

Reviewing the sociotechnical dynamics of carbon removal

Benjamin K. Sovacool^{1 2 3}, Chad M. Baum¹, Sean Low¹,

¹ Aarhus University, Denmark

² University of Sussex Business School, United Kingdom

³ Boston University, United States

Published as Sovacool, BK, CM Baum, and S Low. “Reviewing the sociotechnical dynamics of carbon removal,” Joule 7(1) (January 2023), pp. 57-82.

Abstract: In recent years, carbon removal and associated net-zero energy technologies have emerged as serious options for policymakers and scientists to consider when trying to address climate change. How, where, and when to use these options effectively, however, is polemic, and research examining the social or justice dimensions of deployment—actual or prospective—remains uncommon. This Review provides an interdisciplinary and holistic perspective of the sociotechnical dynamics of carbon removal options. It employs a sociotechnical approach which reveals the different epistemic, economic, technical, social, political, and environmental elements necessary for a net-zero energy transition. In this Review, we first summarize seven broad classes of carbon removal—afforestation and reforestation, soil carbon sequestration, marine biomass and blue carbon, direct air capture with carbon storage, bioenergy with carbon capture and storage, enhanced weathering, and biochar. The Review then explores four critical sociotechnical areas in greater depth: modeling and assessment, social acceptance, innovation and scaling, and policy and governance. We conclude with implications for policy and research.

Keywords: carbon dioxide removal; negative emissions technologies; greenhouse gas removal; net-zero transition; climate engineering

Word count: 6500 (not counting references, abstract, tables, or figures)

Acknowledgements: This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the European Research Council (ERC) Grant Agreement No. 951542-GENIE-ERC-2020-SyG, “GeoEngineering and Negative Emissions pathways in Europe” (GENIE). The content of this deliverable does not reflect the official opinion of the European Union. Responsibility for the information and views expressed herein lies entirely with the author(s).

Reviewing the sociotechnical dynamics of carbon removal

1. Introduction

The most recent United Nations climate agreement has set the goal of keeping global temperature change well below 2 °C.^{1 2} To achieve this goal, technologies such as greenhouse gas removal, hereafter called “carbon removal,” are increasingly recognized as critically important by making it possible to capture carbon dioxide from the atmosphere and store it safely and durably.^{3 4 5} Carbon removal has become a central feature in recent global discussions about the transition to net-zero energy systems that can, on balance, generate energy services without contributing to climate change.^{6 7} This is especially the case in “hard-to-abate” sectors of the economy such as aviation and industry.^{8 9} As the Intergovernmental Panel on Climate Change (IPCC) recently argued, carbon removal “is a necessary element to achieve net-zero carbon dioxide and greenhouse gas emissions both globally and nationally, counterbalancing residual emissions from hard-to-transition sectors” and it is a key element in scenarios likely to limit warming to 2°C or lower by 2100.”¹⁰

How, where, and when to use these options effectively, however, is very controversial, and research examining the social or justice dimensions of deployment—actual or prospective—is sparse. One particular option, bioenergy with carbon capture and storage (BECCS), by itself would require “unprecedented” new sociotechnical systems and alignment with global energy systems, a feat that would only be accomplished by “transformational upscaling” and “unprecedented technological, economic, socio-cultural and political effort.”¹¹ Other land-based options, such as afforestation or reforestation, could run the risk of exceeding planetary boundaries for land system change¹², especially in the forestry sector.¹³

The bulk of research on carbon removal addresses techno-economic aspects but rarely their social, legal, political and even ethical dimensions.¹⁴ Anderson and Peters¹⁵ argue that the bulk of integrated assessment models used to examine scenarios for reaching 2°C “assume that the large-scale rollout of negative-emission technologies is technically, economically, and socially viable.” Van Vuuren and colleagues caution that the expected use of negative emissions technologies after 2050 will have a strong impact on emissions reduction strategies *now*, and that a “timely decision needs to be made on how much we want to limit (or even totally avoid) negative emissions technologies, or not.”¹⁶

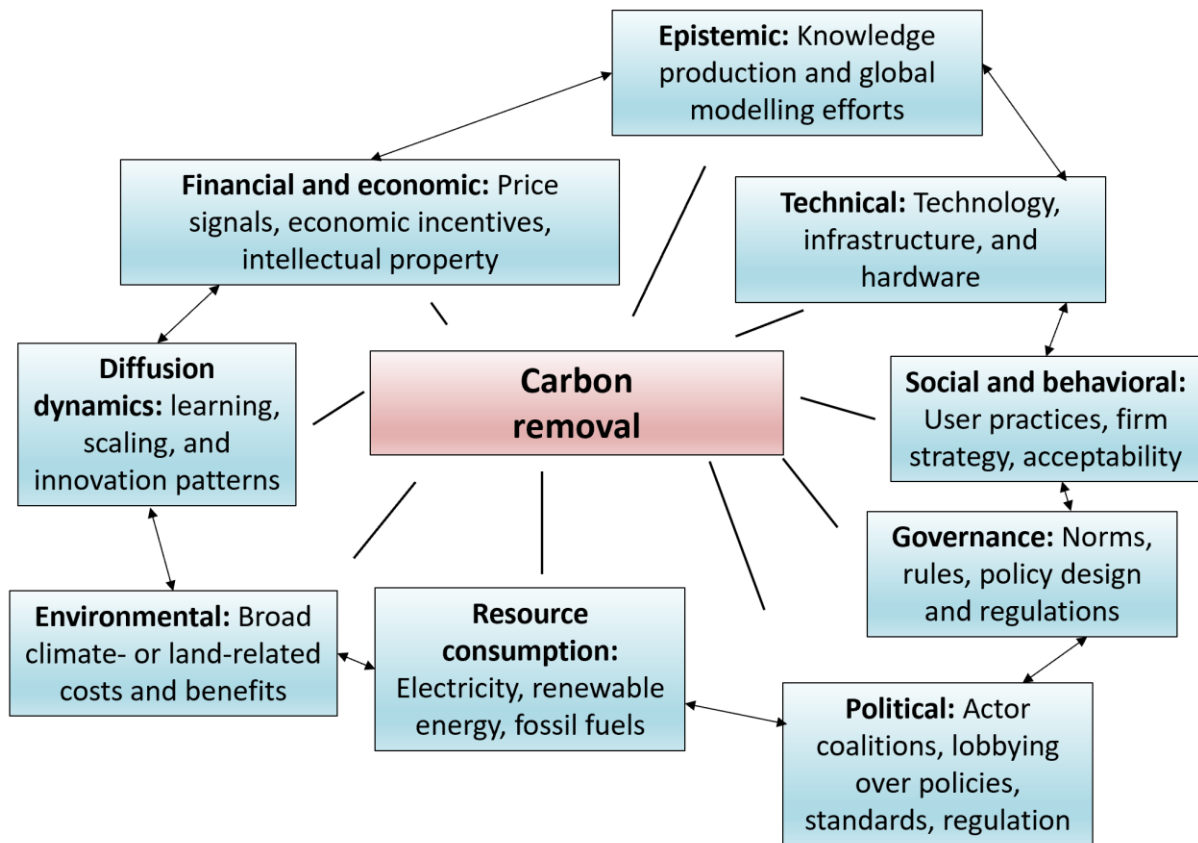
Yet, the pace of enhancing our understanding of innovation in these technologies, other than at the R&D stage, is nascent.¹⁷ Similarly, of all the options policymakers have to address

climate change, the economics, dynamics, and prospective management of carbon removal are one of the most poorly understood, given that pathways have a high degree of uncertainty, risks are complex, and that public acceptance and political support are unknown.^{18 19}

This Review seeks to address some of these gaps, and it provides an urgently needed interdisciplinary and holistic perspective of carbon removal. Such state-of-the-art research is of critical importance in producing a comprehensive, up-to-date, multidisciplinary body of knowledge about future carbon removal pathways, along with, crucially, one more deeply rooted in the social sciences, especially for the research community and policy communities, and affected societies.

To do so, we employ a sociotechnical approach that considers not only the technology of carbon removal, but also how deployment will shape and be shaped by the broader and more heterogenous dimensions summarized by Figure 1. As Sovacool²⁰ summarizes, “the idea of a sociotechnical system helps reveal that technologies must be understood in their societal context, and that the different values expressed by inventors, managers, and consumers shape technological change.” Such “systems thinking” reveals the different elements necessary for a new class of technology such as carbon removal to achieve widespread use, elements (shown in Figure 1) which furthermore interlink and coevolve together. It also maps onto the four core dimensions of the Review which will be introduced in Section 3.

Figure 1: Visualizing carbon removal as a sociotechnical system



Source: Authors, inspired from ²¹. The black bidirectional arrows are meant to depict the interconnected nature of the sociotechnical system, with each distinct dimension able to affect the other dimensions, and vice versa.

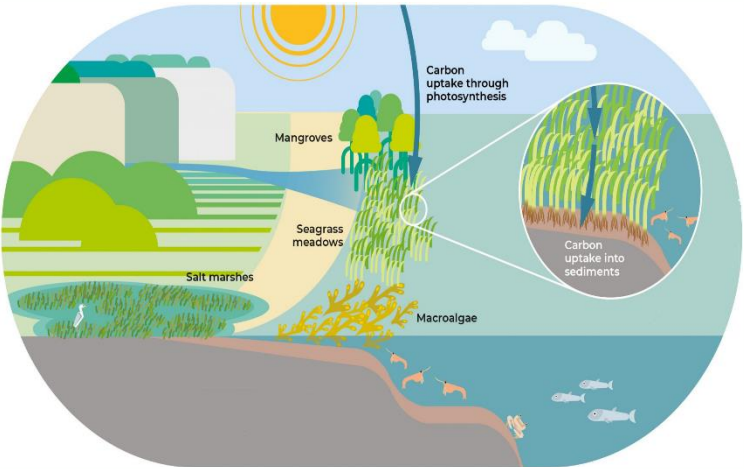
To be clear, a sociotechnical approach still features many of the technical aspects of carbon removal, such as power plants, carbon storage networks, solvents, materials, forest plantations, prospective carbon sinks, and other related technologies or infrastructures. But it also focuses on patterns of resource consumption (electricity, renewable energy, fossil fuels) and the financial mechanisms involved in research and deployment (inclusive of areas such as capital cost of building and operating technologies, business models and markets, and intellectual property). A sociotechnical approach includes political elements (national competitiveness, rivalry, regional cooperation) alongside environmental elements (removed and stored greenhouse gas emissions, a more stable climate, integration with renewable sources of energy, negative externalities) and even behavioral elements (such as the practices of end-users or firms). The approach therefore offers a more holistic assessment of carbon removal, one that seeks to better capture a more complete set of factors involved in any net-zero energy transition.

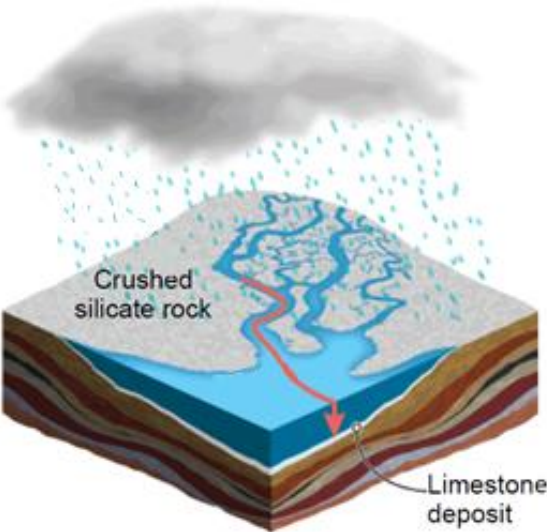
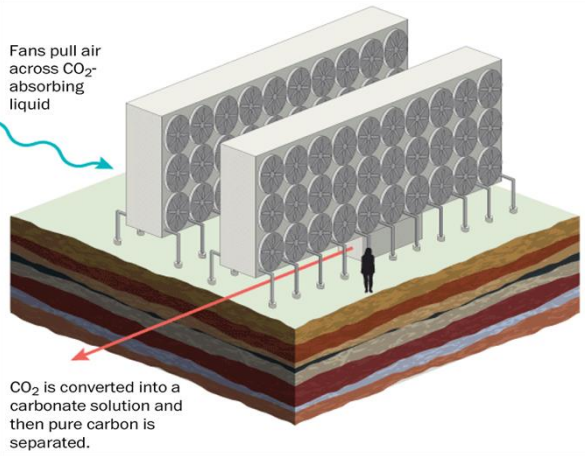
2. Conceptualizing seven carbon removal technologies and practices

The most recent IPCC report defines “carbon dioxide removal” as “anthropogenic activities removing carbon dioxide from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products.”²² A multitude of terms have arisen over the past few decades that seek to describe carbon removal, with some treating it as a reference class of “geoengineering” or “climate geoengineering,”^{23 24} others using terms such as “carbon dioxide removal” or “greenhouse gas removal,”^{25 26} and still others even describing options as parts of climate mitigation or adaptation.²⁷ There is also an intense debate in the literature about whether assessments would do better to “split” to investigate very discrete options or “lump” them together by considering options collectively.^{28 29}

