagined Communities: Reflections on the Origin and Spread of Nationalism*. London: Verso.

Apostolopoulou, E. (2021). Tracing the links between infrastructure-led development, urban transformation, and inequality in China's belt and road initiative. *Antipode* 53, 831–858. doi: 10.1111/anti.12699

Barbier, E. B., and Burgess, J. C. (2017). Natural resource economics, planetary boundaries and strong sustainability. *Sustainability* 9:1858. doi: 10.3390/su9101858

Bauman, Z. (1999). *Culture as Praxis*. London; New York, Thousand Oaks, CA: Sage.

Bauman, Z. (2013). *Liquid Modernity*. Cambridge: Polity Press.

Bauman, Z. (2017). *Retrotopia*. Cambridge: Polity Press. doi: 10.14515/monitoring.2018.6.22

Bellamy, R., and Healey, P. (2018). 'Slippery slope' or 'uphill struggle'? Broadening out expert scenarios of climate engineering research and development. *Environ. Sci. Policy* 83, 1–10. doi: 10.1016/j.envsci.2018.01.021

Böhm, S., Misoczky, M. C., and Moog, S. (2012). Greening capitalism? A Marxist critique of carbon markets. *Organ. Stud.* 33, 1617–1638. doi: 10.1177/0170840612463326

Bonizzi, B., and Powell, J. (2020). "What causes economic crises? And what can we do about them?" in *Recharting the History of Economic Thought, Red Globe Press*, eds K. Deane and E. Van Waeyenberge (London: Red Globe Press), 167–182.

Bottomore, T. (2002). *The Frankfurt School and Its Critics*. London: Routledge. doi: 10.4324/9780203407110

Bourayou, C., and Van Waeyenberge, E. (2020). "How do economies grow," in *Recharting the History of Economic Thought*, eds K. Deane and E. Van Waeyenberge (London: Red Globe Press), 183–208.

Bowman, A., Ertürk, I., Froud, J., Johal, S., and Law, J. (2014). *The End of the Experiment?: From Competition to the Foundational Economy*. Manchester: Manchester University Press. doi: 10.7765/9781847798930

Büchs, M., and Koch, M. (2017). *Postgrowth and Wellbeing: Challenges to Sustainable Welfare*. Cham: Springer. doi: 10.1007/978-3-319-59903-8

Carton, W. (2019). "Fixing" climate change by mortgaging the future: negative emissions, spatiotemporal fixes, and the political economy of delay. *Antipode* 51, 750–769. doi: 10.1111/anti.12532

Castree, N., Adams, W. M., Barry, J., Brockington, D., Büscher, B., Corbera, E., et al. (2014). Changing the intellectual climate. *Nat. Clim. Chang.* 4, 763–768. doi: 10.1038/nclimate2339

Castree, N., and Christophers, B. (2015). Banking spatially on the future: capital switching, infrastructure, and the ecological fix. *Ann. Assoc. Amer. Geograph.* 105, 378–386. doi: 10.1080/00045608.2014.985622

Cox, E., Spence, E., and Pidgeon, N. (2020a). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nat. Clim. Chang.* 10, 744–749. doi: 10.1038/s41558-020-0823-z

Cox, E., Spence, E., and Pidgeon, N. (2020b). Incumbency, trust and the Monsanto effect: stakeholder discourses on greenhouse gas removal. *Environ. Values* 29,197–220. doi: 10.3197/096327119X15678473650947

Davis, A. E. (2020). Waves of populism: a recent manifestation of Polanyi's "double movement?" *J. Econ.* 54, 398–403. doi: 10.1080/00213624.2020.1743602

Davis, M. (2020). Hermeneutics contra fundamentalism: Zygmunt Bauman's method for thinking in dark times. *Thesis Eleven* 156, 27–44. doi: 10.1177/0725513619898285

Dowd, A.-M., Rodriguez, M., and Jeanneret, T. (2015). Social science insights for the BioCCS industry. *Energies* 8, 4024–4042. doi: 10.3390/en8054024

Earle, J., Moran, C., and Ward-Perkins, Z. (2016). *The Econocracy: The Perils of Leaving Economics to the Experts*. Manchester: Manchester University Press. doi: 10.7228/manchester/9781526110121.001.0001