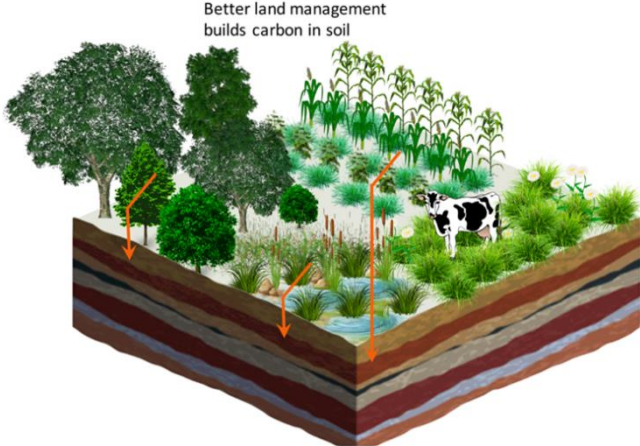
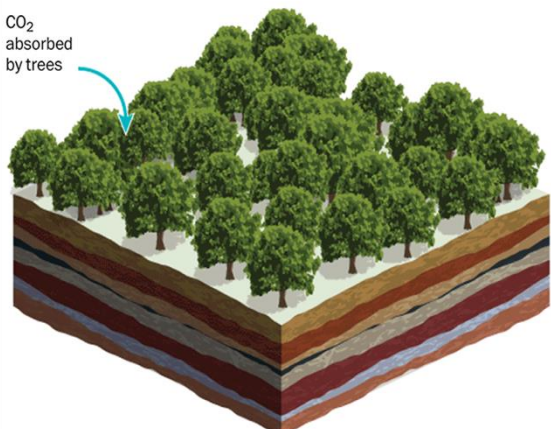
We sidestep such debates in this Review and focus instead on the seven particular classes of carbon removal technologies summarized by Table 1. The first of these is afforestation and reforestation. Both afforestation and reforestation aim to limit the effects of climate change by planting trees (over a period of at least 50 years³⁰), either where there were no trees before in the case of afforestation or where forests have been cut down or damaged for reforestation. As the trees grow, they absorb carbon dioxide from the atmosphere, which is then stored for decades or longer. Some forms of tree harvesting also store carbon by embedding wood into construction material or other harvested wood products. Such measures might result in competition for land and water with agriculture and other uses, however. Also, if trees were harvested or happen to burn down, then the carbon dioxide would again be released into the atmosphere.

Table 1: Overview of seven approaches to carbon removal

Option	Picture	Description	Estimates for carbon removal and sequestration (in GtCo ₂ /year)
Marine biomass and blue carbon	 <p>The diagram illustrates various coastal ecosystems and their carbon sequestration processes. It includes labels for Mangroves, Seagrass meadows, Salt marshes, and Macroalgae. A circular inset provides a detailed view of seagrass meadows, showing 'Carbon uptake through photosynthesis' and 'Carbon uptake into sediments'. The background features a sun, clouds, and a cross-section of the ocean floor with fish and sediment layers.</p>	Harnessing the ability for coastal mangrove forests, tidal marshes, and seagrass meadows to accelerate their uptake of carbon dioxide	<1 (coastal wetlands)

Enhanced weathering and ocean alkalization	 <p>The diagram shows a cross-section of the Earth's crust. A cloud is raining over a landscape where a river flows over a layer of 'Crushed silicate rock'. A red arrow indicates the path of water from the river down into the rock layer, where it eventually reaches a 'Limestone deposit' layer below.</p>	Deploying physical or chemical mechanisms to accelerate the geochemical processes that naturally absorb CO ₂ at slow rates.	2-4 (enhanced weathering) and 1-100 (ocean alkalinity enhancement)
Direct air capture	 <p>The diagram shows a cross-section of the Earth's crust. On the surface, there are two large industrial units with fans. A blue arrow indicates air being pulled across a 'CO₂-absorbing liquid'. A red arrow shows the captured CO₂ being transported underground into a storage layer. Text at the bottom states: 'CO₂ is converted into a carbonate solution and then pure carbon is separated.'</p>	Capturing carbon dioxide from the air via engineering or mechanical systems, and then using solvents or other techniques to store it safely	5-40

Bioenergy with carbon capture and storage	<p>The diagram illustrates the BECCS process. On the left, a forest of green trees is shown with a blue arrow pointing to a red line that descends into the ground, labeled 'CO₂ absorbed by trees'. In the center, a power plant with a cooling tower and smokestack is shown. A blue arrow points from the power plant to a stack of biomass, labeled 'Biomass fuels power plant'. A red arrow points from the power plant down into the ground, labeled 'CO₂ compressed and transported to carbon sequestration site'. The ground is shown in cross-section with various layers of soil and rock.</p>	Harnessing specific energy crops (e.g., perennial grasses, or short-rotation coppicing) or increased forest biomass to replace fossil fuels, and capturing and storing consequent carbon dioxide	0.5-11
Biochar	<p>The diagram illustrates the biochar process. On the left, a forest of green trees is shown. A blue arrow points from the trees to a pile of organic matter, labeled 'Some of the organic matter is converted to biochar'. A blue arrow points from the organic matter to a grey cylinder labeled 'Heat'. A red arrow points from the cylinder down into the ground, labeled 'Carbon returned to soil as biochar'. The ground is shown in cross-section with various layers of soil and rock. A cow is shown grazing in a field next to the ground.</p>	Managing the thermal degradation of organic material in the absence of oxygen to increase soil carbon stocks and improve soil fertility	0.3-6.6

Soil carbon sequestration or enrichment		<p>Growing cover crops, leaving crop residues to decay in the field, applying manure or compost, using low- or no-till systems, and employing other land management techniques to improve soil</p>	<p>0.6-9.3</p>
Afforestation and reforestation		<p>Planting trees or vegetation to absorb carbon dioxide</p>	<p>0.5-10</p>

Source: Compiled by the authors, with estimates for carbon removal and sequestration from Table TS:7 from the most recent IPCC report. Pictures for afforestation and reforestation, BECCS, and enhanced weathering, from ³¹. Pictures for soil carbon sequestration and biochar, from ³². Picture for marine biomass and blue carbon, from ³³.

Both marine biomass and blue carbon focus on improving the capacity of the Earth's oceans to store carbon dioxide. Blue carbon does this by restoring or growing ecosystems such as mangroves, salt marshes, and seagrass meadows, while marine biomass grows seaweeds or macroalgae. As all of these grow and mature, they absorb carbon dioxide from the atmosphere which can be stored for decades to centuries when it is taken up into sediments at the bottom of the ocean after they decay or are eaten by other animals and pass through the food chain. Whether such measures can be easily managed and implemented is uncertain however, given the number of actors involved. Also, if these ecosystems are disturbed or destroyed or the plants are harvested, then the carbon dioxide would again be released into the atmosphere.

Direct air capture with carbon storage utilizes very large fans to remove carbon dioxide directly from the air. Once the carbon dioxide is pulled into the fans, absorptive substances convert the carbon dioxide using a chemical process into a form that can be stored indefinitely underground. This measure takes up limited land but does require high amounts of energy along with being reliant on the availability of geological formations for carbon storage. As the technology is in the early stages of development being developed, it has also not yet been demonstrated to work at a large scale and costs are currently very high.

Bioenergy with carbon capture and storage (BECCS) emphasizes growing and harvesting plants as a source of energy and thus carbon storage. As plants grow, they absorb carbon dioxide from the air. By burning these plants and/or capturing the carbon dioxide that is released through a chemical process, this measure can provide energy for homes and businesses or be stored underground indefinitely. Such techniques might result in competition for land and water with agriculture and other uses, however. It is also reliant on the availability of geological formations for carbon storage and has not yet been demonstrated to be work at a large scale.

Enhanced weathering works by increasing the ability of rocks to absorb carbon dioxide from the atmosphere. As rocks such as limestone and basalt are exposed to natural processes like rain, wind, or the action of waves, they are ground down, which allows them to absorb carbon dioxide from the air. However, this process takes place extremely slowly, so this measure looks to speed it up by physically or chemically grinding the rocks before placing them onto agricultural lands, beaches, or next to rivers. Over time, rocks and their stored carbon dioxide are ultimately stored in oceans indefinitely. Whether this measure will work at a large scale is uncertain however, as is whether the need for rocks will cause negative ecological and human health impacts (and greater energy use) from additional mining and extraction.

Soil carbon sequestration seeks to change agricultural and land-management techniques in order to store more carbon dioxide in the Earth's soils. For instance, by planting different crops, leaving crop residues on the field, or increasing the number of trees on agricultural lands, this measure could help remove carbon dioxide from the atmosphere and bury it underground for decades to centuries. No additional land would be required, and it is possible to also improve soil quality. Whether farmers and land managers are willing to consistently implement these techniques is uncertain, however. Also, if agricultural practices are not sustained, the carbon dioxide would again be released into the atmosphere.

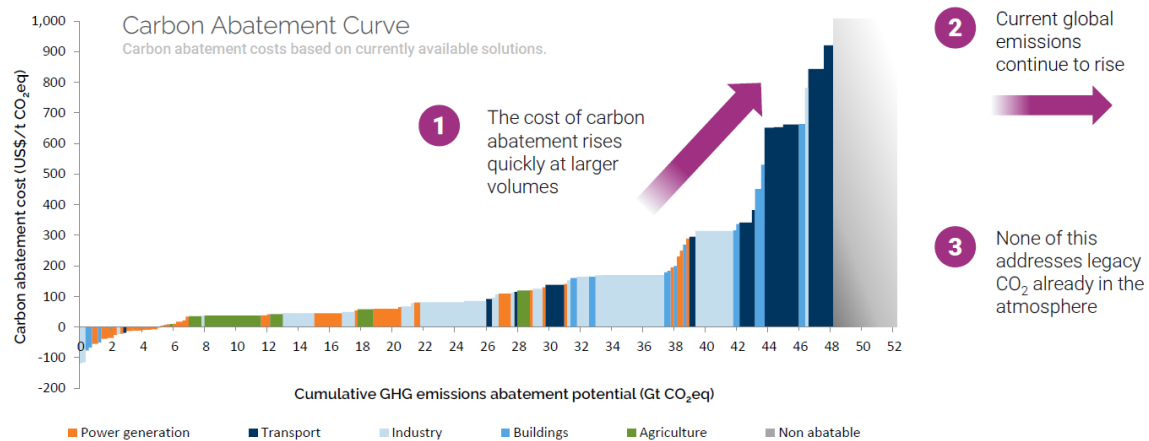
Lastly, biochar removes carbon by converting organic material, whether from plants or animals, into a form of charcoal. By heating such material in the absence of oxygen, it is possible to remove carbon dioxide from the air which, if mixed into the soil, can be stored for decades to centuries. This measure does not require more land while also having the chance to improve soil quality. Whether farmers and land managers are willing to consistently implement these techniques is uncertain, however. Its need for biomass may also result in competition with other uses such as fuel or electricity.

Over time, the understanding of what constitutes “geoengineering” has evolved, to the point where “carbon removal” and “solar radiation management” are increasingly, though not exclusively, considered separately, as distinct options for tackling the climate crisis. This is occurring for various reasons, though one is the increasing acceptance of carbon removal as an option in, e.g., IPCC modelling³⁴ along with concerns that solar geoengineering might constitute an unwanted distraction and/or moral hazard for broader mitigation efforts.^{35 36 37} In part, it is necessary to pushback on this received wisdom, notably, given that it forecloses discussion of portfolios which might employ both kinds of technologies, even potentially in sequence,^{38 39 40} not to mention the tendency for what is taken as a “distraction” from climate mitigation to evolve over time.^{41 42} Accordingly, and in order to adequately reflect the entirety of the literature on public acceptance of carbon removal, we also here consider studies, particularly those conducted closer to the start of the last decade, wherein there was not such a strong distinction between “carbon removal” and “geoengineering”, broadly understood.

Many carbon removal options intersect with net-zero energy technologies, which Azevedo and colleagues define as “energy systems that emit no net CO₂ and potentially no net greenhouse gases.”⁴³ Such net-zero transitions are required across a number of sectors such as electricity and power generation⁴⁴, buildings⁴⁵, transport⁴⁶, and agriculture⁴⁷ (to name a few), with increasing per-ton costs for carbon abated, as Figure 2 indicates. In this way, carbon removal becomes an *energy* policy and security issue because various forms of removal are

advocated to compensate for energy sector emissions, and many forms also have different energy inputs. However, net-zero energy technologies have radically different characteristics in innovation, performance and operations, governance trends and even modeling from the conventional energy systems of today.⁴⁸ Moreover, there is still the issue of handling legacy CO₂ emissions, which is where carbon removal can play a role, depending on its per-ton cost, of helping to substitute for increasingly costly solutions to abate emissions and/or helping to deal with legacy emissions. Net negative emissions technologies and carbon removal are thus tightly coupled at many layers of the sociotechnical system.

Figure 2: Global carbon abatement curve for various net-zero technologies and climate pathways



Source: ⁴⁹

3. Four critical areas of carbon removal research: Assessment, policy, innovation, and behavior

A sociotechnical lens applied to the seven carbon removal options in Section 2 brings into focus four very different, but salient, dimensions related to future research, deployment, policy, and governance. These four dimensions are all cross-cutting in that they involve multiple elements of the sociotechnical system (technology, behavior, policy and politics, resources, finances, and the environment), and some of them involve all elements. We will return to how these four dimensions themselves interact, and germinate interconnections, in Section 4.

3.1 Assessments: From global modelling to critical reflection and multiple scales, actors, and mixed-methods designs

This particular dimension intersects with the epistemic and political aspects of the sociotechnical framework. Building on the recent publication of the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report,⁵⁰ academic communities (reflected in both formal research communities supporting carbon removal⁵¹ as well as less formal knowledge networks and epistemic communities⁵²) have often recognized that the emergent strategy for carbon removal has emphasized a limited number of approaches – afforestation and reforestation, and a more unscaled and immature hybrid of bioenergy and carbon capture and storage. These particular emissions pathways were first prominently featured in the Fifth Assessment Report⁵³ and the Special Report on 1.5C.⁵⁴ IPCC pathways have since helped spur an initial wave of national and corporate commitments towards net-zero (or carbon and greenhouse gas neutrality) by 2050, and expanding efforts in innovation, incentivization, and regulation. The Integrated Assessment Modelling (IAM) community that constructs these pathways has gone to further efforts to expand the inclusion of social science, innovation, and policy inputs, highlighted in future programmes of work surrounding the Shared Socioeconomic Pathways (SSPs), which further cluster mitigation options into sets of “futures” defined by high and low challenges to mitigation or adaptation.⁵⁵

Such modelling efforts, moreover, are not purely technical or scientific, but inherently social and political. Lahn traced the scientific work being done on carbon budgets within the IPCC and identified multiple pressures from scientists to advocate for their work, to be policy relevant, and to include political parameters in their modelling.⁵⁶ This “modifying-work”, consequently, has shaped not only the size and scope of carbon budget assessments but also the adoption of new net-zero targets and social campaigns around divestment and the stranding of fossil-fuel assets. Edwards similarly examined computer-modeling efforts within the IPCC and the broader climate change community, and documented a healthy debate and controversy within particular models and scenarios, which only became misconstrued once taken up by the media and manipulated by particular lobbies.⁵⁷ As he went on to write:

Like most true infrastructures, the climate knowledge infrastructure is made up of many interlocking technical systems representing many links and layers of systems and structure, most of which long predate the IPCC. The assessment process ... has created imperatives, structures, and processes that link a vast array of knowledge producers and bring their disparate methods and products to bear on a common project.⁵⁸

Contestation and disagreement are a normal part about how such iterative climate science is done, and it means climate knowledge is messy—full of countless versions and interpretations, dependent on an ever-expanding base of evidence and refinement, and reliant on entirely new forms of intergovernmental organization. Edwards concludes that these features make global climate science akin to “trying to make a movie out of still photographs shot by millions of different photographers using thousands of different cameras”.⁵⁹ More recently, Low et al. explored how similar processes of divergence and contestation hold true for carbon-removal scenario building.⁶⁰ In their study, anticipatory assessments of climate interventions were labelled as perpetually “undone science,” given that explorations of the emerging societal dimensions of climate pathways required new modes of disciplinary expertise, qualitative and deliberative practices, and degrees of stakeholder involvement that modelling processes have difficulty navigating.

Resonantly described as part of a “cartography of pathways”^{61 62}, carbon-removal-heavy scenarios have thus been critiqued, defended, nuanced, and further expanded. Initial criticism came from social science and policy analysis, pointing out the perceived feasibility of otherwise implausible climate targets – firstly, by creating the concept of a temporary, near-term ‘overshoot’ of temperature targets under the Paris agreement, to be drawn down by carbon removal approaches in later decades, and furthermore, by doing so through socio-technical approaches that were unproven and speculative at scale.^{63 64} In (the leadup to) AR6, modelling efforts have in turn responded by nuancing the scope of carbon removal, and by limiting overshoot in pathways.^{65 66 67}

Critique has been also expanded into interrogation of IAMs – that pathways have not simply mapped alternative mitigation options, but functionally shepherded global climate policy into developing carbon removal⁶⁸; that largely-hidden parameters within modelling heavily influence what options emerge (e.g. the discount rate⁶⁹); on model-centric prioritization of techno-economic solutions in response to policy targets⁷⁰; and that IAMs have a demonstrably long history of meeting targets with “technological promises”.⁷¹ Much critique takes place in the context of “mitigation deterrence”^{72 73}, historically and still colloquially referenced as a “moral hazard”⁷⁴: that the promise of far-off carbon removal presents systemic disincentives to undertake deep-lying decarbonization.^{75 76 77 78} Some studies have attempted to gauge the amount and type of emissions that might be avoided by the prospect of carbon removal.^{79 80}

Mapping the “feasibility” of carbon removal approaches, in particular, has grown, especially insofar as it identifies a misalignment between priorities and contexts that are

techno-economic (for IAMs) vs. socio-political or environmental (for other observers).⁸¹ Calls have therefore emerged exploring how more multi-disciplinary, local-to-regional criteria for examining how carbon removal can be integrated into models and adjoining assessments.^{82 83} ⁸⁴ Further thought has gone into the inclusion of non-quantitative social science knowledge into IAM work, and the expansion of modelling into a more multi-scale, mixed-methods, and actor-focused (from industry, to local communities, to national and regional polities) mode of assessment.^{85 86 87 88 89 90} Particular shortcomings within carbon removal modelling, and areas of needed improvement, include social and political drivers⁹¹ and geopolitics⁹², small-scale experiments and pilot demonstrations⁹³, ethics, equity, and justice⁹⁴, and connections to biodiversity⁹⁵, as well as possible synergies or trade-offs with the Sustainable Development Goals.^{96 97 98} Crucially, calls are emerging for a focus on the thus-far elided perspectives of the Global South.⁹⁹

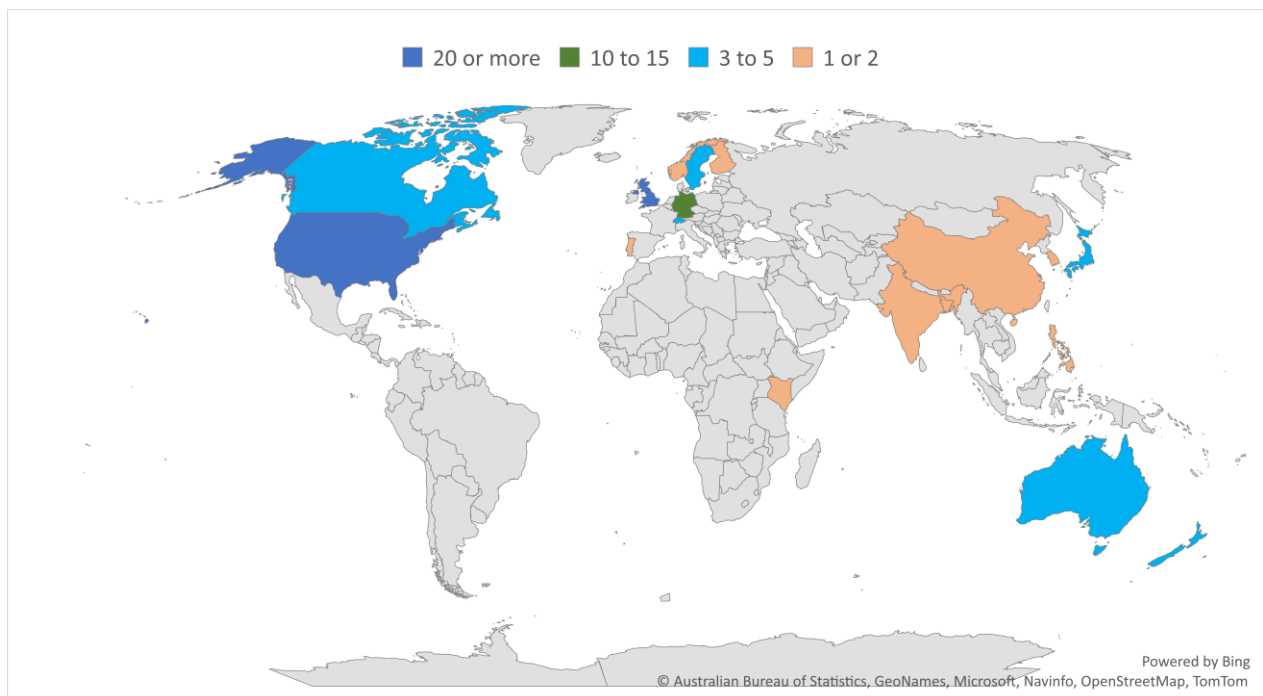
A key aspect of this work, in light of the potential incorporation of carbon removal into Nationally Determined Contributions and into carbon offsetting and trading, is on carbon accounting assessments for life cycle emissions¹⁰⁰, supply chains¹⁰¹, and storage¹⁰² that would stretch unevenly for different kinds of carbon removal across different timelines and geographies¹⁰³. Additionally, there is a pressing need to expand assessment beyond the initial focus on agricultural and forestry management approaches such as BECCS and afforestation and reforestation¹⁰⁴, to consider distributional impacts and the question of who pays¹⁰⁵, and highlight the risks of incorporating removals in markets.¹⁰⁶ In-depth, multidisciplinary, and politically oriented assessments in other spheres – such as DACCS¹⁰⁷, enhanced weathering, or marine and other ocean-based approaches¹⁰⁸ – are only just beginning.

3.2 Social acceptance: Community engagements and perceptions

This dimension connects with the social and behavioral as well as environmental aspects of the sociotechnical framework. An adjoining literature on public understanding and acceptance of carbon removal technologies has increased in scale, complexity, and geographic focus over the past decade. When it comes to the methodology employed, quantitative approaches (and surveys in particular) have tended to dominate, accounting for more than half of all studies. While an additional third have employed qualitative approaches, such as interviews or focus groups, only eight of all studies have utilized a mixed-methods approach, for instance, by combining surveys with deliberative workshops or an economic experiment.¹⁰⁹

Despite the existence of some methodological diversity, the same is less true when it comes to the geographic scope of public-understanding research. As illustrated by Figure 3, a few countries are starkly over-represented in the literature, notably, the United Kingdom (22 times), United States (20), and, to a slightly lesser extent, Germany (13). Together, these countries account for more than 60% of times that a country is included in a research study. No other country appears more than five times, with countries such as Switzerland, Australia, Japan, and Sweden the next-most studied. Quite critically, only seven countries from the Global South have been examined, with China the only one to be considered twice. Of these seven, all but one is in Asia and Oceania, that being Kenya. No country in Latin America has yet been the focus of research.

Figure 3: Geographic Focus of Research on the Social Acceptance of Carbon Removal

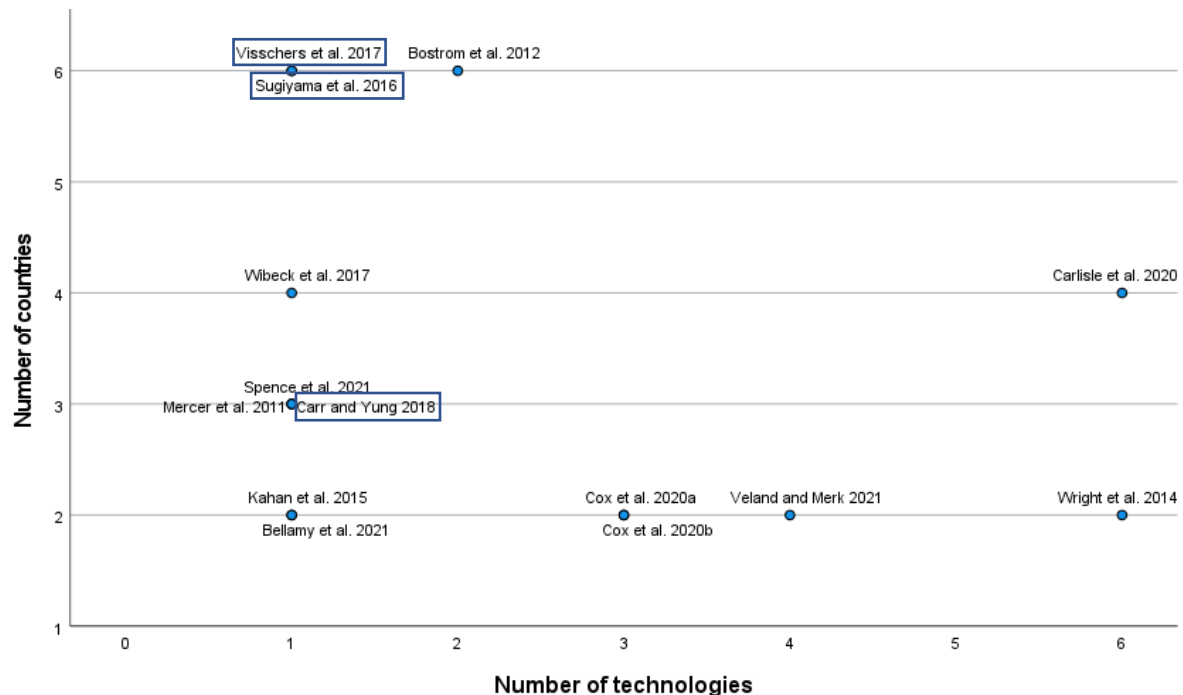


Source: Authors.