Ekers, M., and Prudham, S. (2018). The socioecological fix: fixed capital, metabolism, and hegemony. *Ann. Assoc. Amer. Geograph.* 108,17–34 doi: 10.1080/24694452.2017.1309963

Forster, J., Vaughan, N. E., Gough, C., Lorenzoni, I., and Chilvers, J. (2020). Mapping feasibilities of greenhouse gas removal: key issues, gaps and opening up assessments. *Glob. Environ. Change* 63:102073. doi: 10.1016/j.gloenvcha.2020.102073

Giacché, V. (2011). Marx, the falling rate of profit, financialization, and the current crisis. *Int. J. Polit. Econ.* 40, 18–32. doi: 10.2753/IJP0891-1916400302

Groom, B., and Talevi, M. (2020). "How does economics address the environment," in eds K. Deane and E. Van Waeyenberge, *Recharting the History of Economic Thought* (London: Macmillan), 247–268.

Habermas, J. (1988). *Legitimation Crisis*. Trans. by T. McCarthy. Cambridge: Polity Press.

Hall, P. A., and Soskice, D. (ed.). (2001). *Varieties of Capitalism. The Institutional Foundations of Comparative Advantage*. Oxford: Oxford University Press.

Hall, S., Foxon, T. J., and Bolton, R. (2016). Financing the civic energy sector: how financial institutions affect ownership models in Germany and the United Kingdom. *Energy Res. Soc. Sci.* 12, 5–15. doi: 10.1016/j.erss.2015.11.004

Hampden-Turner, C., and Trompenaars, F. (2021). *Culture, Crisis and COVID-19: The Great Reset*. Cambridge: Cambridge Scholars Publishing.

Hancké, B. (2001). "Revisiting the french model: coordination and restructuring in french industry," in *Varieties of Capitalism. The Institutional Foundations of Comparative Advantage*, eds P. A. Hall and D. Soskice (Oxford: Oxford University Press), 307–334. doi: 10.1093/0199247757.003.0009

Hardt, L., Barrett, J., Taylor, P. G., and Foxon, T. J. (2021). What structural change is needed for a post-growth economy: a framework of analysis and empirical evidence. *Ecol. Econ.* 179:106845. doi: 10.1016/j.ecolecon.2020.106845

Hardt, M., and Negri, A. (2009). *Commonwealth*. Cambridge, MA: Harvard University Press. doi: 10.2307/j.ctvjsf48h

Harvey, D. (1978). The urban process under capitalism: a framework for analysis. *Int. J. Urban Reg. Res.* 2:101–131. doi: 10.1111/j.1468-2427.1978.tb00738.x

Harvey, D. (2010). *The Enigma of Capital and the Crises of Capitalism*. London: Profile Books.

Harvey, D. (2014). *Seventeen Contradictions and the End of Capitalism*. London: Profile Books.

Harvey, D. (2017). *Marx, Capital, and the Madness of Economic Reason*. Oxford University Press.

Hay, C. (2020). Does capitalism (still) come in varieties? *Rev. Int. Polit. Econ.* 27, 302–319. doi: 10.1080/09692290.2019.1633382

Hickel, J., and Kallis, G. (2020). Is green growth possible? *New Polit. Econ.* 25, 469–486. doi: 10.1080/13563467.2019.1598964

Hopkin, J. (2017). When Polanyi met Farage: market fundamentalism, economic nationalism, and Britain's exit from the European Union. *Brit. J. Polit. Int. Relat.* 19, 465–478. doi: 10.1177/1369148117710894

IIASA (2020). *IAMC 1.5c Scenario Explorer hosted by IIASA*. Available online at: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/workspaces (accessed May 2021).

Jackson, T. (2009). *Prosperity Without Growth: Economics for a Finite Planet*. London: Routledge. doi: 10.4324/9781849774338

Jackson, T. (2021). *Post-Growth: Life After Capitalism*. Cambridge: Polity.

Jacobs, M., and Mazzucato, M. (eds.). (2016). *Rethinking Capitalism: Economics and Policy for Sustainable and Inclusive Growth*. Chichester: John Wiley and Sons.