In addition, there is a significant tendency for research on this topic to focus on a single country, often with a focus on only one technology or by looking at “carbon dioxide removal” as a suite of “climate geoengineering” (see Figure 4). Of the 57 studies that we catalogued, less than a quarter have employed a cross-country design: six surveys;^{117 118 119 120 121 122} five focus groups and/or interviews;^{123 124 125 126 127} and three with mixed methods.^{128 129 130} For the most part, such studies tend to compare views of the public in western, industrialized countries to one another, with the most frequent pairings including United States and United Kingdom, either on their own or with a couple of other countries. Moreover, only three studies have employed a cross-country design to compare and contrast perceptions in the Global North with

those in the Global South.^{131 132 133} All of these, however, only explore views on a single technology, notably BECCS, or for the topic of geoengineering in general.

Figure 4: Breakdown of Studies with Cross-Country Design



Source: Authors. The three studies that are outlined represent those that included at least one country from the Global South. Although Bostrom et al.¹³⁴ does include Bangladesh, this amounts to only 25 undergraduate students versus, for instance, nearly 300 in Austria and around 150 in both Norway and Germany.

Lastly, given the predominant reliance on surveys in the literature, including as part of mixed-method designs, some discussion of the kinds of surveys conducted is required. To give a sense of how this research has been conducted, an overview of all surveys exploring multiple technologies is provided in Table 2 (also, we provide a full enumeration of all studies on public acceptance and their relevant factors in the Supplementary Material). The principal explanandum of such research is acceptance or support for the technology in question – or, e.g., geoengineering or CDR in general – and, as a secondary aspect, perceptions of risks and benefits. At the same time, what is notable is how research has tended to focus on a handful of factors to explain public perceptions. In particular, most studies have inquired on prior familiarity or knowledge on geoengineering or certain technologies^{135 136 137 138 139 140 141} and perceptions of and concern about climate change.^{142 143 144 145 146 147 148 149 150 151 152 153} Values have also played a prominent role, typically drawing on the value orientations scale,^{154 155} which enables studies to explore the relative impacts of altruistic, egoistic, and biospheric values on individual attitudes.^{156 157 158 159 160 161 162}

Table 2: Surveys of carbon removal perceptions looking at multiple technologies

Authors	Year	Journal	Countries	Sample Size	Carbon removal technologies included	Measures
Campbell-Arvai et al.	2017	<i>Climatic Change</i>	United States	N=984	CDR in general; BECCS; DACCS; Reforestation	Perceived threat of climate change; Support for climate change mitigation; Political ideology
Braun et al.	2018	<i>Climate Policy</i>	Germany	N=3526	Afforestation; SAI	Awareness; Attitudes towards risk; Environmental beliefs (NEP); Perceived seriousness of climate change; Trust in institutions; Acceptance; Attitudes; Value orientations; Cognitive reflection
Merk et al.	2019	<i>GAIA</i>	Switzerland	N=891	BECCS; SAI	Familiarity; Perceived risks and benefits; Support for research and deployment
Wolske et al.	2019	<i>Climatic Change</i>	United States	N=980	Afforestation; DACCS; BECCS	Familiarity; Tampering with nature; Aversion to tampering with nature; Support
Jobin and Siegrist	2020	<i>Risk Analysis</i>	Switzerland	N=1575	DACCS; BECCS; Afforestation; Biochar; Enhanced weathering; Ocean fertilization; Soil carbon sequestration; SAI; Cloud brightening; Mirrors in space	Subjective knowledge; Perceived risks and benefits; Tampering with nature; Trust in science/institutions; Support for research/deployment; Concern about climate change
Klaus et al.	2020	<i>Technology in Society</i>	Germany	N=678	BECCS; SAI	Perception of climate change; Severity of climate change threat; Positive and negative affect; Perceived risks and benefits; Perceived fairness; Trust in decision-makers; Trust in society; Locus of control; Subjective norm; Tampering with nature; Ecological behavior; Acceptance; Behavioral intentions
Sweet et al.	2021	<i>Climatic Change</i>	United States	N=1222	Soil carbon storage (with and without biochar); BECCS; DACCS; Afforestation	Climate change beliefs; Aversion to tampering with nature; Perceived naturalness; Support for CDR
Wenger et al.	2021	<i>Climatic Change</i>	Switzerland	N=693	BECCS; DACCS; biochar; afforestation; soil carbon sequestration	Tampering with nature; Trust in responsible actors; Perceived risks and benefits; Support for CDR; Affective evaluation

Note: Details for Merk et al. (2019) pertain to the first of the two surveys, since this was the only one to include multiple technologies. DACCS stands for Direct Air Capture with Carbon Storage: BECCS stands for Bioenergy with Carbon Capture and Storage. CDR stands for Carbon Dioxide Removal. SAI stands for stratospheric aerosol injection.

Other studies have looked at the role of environmental beliefs in particular, almost exclusively using the New Ecological Paradigm scale^{163 164 165 166 167 168 169} Still others, meanwhile, consider the impact of trust, whether in decision-makers, climate science, scientists, or various institutions.^{170 171 172 173 174 175 176 177 178 179}

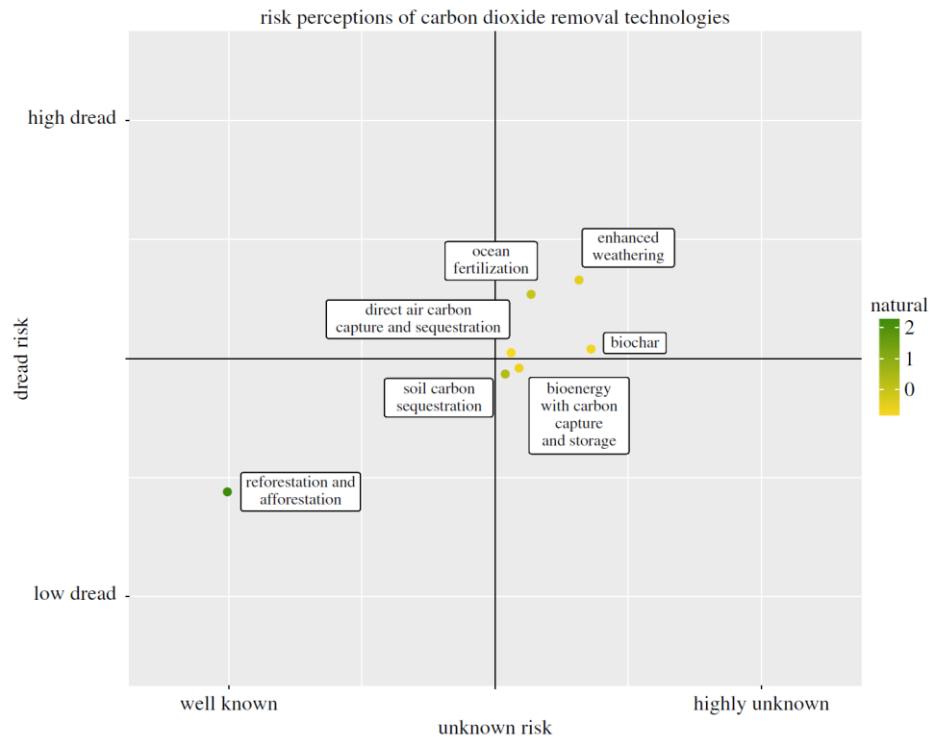
In view of the special importance of naturalness concerns in this context,^{180 181} there is an undercurrent related to perceptions of the relationship between negative-emissions and geoengineering technologies and the natural world,^{182 183} notably, through the “tampering with nature” factor.^{184 185 186 187 188 189} Recently, such interest has prompted development, validation, and application of the “aversion to tampering with nature” scale, which offers a corresponding individual factor to perceptions that a technology tampers with the natural world.^{190 191 192} While still at a minimal level, several studies have tried to explore the role of affective factors.^{193 194 195 196 197 198 199}

As a final note, we highlight another notable limitation, which is the principal focus on attitudes of the public instead of, e.g., intention or behavior. Indeed, only one study²⁰⁰ explicitly inquires about behavioral intentions, e.g., if participants would support a petition in favor or against the measure, might try to convince others, or would vote for a party or national referendum which took a stance one way or the other. Two other interesting exceptions include a survey by Klaus et al.²⁰¹ that established how type and stance of different information sources, i.e., of information use by individuals, affected acceptance of various geoengineering options. Furthermore, by means of a “framed field experiment”, Merk et al.²⁰² not only looked at the potential risk of moral hazard from being informed about geoengineering but also, using a follow-up task, if this was reflected in the decision to purchase voluntary carbon offsets. Rather than pointing to evidence of moral hazard, they found that those informed were more likely to purchase offsets, that is, to attempt to mitigate their climate impact. Of course, the presently hypothetical nature of most geoengineering technologies limits the degree to which intentions or behavior can be explored, even if certain options are gradually becoming more feasible. Nevertheless, more such creative attempts would provide key insights into public acceptance.

As a result, there is a gap within the literature in terms of both the scope and breadth of understanding of carbon dioxide removal approaches, especially in view of the growing scientific and media attention to these as a potential option for dealing with global carbon budgets and climate targets.²⁰³ In sum, there is a need for more research that simultaneously explores and attempts to offers insights into perceptions of multiple climate-intervention technologies across multiple countries.

A final relevant theme concerns social opposition to the technologies, or resistance. As an example, one study noted a high amount of “dread” associated with carbon removal technologies, with variations in the level of dread evoked summarized in Figure 5.²⁰⁴ Bertram and Merk²⁰⁵ found in their review that direct injection of carbon dioxide was viewed “very negatively” and strongly opposed by the public, while Low et al.²⁰⁶ catalogued 21 cases of opposition against ten early-stage enhanced weathering experiments (among other non-CDR based climate measures) and noted social opposition across all types, including terrestrial environments such as croplands and rangelands (e.g., the Guelph wollastonite trials, Working Lands Innovation Center, and Project Carbdow), coastal and marine environments (e.g., One Tree Reef, Project Vesta, OceanNETs.), and the mining sector (e.g. FPX Nickel Corporation trials or CarbonVault™). Cox et al.²⁰⁷ add that when one takes into consideration social opposition and lack of social acceptance, some options, such as iron fertilization, become completely infeasible and must be taken entirely off the table. In some situations, opposition is not to the technologies themselves, but the “place-blind” ways they are implemented, i.e., as being perceived as unfair or inequitable.²⁰⁸ Furthermore, there is a growing tendency to aim at understanding not just the support or opposition for technologies in a broad sense but also their particular fit in different national or policy contexts as well as the particular concatenations of how they will be rolled-out and deployed. Other forms of opposition could therefore relate to a perceived inequity in the distribution of costs and benefits, whether within a given nation or between nations in a global context, or frustration over procedural issues of fairness and representation in policymaking and planning.^{209 210}

Figure 5: Risk perceptions of carbon removal technologies

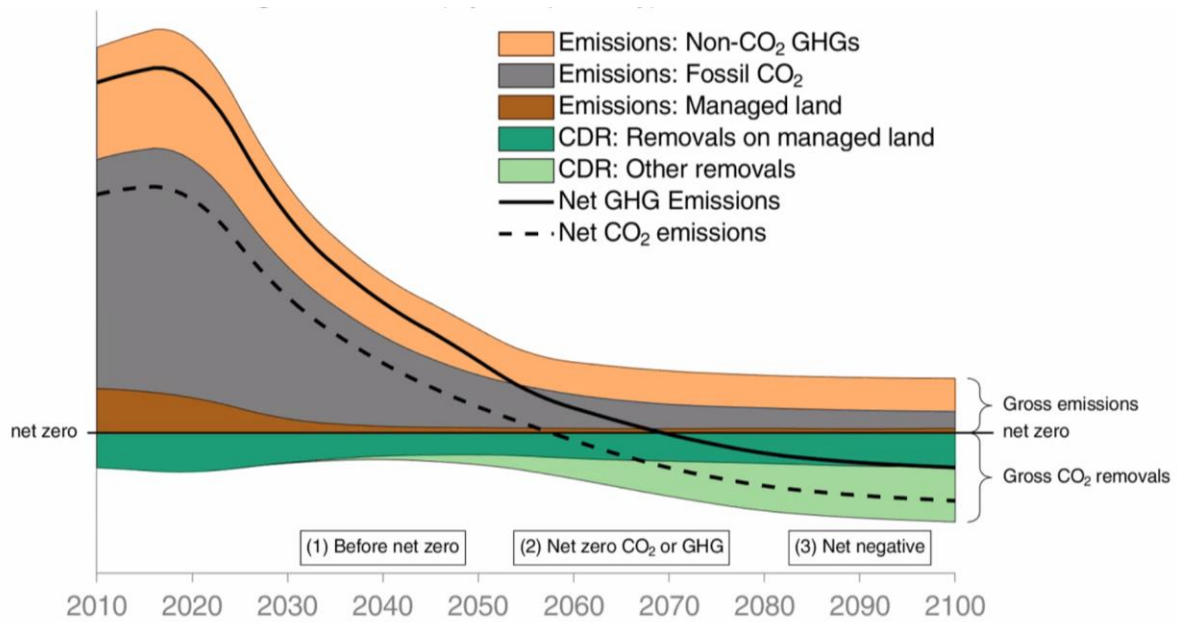


Source: ²¹¹ As noted by the authors, values stem from a survey of Amazon MTurk participants (N=113) and should not thus be considered a representative sample.

3.3 Innovation: Diffusion, learning and scaling

This dimension interrelates with the diffusion dynamics and technical aspects of the sociotechnical framework, as well as some of the epistemic and resource aspects. Understanding pathways for research, innovation, and technology diffusion for carbon removal is a third sociotechnical topic demanding further inquiry. Most of the modeling results discussed in Section 3.1 show that carbon removal needs to be scaled up massively to remove net gigatonnes of additional CO₂ annually by mid-century²¹², a process which needs to begin soon given the decadal time scales inherent to technology adoption (see Figure 6) BECCS in particular would need to expand to restore the climate at the scale of billions of tons of additional production of fuels or building materials per year.²¹³

Figure 6: Stylized pathways for greenhouse gas emissions and carbon removal from 2010 to 2100



Source: ²¹⁴ Note: GHG = greenhouse gases, CDR = carbon dioxide removal.

However, previous work locating carbon removal papers in the process of innovation has identified many “knowledge gaps,” including some of the up-scaling issues or side-effects shown in Table 3. These gaps extend far beyond mere “modeling gaps” to include gaps in empirical data, inconsistent data, and a lack of comprehensive field studies. For enhanced weathering, knowledge gaps may relate more to being able to detect experiments and attribute impacts, whereas for direct air capture knowledge gaps are more about upscaling and side-effects. Afforestation has gaps related to knowledge about land use practices, biochar and BECCS about soil quality and fertilizer use.

Table 3: Gaps in knowledge and evidence for selected carbon removal technologies

Technology	Category	Nature of field studies	Knowledge gaps
Enhanced weathering	Land-based and/or coastal (in application), ocean-based (for storage)	Unconstrained, transient, small scale, sometimes illegal	Detecting experiments, attributing impacts, upscaling issues, unanticipated side-effects
Direct air capture	Land-based, physical transport of carbon	Unconstrained, transient, medium scale	Upscaling issues, side-effects
Land-based carbon dioxide removal	Afforestation	Impermanent, large scale	MRV of forest management practices, permanence of emissions reductions
Biochar	Soil amendments	Unconstrained, transient, small to medium scale	Extent of fertilization use, interactions with

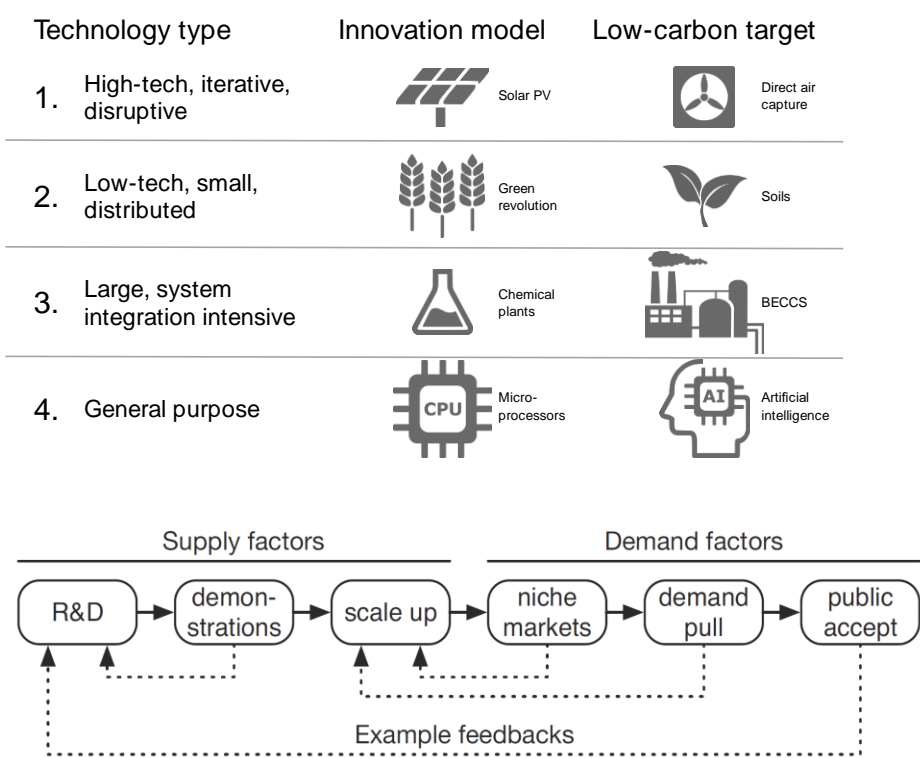
			other systems (water, air pollution)
BECCS	Bioenergy crop plantations	Unconstrained, transient, small to large scale	Extent of fertilizer use, interactions with other systems (water, air pollution)

Source: Modified substantially from ²¹⁵. MRV = monitoring, reporting, and verification.

Further research has revealed “innovation gaps”²¹⁶; most carbon-removal technology analyses are limited to the early stages of innovation (e.g., R&D) and have yet to seriously assess “demand pull”—market opportunities, policies, and niche markets that would stimulate their investment, improvement, and adoption. No comprehensive information exists on which private and public organizations are actively developing and patenting these technologies.

Some cutting-edge work has begun to address this. Nemet²¹⁷ places carbon removal within a taxonomy of low-carbon technology types captured in Figure 7. Such typologizing helps examine carbon removal technology in terms of possible scale, markets, adoption, system integration, and policy relevance.²¹⁸ Reliability among carbon removal options varies; some geological storage sites may be more secure than others, while others seek to store carbon in the biosphere or forests. Further, lifecycle emissions reduce net sequestration and add uncertainty, especially in the case of bioenergy for BECCS.^{219 220} Innovation accelerators for carbon removal could also have a role to play for technology push, knowledge spillovers, and demand pull that emerge from assessing both case studies as well as technology dynamics, adoption, and portfolio analysis.²²¹

Figure 7: Typologies of technologies and innovation dynamics for carbon removal



Source: ^{222 223}

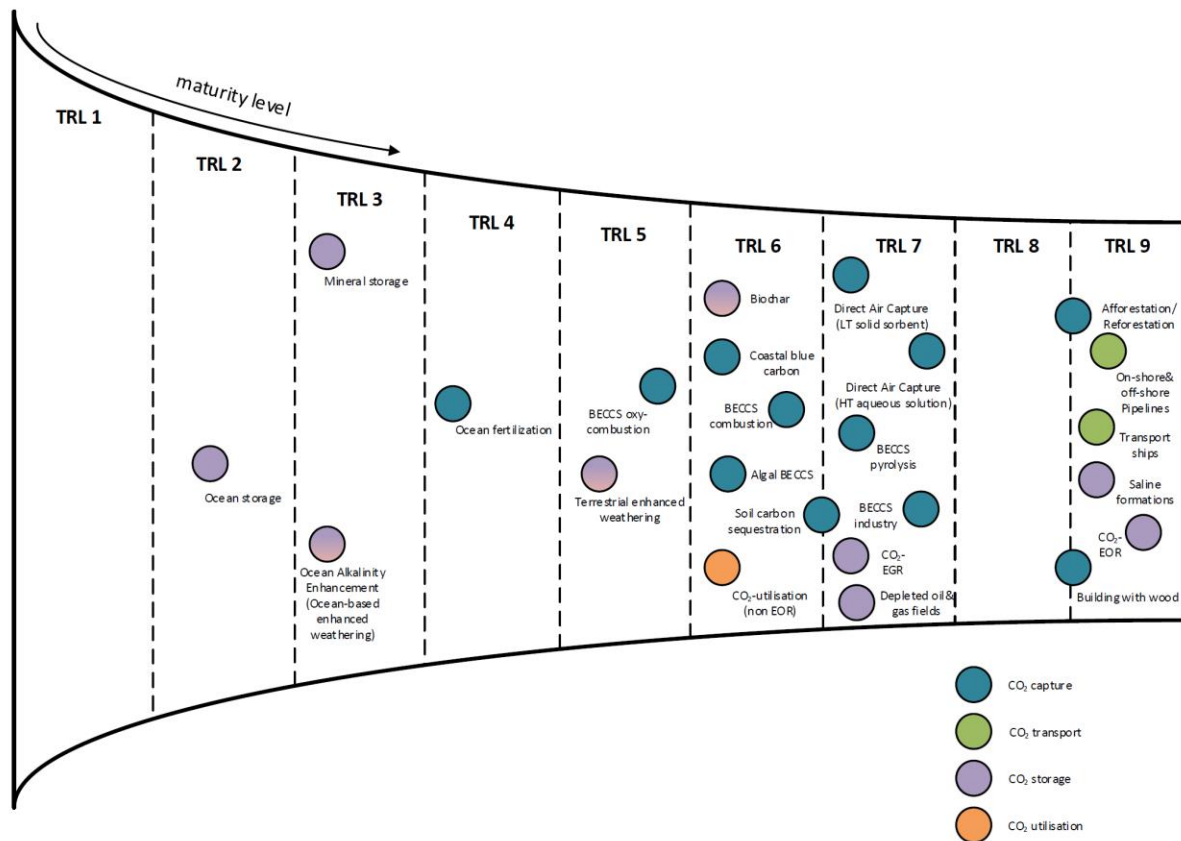
A final innovation challenge relates to the heterogeneity of particular carbon removal options themselves, in terms of readiness. One helpful framework for examining the readiness of a technology is the “Technology Readiness Level,” or TRL. TRLs are a widely used conceptual metric and framework for systematically measuring and managing technologies over different parts of the journey from invention to maturity²²⁴. Nine TRLs are often identified in order to track the status of development progression:

1. Initial idea: basic principles have been defined
2. Application formulated: concept and application of solution have been formulated
3. Concept needs validation: solution needs to be prototyped and applied
4. Early prototype: prototype proven in test conditions
5. Large prototype: components proven in conditions to be deployed
6. Full prototype at scale: prototype proven at scale in conditions to be deployed
7. Pre-commercial demonstration: solution working in expected conditions
8. First-of-a-kind commercial: commercial demonstration, full-scale deployment in final form
9. Commercial operation in relevant environment: solution is commercially available, needs evolutionary improvement to stay competitive

The TRL framework is increasingly used and expanded as a springboard to investigate the social dimensions of new or experimental technologies, especially in the context of climate change mitigation or decarbonization.^{225 226 227 228}

In Figure 8, we draw from a recent review of carbon removal-experiments to depict the specific TRLs for 24 specific applications of our seven types of carbon removal. The TRL diagram has three implications for research and policy. First, it requires the horizontal or vertical coupling together of different elements of the sociotechnical system, such as capture, transport, or storage. As the diagram indicates, some options (in blue) deal only with the carbon capture element of carbon removal, such as afforestation, direct air capture, or BECCS. Others, in green, deal only with transport, such as pipelines or ships. Options in purple deal almost entirely with storage, such as biochar, mineral storage, or ocean storage. One option in orange could even be used (or misused) via direct air capture to promote advanced oil recovery and enhanced fossil fuel use.²²⁹ Second, it illustrates very different levels of readiness, with some options (ocean storage, mineral storage) having low TRLs, and on the cusp of basic research; conversely, options such as afforestation or storage in saline formations are fully developed and commercialized. Other options such as enhanced weathering, BECCS, and direct air capture fall into the middle. Each therefore exist at a different stage of research, development, and deployment and may need very different support mechanisms; in short, there is no “one-size-fits-all” policy to assist and promote carbon removal innovation. Third, given many of the options have low- to mid-TRLs, there is great uncertainty about future deployment and performance; some options may never actually achieve readiness nor escape their lower-bound TRLs.

Figure 8: Visualizing the Technological Readiness Levels for Carbon Removal Options and Particular Applications



Source: Authors, modified from ²³⁰. Note: we also include the technologies themselves given that, among other things, these help to provide reference for how particular applications can vary depending how and in which sector the technology is applied.

Existing experiments, and accompanying learning processes, may not be attuned to overcoming innovation gaps and may not necessarily help to advance options to graduate out of the early-stage TRLs. One review noted, for example, that for ocean-based and marine carbon-removal options, experiments remain limited to very small scales, run over limited periods of time, function as one-off events, and have little capability to scale up.²³¹ Yet experiments that are larger and cut across national or even transboundary locations will be even more challenging to monitor, regulate, and approve.²³² Existing supply chains for biomass, similarly, are not extensive enough to move beyond smaller, more distributed BECCS facilities.²³³ Scaling up of both BECCS and direct air capture are limited and have challenges in the form of unclear monitoring, reporting and verification (MRV) or high energy costs per ton of captured or avoided carbon dioxide; increasing conflicts over land use or biodiversity; and competition from wind and solar that undercut the need for storage (i.e., because mitigation is cheaper) or for bioenergy (since biomass is more expensive).²³⁴ Scaling up of carbon storage, especially in saline aquifers or at other underground geological sites, will also face extreme limits; they need to grow at no less than 10% per year every year from 2020, and yet the

National Academies of Sciences, Engineering, and Medicine warned²³⁵ that “scale-up could be limited by materials shortages, regulatory barriers, infrastructure development (i.e., CO₂ pipelines and renewable electricity), the availability of trained workers, and many other barriers.”