Jay, M. (1996). *The Dialectical Imagination: A History of the Frankfurt School and the Institute of Social Research, 1923-1950.* Vol. 10. Berkeley, CA: Univ of California Press.

Jessop, B. (2006). "Spatial fixes, temporal fixes and spatio- temporal fixes," in *David Harvey: A Critical Reader*, eds N. Castree and D. Gregory (Chichester: John Wiley and Sons), 142–166. doi: 10.1002/9780470773581.ch8

Jessop, B., and Sum, N. L. (2006). *Beyond the Regulation Approach: Putting Capitalist Economies in Their Place*. Glos: Edward Elgar Publishing.

Kellner, D. (1990). Critical theory and the crisis of social theory. *Sociol. Perspect.* 33, 11–33. doi: 10.2307/1388975

Knox-Hayes, J. (2013). The spatial and temporal dynamics of value in financialization: analysis of the infrastructure of carbon markets. *Geoforum* 50, 117–128. doi: 10.1016/j.geoforum.2013.08.012

Lamb, W. F., Antal, M., Bohnenberger, K., Brand-Correa, L. I., Müller-Hansen, F., Jakob, M., et al. (2020). What are the social outcomes of climate policies? A systematic map and review of the ex-post literature. *Environ. Res. Lett.* 15:113006. doi: 10.1088/1748-9326/abc11f

Lane, D., and Myant, M. R. (eds.). (2007). *Varieties of Capitalism in Post-Communist Countries*. Basingstoke: Palgrave Macmillan, p. xiv. doi: 10.1057/9780230627574

Lenzi, D., Lamb, W. F., Hilaire, J., Kowarsch, M., and Minx, J. C. (2018). Don't deploy negative emissions technologies without ethical analysis. *Nature* 561, 303–305. doi: 10.1038/d41586-018-06695-5

Livingston, J. E., and Rummukainen, M. (2020). Taking science by surprise: the knowledge politics of the IPCC special report on 1.5 degrees. *Environ. Sci. Policy* 112, 10–16. doi: 10.1016/j.envsci.2020.05.020

Mares, I. (2002). "Firms and the welfare state: when, why, and how does social policy matter to employers?," in *Varieties of Capitalism. The Institutional Foundations of Comparative Advantage*, eds P. A. Hall and D. Soskice (Oxford: Oxford University Press), 184–212. doi: 10.1093/0199247757.003.0005

Markusson, N., Balta-Ozkan, N., Chilvers, J., Healey, P., Reiner, D., and McLaren, D. (2020). Social science sequestered. *Front. Clim.* 2:2. doi: 10.3389/fclim.2020.00002

Markusson, N., Gjefsen, M. D., Stephens, J. C., and Tyfield, D. (2017). The political economy of technical fixes: the (mis) alignment of clean fossil and political regimes. *Energy Res. Soc. Sci.* 23, 1–10. doi: 10.1016/j.erss.2016.11.004

Markusson, N., McLaren, D., and Tyfield, D. (2018). Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Glob. Sustain.* 1:e10. doi: 10.1017/sus.2018.10

Mikler, J. (2009). *Greening the Car Industry: Varieties of Capitalism and Climate Change*. Cheltenham: Edward Elgar Publishing. doi: 10.4337/9781849802246

Naremore, J. and Brantlinger, P. (eds.). (1991). *Modernity and Mass Culture*. Bloomington: Indiana University Press.

O'Neill, D. W., Fanning, A. L., Lamb, W. F., and Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nat. Sustain.* 1, 88–95. doi: 10.1038/s41893-018-0021-4

O'Neill, P. (2019). The financialisation of urban infrastructure: a framework of analysis. *Urb. Stud.* 56, 1304–1325. doi: 10.1177/0042098017751983

Polanyi, K., and MacIver, R. M. (1944). *The Great Transformation,* Vol. 2. Boston, MA: Beacon Press. p. 145.

Pollock, G., and Davis, M. (2020). Thinking in dark times: assessing the transdisciplinary legacies of Zygmunt Bauman. *Thesis Eleven* 156, 3–9. doi: 10.1177/0725513619898090

Raworth, K. (2017). *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. Chelsea Green Publishing.