3.4 Policy: Firm behaviour, carbon accounting, and regulation

This dimension connects to the governance and financial aspects of the sociotechnical framework. Policy formation for carbon removal is nascent but escalating²³⁶. The European Commission has issued a communique that frames and develops a number of agricultural, forestry, and marine-space management approaches as “carbon farming”, in the context of “sustainable carbon cycles.”²³⁷ Mappings of policy contexts and efforts – existing, still-forming, or needed – are taking place primarily in OECD states²³⁸, as well as supported by the European Green Deal²³⁹. Main strands within this body of work on policy design include incremental modification of existing policy – notably, upscaled incentives for direct air capture in the United States under the 45Q tax-credit program, as part of the newly legislated Inflation Reduction Act. This includes incentives being increased from \$50 to \$180/ton for carbon which is stored underground, a tenfold reduction in the capture thresholds needed to qualify, direct payment of tax credits for small businesses, and the extension of the deadline for breaking ground by a decade.^{240 241} Other related developments include policies treating emissions reductions and removals as fungible (a cornerstone for the functioning of carbon markets²⁴²), and support for niche technological development.²⁴³ At the same time, such efforts need to remain vigilant and wary of the risks to marketization and perverse outcomes that we will also explore in this section.

In terms of firm behavior, there are many incentives for businesses to try to utilize their supply chains or strategies to involve carbon removal. One review found multiple areas of carbon removal that could be monetized by businesses, including²⁴⁴:

- forest-related payments for ecosystem services or tourism revenue (for afforestation);
- heat sales, electricity sales, or waste-treatment charges (for BECCS);
- Heat sales, electricity sales, soil amendments or enhanced agricultural productivity (for biochar);
- Sale of pure carbon as feedstock (for direct air capture);
- Sale of sand, pebbles, formed carbonates, paper and fertilizer (for enhanced weathering);
- Increased fisheries yields or marine conservation (for marine-based approaches).

These reasons may be why so much climate finance and equity has recently been put into carbon removal options, with the Biden Administration committing \$3.5 billion to regional direct air carbon capture hubs in May 2022, although it is unclear whether the carbon dioxide will be utilized (i.e., for synfuels) or lead to longer term carbon storage. The State of New York has passed its “Carbon Dioxide Removal Leadership Act”, a first-ever, state-level bill aiming to advance near-term deployment and scaling-up through, *inter alia*, an advance market commitment to purchase durable carbon removal. The City of Ottawa recently unveiled a \$2.6 billion Carbon Capture Tax Credit for Energy Sector to help industry finance net-zero ambitions (including carbon removal). In addition, Finland became the first country in May 2022 to have enshrined their commitment to not just carbon neutrality but indeed “carbon negativity” into law, setting a goal of 2040. With support from Google, Stripe similarly announced a \$925 million carbon removal fund (Frontier) in April 2022. Conceived as its own “advance market commitment”, Frontier was established with other major big technology firms such as Meta (Facebook), Shopify, and McKinsey Sustainability, and it attempts to act as a “startup accelerator” so that companies invited into Frontier’s portfolio have access to advanced capital to develop and scale selected carbon removal technologies.²⁴⁵ To be very accurate, there is both an element of an “advance market commitment” as well as of an “offtake agreement”, where Frontier pledges to buy a certain amount of carbon removal as soon as available (useful if a start-up needs to demonstrate to a bank that they have customers waiting).^{246 247} Elsewhere, Lowercarbon Capital has raised \$350 million to support carbon removal start-ups in 2022. And this does not count further private sector support to firms such as Climeworks (CarbFix project in Iceland), Carbon Engineering, Global Thermostat, InfiniTree LLC and Skytree.²⁴⁸ Other revenues could come from ancillary markets associated with carbon removal such as water markets and rights in rural areas²⁴⁹, as well as carbon offsetting and emissions credits markets.²⁵⁰ That said, consensus does not yet exist on the optimal balance between the level of carbon removals and how it affects emissions abatement, and the ability for emissions trading systems to achieve net-zero targets has yet to be tested in global carbon markets.²⁵¹

However, since carbon is primarily a waste product, business models are constrained – represented by a currently limited range of second-life uses (e.g., construction materials, synthetic fuels), a still-unscaled CCS infrastructure, early DACCS projects, biochar, and forestry credit-generation projects for voluntary carbon markets. Calls for adequate carbon pricing are ubiquitous, both to escalate niche technological development and to set the stage for more strongly regulated carbon markets and trading^{252 253 254} Some highlight the emerging

potential of incorporating carbon removal into the revival of the EU Emissions Trading Scheme.²⁵⁵

Adjoined are calls to improve monitoring, reporting, and verification (MRV) as part of carbon accounting and accreditation – strongly motivated by historic difficulties in establishing additionality in projects developed through the now-defunct Clean Development Mechanism and the ongoing REDD+ mechanism, as well as the long-running but questionable practice of developing cheap credits from forestry projects (in tropical developing countries) for voluntary carbon markets^{256 257}. Disguising the delay of emissions reductions within carbon removal is an overarching concern. Three dangerous “non-equivalences” exist in treating distinct (i) approaches (e.g. biogenic or nature-based forestry practices vs. engineered e.g. DACCS), (ii) geographies, and (iii) permanence (or time-lengths of storage), as fungible²⁵⁸. Others similarly call for future net-zero commitments to clearly specify their emissions baskets, their variegated timelines, and whether they are to be achieved by reductions, removals, or offsets.²⁵⁹

A key element of new regulations for offsets is defining what sectors and emissions baskets are “hard-to-abate” or “residual” (left over after as much meaningful reduction as possible has taken place) – and therefore first in line in eligibility for offsets.²⁶⁰ Combining insights from the “non-equivalence” of different carbon removal approaches with potential efforts by industries to self-define as “hard-to-abate”, many argue for the need to separate industry and aviation from using offsets derived from biogenic or nature-based approaches.²⁶¹

Accordingly, many call for closer scrutiny of industry and corporate actors²⁶², where commitments towards net zero have escalated in recent years²⁶³. There are adjoining concerns that carbon removal presents opportunities for innovation actors to use the promise of future up-scaling for creating phantom commodities that eventually fail but will momentarily enrich initial founders and investors, or are incorporated into incumbent industries as incremental and fringe efforts²⁶⁴. A related recommendation calls for the separation of targets for emissions reduction and carbon removal, with the goal of preventing the latter from substituting for the former in developing future net-zero commitments.²⁶⁵ A legitimate debate also exists concerning whether the marketization of carbon removal is a positive or negative phenomenon, given that some forms of policy mechanisms that treat removals as homogenous could create perverse outcomes. Examples of such market failure or abuse already occur in forest management and conservation^{266 267} as well as previous trading regimes for carbon credits under the Kyoto Protocol.²⁶⁸

Many proposals go beyond carbon pricing, markets, and offsets, to focus on multi-level policy levers, financing, and long-term roadmaps.^{269 270 271} These also call for combinations of

“incentives and mandates” targeting key industries – such as repurposing the assets of the oil and gas sector in relation to DACCS²⁷², or agriculture and biomass with relation to BECCS, and fertilizer and waste rock with relation to enhanced weathering²⁷³. The long arc of solar-photovoltaics development is cited as an analogy for DACCS systems, where a combination of targeted early investments and a range of niche applications that developed advanced materials and expanded business models have contributed to a now un-arrestable progress.²⁷⁴

²⁷⁵ Co-benefits for industry and communities are stressed for up-scaling initial, near-term demonstration efforts, with an eye towards portfolios of approaches catered to local-to-regional technical, socio-economic, and regulatory contexts.^{276 277} A lurking but incoming issue will be on how to square MRV processes that currently focus on carbon management – already a difficult prospect due to varied supply chains, life cycles, storage permanence, and geographies – with the incorporation of even more varied societal co-benefits.²⁷⁸

Many accordingly call for policy formation with an eye to climate justice and equity. The key point here is that policy for aiding innovation is not enough; regulation to prevent incoming carbon removal efforts from being captured by incumbent interests must be forestalled by policy guardrails. Furthermore, incentivization of carbon removal requires concerted stakeholder participation and meaningful co-design²⁷⁹ (also covered in detail section 3.2 on public and social acceptance), to ensure that historic inequities – the dominance of the Global North in agenda-setting and technological capacity, in land grabs for carbon stocks or pollution exporting, and asymmetrical power relations – are not repeated.^{280 281 282} This has been especially demonstrable in the terrestrial carbon removal approaches that intersect with agricultural, forestry, and ecosystems management – where food vs. fuel vs. fiber conflicts and monoculture plantations offer ample negative precedents^{283 284}. Here, developing new carbon removal projects offers opportunities to improve tenure and rights for millions of smallholders, and to develop more nuanced mixed-uses of terrestrial space that combine preserving or re-growing carbon stocks with ecosystems services or crop growing²⁸⁵. These conversations – on improving MRV, on diverse mixed-uses, and on local co-benefits and co-design of projects – are being carried forward from terrestrial environments into marine (coastal and ocean) spaces, where policy opportunities exist for leap-frogging issues that confound the land sector.^{286 287}

288

A second aspect of justice and equity is the prospect for carbon removal to expand the carbon budget for states in the Global South – e.g., by developed countries reaching net-negative (instead of merely net-zero) emissions^{289 290}. Indian and Chinese representatives have

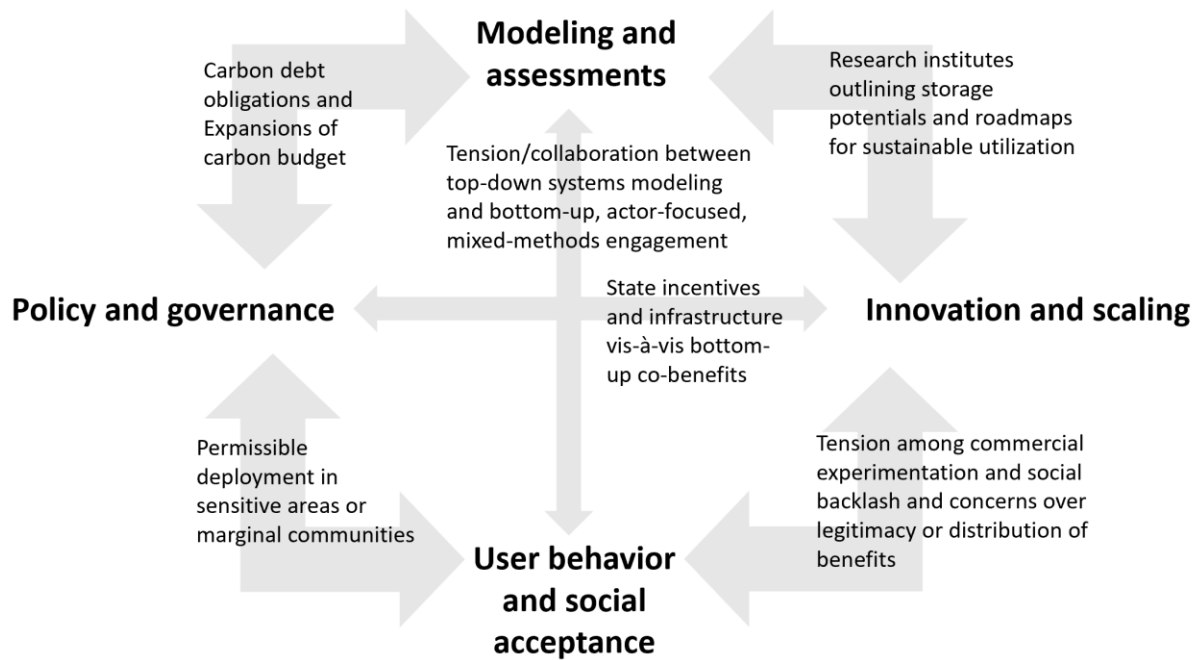
already made this demand, but with unclear further uptake. It is for now a space to watch – that may escalate near term carbon removal commitments and all its complexities.

4. Discussion and Conclusion

Employing a sociotechnical perspective, we have enumerated four particular dimensions of carbon removal that we believe should (continue to) constitute the evolving frontier of research. Our Review therefore not only offers an assessment of the current body of evidence on modeling, policy, innovation, and social acceptance; it also reveals ongoing focus of these areas as well as of topics and themes insufficiently considered. Tracking developments within and between these four dimensions would offer analysts and policymakers a more complete picture of the contexts and activities by which carbon removal is being envisioned, researched, deployed, and even critiqued.

As Figure 9 indicates, however, these dimensions also intersect, and some very interesting research topics emerge in the boundary zones between those topics. For example, some of the roadmaps produced by the foregoing assessments could intersect with innovation and scaling in a transmission zone about adequate storage potential or the sustainability of deployment. A tension between experimentation and social backlash would emerge from the transmission zone between innovation and social acceptance, notably, with called-for attempts to gain greater understanding into the risks and benefits of employing these technologies at scale resulting in both greater awareness in the public and, potentially, the emergence of opposing coalitions. The determination of adequate global carbon budgets is both a matter of policy and governance^{291 292} and modeling and assessment.^{293 294} The relaxing of standards or push for more aggressive policy deployment would also intersect in a transmission zone with concerns from marginal communities or perceptions of damaging environmentally (or culturally sensitive) areas.

Figure 9: Emerging frontiers for the sociotechnical dynamics of carbon removal



Source: Authors, inspired and substantially modified from ²⁹⁵. Note: Grey arrows depict “boundary zones” between the four sociotechnical dimensions explored in this Review.

Another implication of Figure 9 is that the potential consequences of transmission are double-edged: some possibilities are exploitative or may delay deployment, especially issues over scaling and social acceptance, while others present co-benefits underpinned by modeling and assessment or supportive policy efforts.²⁹⁶ Moreover, all of our sociotechnical dimensions call into question any reliance on more simplified and overly artificial divides between technology and policy or scaling and acceptance. Instead, our review strongly suggests the potential for all of these to coevolve as part of the same sociotechnical system, with the particular evolutionary trajectory depending on the underlying “terms of agreement” or “rules of the road”, that is, the norms, behavior, standards, rules, etc., that determine how these different dimensions relate to one another. In addition, as highlighted by the exemplary tensions presented above, the foregoing also provides an illustration of not considering these ongoing and emergent dynamics through such a sociotechnical lens. After all, this system is also inherently multi-scalar, blurring distinctions between actors (local and global, corporate or government) and jurisdictions (land use, food security, energy supply, innovation systems).

Our findings therefore offer a challenge to attempts to model integrated portfolios, to determine interactions, and to better understand the non-technical constraints of carbon removal.²⁹⁷ Before national and global scientists, policymakers, financiers and industry leaders commit fully to carbon removal, there is a fundamental need to pursue a more broad-based,

more interdisciplinary research program that acknowledges, rather than obscures, the sociotechnical dynamics of carbon removal.

References

-
- ¹ IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926
- ² Meinshausen, M., Lewis, J., McGlade, C. et al. Realization of Paris Agreement pledges may limit warming just below 2 °C. *Nature* 604, 304–309 (2022).
- ³ Bednar, J., Obersteiner, M., Baklanov, A., Thomson, M., Wagner, F., Geden, O., Allen, M., and Hall, J.W. (2021). Operationalizing the net-negative carbon economy. *Nature* 596: 377–383.
- ⁴ Daniel J A Johansson et al. “The role of negative carbon emissions in reaching the Paris climate targets: The impact of target formulation in integrated assessment models.” 2020 *Environ. Res. Lett.* 15 124024
- ⁵ Rogelj et al., Net-zero emissions targets are vague: three ways to fix, *Nature* 10.1038/d41586-021-00662-3(2021)
- ⁶ Committee on Climate Change. Net Zero Technical report. London: May, 2019.
- ⁷ International Energy Agency. Net Zero by 2050: A Roadmap for the Global Energy Sector. Paris: OECD, May, 2021.
- ⁸ International Energy Agency. 2022. Tracking Industry 2021. Paris, OECD, available at <https://www.iea.org/reports/tracking-industry-2021>
- ⁹ Paul Fennell, Justin Driver, Christopher Bataille & Steven J. Davis, Going net zero for cement and steel, *Nature* 603 (March 24, 2022), pp. 574–577.
- ¹⁰ Babiker, M., G. Berndes, K. Blok, B. Cohen, A. Cowie, O. Geden, V. Ginzburg, A. Leip, P. Smith, M. Sugiyama, F. Yamba, 2022: Cross-sectoral perspectives. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.005
- ¹¹ Isabela Butnar et al., A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): a transparency exercise, *Environ. Res. Lett.* 15 (2020) 084008
- ¹² Heck, Vera, Jonathan F. Donges, and Wolfgang Lucht. "Collateral transgression of planetary boundaries due to climate engineering by terrestrial carbon dioxide removal." *Earth System Dynamics* 7.4 (2016): 783–796.
- ¹³ Hetemäki, L. and Seppälä, J., 2022. Planetary boundaries and the role of the forest-based sector. In *Forest Bioeconomy and Climate Change* (pp. 19–31). Springer, Cham.
- ¹⁴ Fuss, S., Jones, C.D., Kraxner, F., Peters, G.P., Smith, P., Tavoni, M., Vuuren, D.P. van, Canadell, J.G., Jackson, R.B., Milne, J., Moreira, J.R., Nakicenovic, N., Sharifi, A., Yamagata, Y., 2016. Research priorities for negative emissions. *Environ. Res. Lett.* 11, 115007. <https://doi.org/10.1088/1748-9326/11/11/115007>

- ¹⁵ Anderson, Kevin and Glen Peters, "The trouble with negative emissions", *Science*, 354, 182-183 (14 October, 2016).
- ¹⁶ Van Vuuren, DP, Andries F. Hof, Mariësse A. E. van Sluisveld and Keywan Riahi, Open discussion of negative emissions is urgently needed, *Nature Energy* 2 (December, 2017), 902–904
- ¹⁷ Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., ... Smith, P. (2018). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, 13(6), 063003. <https://doi.org/10.1088/1748-9326/aabff4>
- ¹⁸ Honegger, Matthias & David Reiner (2018) The political economy of negative emissions technologies: consequences for international policy design, *Climate Policy*, 18:3, 306-321
- ¹⁹ Sovacool, BK, C Baum, and SJ Low. "Risk-risk governance in a low-carbon future: Exploring institutional, technological, and behavioral tradeoffs in climate geoengineering pathways," *Risk Analysis* (in press)
- ²⁰ Benjamin K. Sovacool, Reckless or righteous? Reviewing the sociotechnical benefits and risks of climate change geoengineering, *Energy Strategy Reviews*, Volume 35, 2021, 100656.
- ²¹ Benjamin K. Sovacool, Reckless or righteous? Reviewing the sociotechnical benefits and risks of climate change geoengineering, *Energy Strategy Reviews*, Volume 35, 2021, 100656.
- ²² IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926
- ²³ Ken Caldeira et al., The Science of Geoengineering, *Annu. Rev. Earth Planet. Sci.* 2013. 41:231–56
- ²⁴ Mark G. Lawrence et al., Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals, *Nature Communications* (2018) 9:3734 | DOI: 10.1038/s41467-018-05938-3 |
- ²⁵ David R. Morrow et al., Principles for Thinking about Carbon Dioxide Removal in Just Climate Policy, *One Earth* (in press, 2020)
- ²⁶ National Research Council 2015. Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration. Washington, DC: The National Academies Press. <https://doi.org/10.17226/18805>.
- ²⁷ Joana Castro Pereira, Geoengineering, Scientific Community, and Policymakers: A New Proposal for the Categorization of Responses to Anthropogenic Climate Change, *SAGE Open* January-March 2016: 1–11
- ²⁸ Sikina Jinnah and Simon Nicholson, The hidden politics of climate engineering, *Nature Geoscience* 12 (November, 2019), 874–879
- ²⁹ Augustine Pamplany et al., The Ethics of Geoengineering: A Literature Review, *Science and Engineering Ethics* 2020, <https://doi.org/10.1007/s11948-020-00258-6>
- ³⁰ United Nations Framework Convention on Climate Change. Afforestation and Reforestation Projects under the Clean Development Mechanism: A Reference Manual. UNFCCC, 2013.
- ³¹ Meko, T. (2016). Four ways to suck carbon out of thin air. *Washington Post*, 27 February 2016. <https://www.washingtonpost.com/graphics/national/carboncapture/>
- ³² Sweet, S. K., Schuldt, J. P., Lehmann, J., Bossio, D. A., & Woolf, D. (2021). Perceptions of naturalness predict US public support for Soil Carbon Storage as a climate solution. *Climatic Change*, 166(1), 22. <https://doi.org/10.1007/s10584-021-03121-0>

-
- ³³ OceanNETs. (2022). *Blue Carbon Management*. OceanNETs: Kiel, Germany.
<https://www.oceannets.eu/blue-carbon-management/>
- ³⁴ IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926
- ³⁵ McLaren, D. (2016). Mitigation deterrence and the “moral hazard” of solar radiation management. *Earth’s Future* 4(12), 596– 602. <https://doi.org/10.1002/2016ef000445>
- ³⁶ Hart, P. S., Campbell-Arvai, V., Wolske, K. S., & Raimi, K. T. (2022). Moral hazard or not? The effects of learning about carbon dioxide removal on perceptions of climate mitigation in the United States. *Energy Research & Social Science*, 89, 102656.
<https://doi.org/10.1016/j.erss.2022.102656>
- ³⁷ Andrews, T. M., Delton, A. W., & Kline, R. (2022). Anticipating moral hazard undermines climate mitigation in an experimental geoengineering game. *Ecological Economics*, 196, 107421. <https://doi.org/10.1016/j.ecolecon.2022.107421>
- ³⁸ MacMartin, D. G., Ricke, K. L., & Keith, D. W. (2018). Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2119), 20160454.
<https://doi.org/10.1098/rsta.2016.0454>
- ³⁹ Ricke, K., & Moreno-Cruz, J. (2022). 9.03 - Geo-Wedges: A Portfolio Approach to Geoengineering the Climate. In T. M. Letcher (Ed.), *Comprehensive Renewable Energy* (pp. 14–24). <https://doi.org/10.1016/B978-0-12-819727-1.00008-X>
- ⁴⁰ Benjamin K. Sovacool, Reckless or righteous? Reviewing the sociotechnical benefits and risks of climate change geoengineering, *Energy Strategy Reviews*, Volume 35, 2021, 100656.
- ⁴¹ Bodansky, D., & Parker, A. (2021). Research on Solar Climate Intervention Is the Best Defense Against Moral Hazard. *Issues in Science and Technology*, 37(4), 19–21.
- ⁴² Jebari, J., Táíwò, O. O., Andrews, T. M., Aquila, V., Beckage, B., Belaia, M., Clifford, M., Fuhrman, J., Keller, D. P., Mach, K. J., Morrow, D. R., Raimi, K. T., Visioni, D., Nicholson, S., & Trisos, C. H. (2021). From moral hazard to risk-response feedback. *Climate Risk Management*, 33, 100324. <https://doi.org/10.1016/j.crm.2021.100324>
- ⁴³ Inês Azevedo, Christopher Bataille, John Bistline, Leon Clarke, Steven Davis, Net-zero emissions energy systems: What we know and do not know, *Energy and Climate Change*, Volume 2, 2021, 100049.
- ⁴⁴ Bistline, J.E.T., Blanford, G.J. Impact of carbon dioxide removal technologies on deep decarbonization of the electric power sector. *Nat Commun* 12, 3732 (2021).
- ⁴⁵ S. Deng, R.Z. Wang, Y.J. Dai, How to evaluate performance of net zero energy building – A literature research, *Energy*, Volume 71, 2014, Pages 1-16
- ⁴⁶ Griffiths, S, et al. “Policy mixes to achieve sustainable mobility after the COVID-19 crisis,” *Renewable & Sustainable Energy Reviews* 143 (June, 2021), 110919, pp. 1-9.
- ⁴⁷ Michelle Della Vigna et al., Carbonomics: Introducing the GS Net Zero Carbon Models and Sector Frameworks, Goldman Sachs Research, June 23, 2021.
- ⁴⁸ S. Pye, O. Broad, C. Bataille, P. Brockway, H. E. Daly, R. Freeman, A. Gambhir, O. Geden, F. Rogan, S. Sanghvi, J. Tomei, I. Vorushylo & J. Watson (2021) Modelling net-zero emissions energy systems requires a change in approach, *Climate Policy*, 21:2, 222-231
- ⁴⁹ Michelle Della Vigna et al., Carbonomics: Introducing the GS Net Zero Carbon Models and Sector Frameworks, Goldman Sachs Research, June 23, 2021.

- ⁵⁰ IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926
- ⁵¹ Carton, Wim, Adeniyi Asiyanbi, Silke Beck, Holly J. Buck, and Jens F. Lund. "Negative emissions and the long history of carbon removal." *Wiley Interdisciplinary Reviews: Climate Change* 11, no. 6 (2020): e671.
- ⁵² Delina LL. Potentials and critiques of building a Southeast Asian interdisciplinary knowledge community on critical geoengineering studies. *Climatic Change*. 2020 Nov;163(2):973-87.
- ⁵³ IPCC (2014). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- ⁵⁴ 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 [V. Masson-Delmotte, 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, T. Waterfield (eds.)].
- ⁵⁵ O'Neill, B.C., Carter, T.R., Ebi, K., Harrison, P.A., Kemp-Benedict, E., Kok, K. ... & Pichs-Madruga, R. (2020). Achievements and needs for the climate change scenario framework. *Nature Climate Change* 10: 1074-1084
- ⁵⁶ Lahn, B. (2021). Changing climate change: The carbon budget and the modifying-work of the IPCC. *Social Studies of Science*, 51(1), 3–27
- ⁵⁷ Paul N. Edwards. *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, MA: MIT Press, 2010.
- ⁵⁸ Paul N. Edwards. *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, MA: MIT Press, 2010.
- ⁵⁹ Paul N. Edwards. *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, MA: MIT Press, 2010, p. 6.
- ⁶⁰ Low, S, et al. "Undone Science in Climate Interventions: Contrasting and contesting anticipatory assessments by expert networks," *Environmental Science & Policy* 137 (November, 2022), pp. 249-270.
- ⁶¹ Edenhofer, O, & Kowarsch, M (2015). Cartography of pathways: A new model for environmental policy assessments. *Environmental Science & Policy*, 51, 56–64.
- ⁶² van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D. & Cassen. C. (2020). Anticipating futures through models: Integrated Assessment Modeling in the climate science-policy interface since 1970. *Global Environmental Change* 65: 102191.
- ⁶³ Beck, S., & Mahony, M. (2018). The politics of anticipation: the IPCC and the negative emissions technologies experience. *Global Sustainability* 1(8): 1–8.
- ⁶⁴ Geden, O., Löschel, A. Define limits for temperature overshoot targets. *Nature Geosci* 10, 881–882 (2017). <https://doi.org/10.1038/s41561-017-0026-z>