Rentier, G., Lelieveldt, H., and Kramer, G. J. (2019). Varieties of coal-fired power phase-out across Europe. *Energy Policy* 132, 620–632. doi: 10.1016/j.enpol.2019.05.042

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5○C. *Nature Clim. Change* 8, 325–332. doi: 10.1038/s41558-018-0091-3

Rose, D. B., Van Dooren, T., Chrulew, M., Cooke, S., Kearnes, M., and O'Gorman, E. (2012). Thinking through the environment, unsettling the humanities. *Environ. Human.* 1, 1–5. doi: 10.1215/22011919-3609940

Røttereng, J. K. S. (2018). The comparative politics of climate change mitigation measures: who promotes carbon sinks and why? *Glob. Environ. Polit.* 18, 52–75. doi: 10.1162/GLEP_a_00444

Sapinski, J. P., Buck, H. J. and Malm, A. eds., (2020). *Has It Come to This?: The Promises and Perils of Geoengineering on the Brink*. New Brunswick, NJ: Rutgers University Press. doi: 10.36019/9781978809390

Schedelik, M., Nölke, A., Mertens, D., and May, C. (2021). Comparative capitalism, growth models and emerging markets: the development of the field. *New Polit. Econ.* 26, 514–526. doi: 10.1080/13563467.2020.1807487

Schneider, M. R., and Paunescu, M. (2012). Changing varieties of capitalism and revealed comparative advantages from 1990 to 2005: a test of the Hall and Soskice claims. *Socio Econ. Rev.* 10, 731–753. doi: 10.1093/ser/mwr038

Schumpeter, J. A. (1934). The theory of economic development. Transl. by R. Opie. *Harv. Econ. Stud.* 46, 1600–0404.

Shaikh, A. (2016). *Capitalism: Competition, Conflict, Crises*. Oxford: Oxford University Press. doi: 10.1093/acprof:oso/9780199390632.001.0001

Stern, N. (2006). *Stern Review: The Economics of Climate Change*. Cambridge: Cambridge University Press. doi: 10.1017/CBO9780511817434

Sweezy, P. (1942). *The Theory of Capitalist Development*. New York: Monthly Review Press.

Swingewood, A. (1977). *The Myth of Mass Culture*. London: Palgrave. doi: 10.1007/978-1-349-15783-9

Torrance, M. (2009). The rise of a global infrastructure markets through relational investing. *Econ. Geogr.* 85, 75–97. doi: 10.1111/j.1944-8287.2008.01004.x

Vitolis, S. (2001). "Varieties of corporate givfernance: comparing Germany and the UK," in *Varieties of Capitalism. The Institutional Foundations of Comparative Advantage,* eds P. A. Hall and D. Soskice (Oxford: Oxford University Press), 337–360.

Waller, L., Rayner, T., Chilvers, J., Gough, C. A., Lorenzoni, I., Jordan, A., et al. (2020). Contested framings of greenhouse gas removal and its feasibility: social and political dimensions. *Wiley Interdiscipl. Rev. Clim. Change* 11:e649. doi: 10.1002/wcc.649

Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Streeck, J., Pichler, M., et al. (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping. *Environ. Res. Lett.* 15:063002. doi: 10.1088/1748-9326/ab8429

Wood, E. M. (2002). *The Origin of Capitalism: A Longer View*. Brooklyn, NY: Verso Books.

Wood, S. (2001). "Business, government, and patterns of labor market policy in Britain and the Federal Republic of Germany," in *Varieties of Capitalism. The Institutional Foundations of Comparative Advantage*, eds P. A. Hall and D. Soskice (Oxford: Oxford University Press). 247–274, doi: 10.1093/0199247757.003.0007

Zhang, X., and Whitley, R. (2013). Changing macro-structural varieties of East Asian capitalism. *Socio Econ. Rev.* 11, 301–336. doi: 10.1093/ser/mws029

Žižek, S. (2008) *SubStance. The Political Animal*, Vol. 37. Baltimore, MD: The Johns Hopkins University Press. 37–72. doi: 10.1353/sub.0.0017

Žižek, S. (2017). *The Courage of Hopelessness: Chronicles of a Year of Acting Dangerously*. New York, NY: Penguin UK.

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