-
- ⁶⁵ IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.
- ⁶⁶ Riahi, K., Bertram, C., Huppmann, D. et al. Cost and attainability of meeting stringent climate targets without overshoot. *Nat. Clim. Chang.* 11, 1063–1069 (2021). <https://doi.org/10.1038/s41558-021-01215-2>
- ⁶⁷ Drouet, L., Bosetti, V., Padoan, S.A. et al. Net zero-emission pathways reduce the physical and economic risks of climate change. *Nat. Clim. Chang.* 11, 1070–1076 (2021). <https://doi.org/10.1038/s41558-021-01218-z>
- ⁶⁸ Beck, S. & Oomen, J. (2021). Imagining the corridor of climate mitigation – What is at stake in the IPCC’s politics of anticipation. *Environmental Science and Policy* 123: 169–178.
- ⁶⁹ Emmerling, J., Drouet, L., van der Wijst, K. I., Van Vuuren, D., Bosetti, V., & Tavoni, M. (2019). The role of the discount rate for emission pathways and negative emissions. *Environmental Research Letters*, 14(10), 104008.
- ⁷⁰ Cointe, B., Cassen, C. & Nadaï, A. (2020). Organizing policy-relevant knowledge for climate action: Integrated assessment modeling, the IPCC, and the emergence of a collective expertise on socioeconomic emission scenarios. *Science & Technology Studies*.
- ⁷¹ McLaren, D. P. & Markusson, N. (2020). The co-evolution of technological promises, modelling, policies and climate change targets. *Nature Climate Change* 10, 392–397. doi:10.1038/s41558-020-0740-1.
- ⁷² Grant, Neil, Adam Hawkes, Shivika Mittal, and Ajay Gambhir. "Confronting mitigation deterrence in low-carbon scenarios." *Environmental Research Letters* 16, no. 6 (2021): 064099.
- ⁷³ Markusson, N., McLaren, D. and Tyfield, D., 2018. Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Global Sustainability*, 1.
- ⁷⁴ McLaren, D. (2016). Mitigation deterrence and the “moral hazard” of solar radiation management. *Earth’s Future* 4(12), 596– 602. <https://doi.org/10.1002/2016ef000445>
- ⁷⁵ Low, S. and Boettcher, M. (2020). Delaying Decarbonization: Climate governmentalities and sociotechnical strategies from Copenhagen to Paris. *Earth System Governance*. DOI: 10.1016/j.esg.2020.100073
- ⁷⁶ Stoddard, I., Anderson, K., Capstick, S., Carton, W., Depledge, J., Facer, K. ... & Williams, M. (2021). Three Decades of Climate Mitigation: Why Haven’t We Bent the Global Emissions Curve? *Annu. Rev. Environ. Resour.* 46:12.1–12.37
- ⁷⁷ Boettcher, M. (2020). Coming to GRIPs With NETs Discourse: Implications of Discursive Structures for Emerging Governance of Negative Emissions Technologies in the UK. *Front. Clim.* 2:595685. doi: 10.3389/fclim.2020.595685
- ⁷⁸ McLaren, D.P., Willis, R., Szerszynski, B., Tyfield, D., and Markusson, N. (2021). Attractions of delay: Using deliberative engagement to investigate the political and strategic impacts of greenhouse gas removal technologies. *Environmental Policy and Planning E: Nature and Space* DOI: 10.1177/25148486211066238
- ⁷⁹ Grant, N., Hawkes, A., Mittal, S., and Gambhir, A. (2021). Confronting mitigation deterrence in low-carbon scenarios. *Environmental Research Letters* 16 064099.
- ⁸⁰ McLaren, D. (2020). Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. *Climatic Change* 162, 2411–2428.
- ⁸¹ Low, S. and Schäfer, S. (2020). Is Bio-energy CCS Feasible? The contested authority of

integrated assessment modeling. *Energy Research & Social Science* 20, 101326. DOI: 10.1016/j.erss.2019.101326

⁸² Jewell, J. & Cherp, A. (2019). On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5C? *WIREs Climate Change* 11: e621.

⁸³ Thoni T, Beck S, Borchers M, Förster J, Görl K, Hahn A, Mengis N, Stevenson A and Thrän D (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.

⁸⁴ 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’, *Global Environmental Change*, 63, 102073.

⁸⁵ Braunreiter, L., van Beek, L., Hajer, M., van Vuuren, D.P. (2021). Transformative pathways – Using integrated assessment models more effectively to open up plausible and desirable low-carbon futures. *Energy Research & Social Science* 80(4): 102220.

⁸⁶ Gambhir, A., Cronin, C., Matsumae, E., Rogelj, J., Workman, M. (2019b). Using futures analysis to develop resilient climate change mitigation strategies. Grantham Institute, Imperial College London, Briefing paper No 33.

⁸⁷ Uden, S., Dargusch, P., and Grieg, P. (2021). Cutting through the noise on negative emissions. *Joule* 5, 1956–1970.

⁸⁸ Pereira, L., Kuiper, J.J., Selomane, O., Aguiar, A.P., Asrar, G.R., Bennett, E.M. ... & Ward, J. (2021). Advancing a toolkit of diverse futures approaches for global environmental assessments. *Ecosystems and People* 17(1): 191-204.

⁸⁹ Hofbauer, L., McDowall, W., & Pye, S. (2022). Challenges and opportunities for energy system modelling to foster multi-level governance of energy transitions. *Renewable and Sustainable Energy Reviews* 161: 112330.

⁹⁰ Moore, F.C., Lacasse, K., Mach, K.J., Shin, Y.A. Gross, L.J., & Beckage, B. (2022). Determinants of emissions pathways in the coupled climate-social system. *Nature*. <https://doi.org/10.1038/s41586-022-04423-8>

⁹¹ Rickels, W., Merk, C., Reith, F., Keller, D. P., & Oschlies, A. (2019). (Mis) conceptions about modeling of negative emissions technologies. *Environmental Research Letters*, 14(10), 104004.

⁹² Kreuter, J. and Lederer, M. (2021). The Geopolitics of Negative Emissions Technologies – Learning lessons from REDD+ and Renewable Energies for Afforestation, BECCS and Direct Air Capture, *Global Sustainability*.

⁹³ Low, S., Baum, C.M., and Sovacool, B.K. (2022). Taking it Outside: Exploring social opposition to 21 early-stage experiments in radical climate interventions. *Energy Research & Social Science* 90, 102594. DOI: 10.1016/j.erss.2022.102594

⁹⁴ Lenzi, D., Jakob, M., Honegger, M., Droege, S., Heyward, J.C., and Kruger, T. (2021). Equity implications of net zero visions. *Climatic Change* 169, 20.

⁹⁵ Dooley, K., Harrould-Kolieb, E., and Talberg, A. (2020). Carbon-dioxide Removal and Biodiversity: A Threat Identification Framework. *Global Policy* 12(1): 34-44.

⁹⁶ Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W., & Clarens, A. F. (2019). From zero to hero?: why integrated assessment modeling of negative emissions technologies is hard and how we can do better. *Frontiers in Climate*, 11.

⁹⁷ Honegger, M.A., Michaelowa, A., and Roy, J. (2021a). Potential implications of carbon dioxide removal for the sustainable development goals, *Climate Policy*, 21:5, 678-698, DOI: 10.1080/14693062.2020.1843388

-
- ⁹⁸ Smith, S.M. (2021). A case for transparent net-zero carbon targets. *Communications Earth & Environment* 2, 24. <https://doi.org/10.1038/s43247-021-00095-w>
- ⁹⁹ Mohan, A., Geden, O., Fridahl, M., Buck, H.J., and Peters, G.P. (2021). UNFCCC must confront the political economy of net-negative emissions. *One Earth* 4: 1348-1351.
- ¹⁰⁰ Terlouw, T., Bauer, C., Rosa, L. and Mazotti, M. (2021). Life cycle assessment of carbon dioxide removal technologies: a critical review. *Energy & Environmental Science* 14:1701-1721.
- ¹⁰¹ Clery D.S., Vaughan, N.E., Forster, J., Lorenzoni, I., Gough, C.A., and Chilvers, J. (2021). Bringing greenhouse gas removal down to earth: Stakeholder supply chain appraisals reveal complex challenges. *Global Environmental Change* 71: 102369.
- ¹⁰² Lane, J., Greig, C., and Garnett, A. (2021). Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. *Nature Climate Change* 11: 925–936.
- ¹⁰³ Carton, W., Lund, J.F., and Dooley, K. (2021). Undoing Equivalence: Rethinking Carbon Accounting for Just Carbon Removal. *Frontiers in Climate* DOI:10.3389/fclim.2021.664130.
- ¹⁰⁴ Dooley, K. and Kartha, S. (2018) ‘Land-based negative emissions: risks for climate mitigation and impacts on sustainable development’, *International Environmental Agreements* 18, p79-98.
- ¹⁰⁵ University of Leeds and Grantham Research Institute on Climate Change and the Environment (2021) Distributional impacts analysis of engineered greenhouse gas removal technologies in the UK: Report Prepared for the National Infrastructure Commission. University of Leeds and Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science.
- ¹⁰⁶ Burke, J. and Gambhir, A. (2022). Policy incentives for Greenhouse Gas Removal Techniques: the risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework, *Energy and Climate Change*, Volume 3, 100074.
- ¹⁰⁷ Batres, M., Wang, F.M., Buck, H.J., Kapila, R., Kosar, U., Licker, R., Nagabhushan, D., Rekhelman, E., and Suarez, V. (2021). Environmental and climate justice and technological carbon removal. *The Electricity Journal* 34(7): 107002.
- ¹⁰⁸ 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. *Frontiers in Climate*. DOI: 10.3389/fclim.2021.664456
- ¹⁰⁹ Pidgeon, N., Corner, A., Parkhill, K., Spence, A., Butler, C., & Poortinga, W. (2012). Exploring early public responses to geoengineering. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1974), 4176–4196. <https://doi.org/10.1098/rsta.2012.0099>
- ¹¹⁰ Wright, M. J., Teagle, D. A. H., & Feetham, P. M. (2014). A quantitative evaluation of the public response to climate engineering. *Nature Climate Change*, 4(2), 106–110. <https://doi.org/10.1038/nclimate2087>
- ¹¹¹ Amelung, D., & Funke, J. (2015). Laypeople’s Risky Decisions in the Climate Change Context: Climate Engineering as a Risk-Defusing Strategy? *Human and Ecological Risk Assessment: An International Journal*, 21(2), 533–559. <https://doi.org/10.1080/10807039.2014.932203>
- ¹¹² Tingley, D., & Wagner, G. (2017). Solar geoengineering and the chemtrails conspiracy on social media. *Palgrave Communications*, 3(1), 1–7. <https://doi.org/10.1057/s41599-017-0014-3>
- ¹¹³ Bellamy, R., Lezaun, J., & Palmer, J. (2019). Perceptions of bioenergy with carbon capture and storage in different policy scenarios. *Nature Communications*, 10(1), 743. <https://doi.org/10.1038/s41467-019-08592-5>

- ¹¹⁴ Merk, C., Klaus, G., Pohlers, J., Ernst, A., Ott, K., & Rehdanz, K. (2019). Public perceptions of climate engineering: Laypersons' acceptance at different levels of knowledge and intensities of deliberation. *GAIA - Ecological Perspectives for Science and Society*, 28(4), 348–355. <https://doi.org/10.14512/gaia.28.4.6>
- ¹¹⁵ Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (2020). The public remain uninformed and wary of climate engineering. *Climatic Change*, 160(2), 303–322. <https://doi.org/10.1007/s10584-020-02706-5>
- ¹¹⁶ Cox, E., Spence, E., & Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nature Climate Change*, 10(8), 744–749. <https://doi.org/10.1038/s41558-020-0823-z>
- ¹¹⁷ Mercer, A. M., Keith, D. W., & Sharp, J. D. (2011). Public understanding of solar radiation management. *Environmental Research Letters*, 6(4), 044006. <https://doi.org/10.1088/1748-9326/6/4/044006>
- ¹¹⁸ Bostrom, A., O'Connor, R. E., Böhm, G., Hanss, D., Bodi, O., Ekström, F., Halder, P., Jeschke, S., Mack, B., Qu, M., Rosentrater, L., Sandve, A., & Sælensminde, I. (2012). Causal thinking and support for climate change policies: International survey findings. *Global Environmental Change*, 22(1), 210–222. <https://doi.org/10.1016/j.gloenvcha.2011.09.012>
- ¹¹⁹ Kahan, D. M., Jenkins-Smith, H., Tarantola, T., Silva, C. L., & Braman, D. (2015). Geoengineering and Climate Change Polarization: Testing a Two-Channel Model of Science Communication. *The ANNALS of the American Academy of Political and Social Science*, 658(1), 192–222. <https://doi.org/10.1177/0002716214559002>
- ¹²⁰ Sugiyama, M., Kosugi, T., Ishii, A., & Asayama, S. (2016). *Public attitudes to climate engineering research and field experiments: Preliminary results of a web survey on students' perception in six Asia-Pacific countries*. 39.
- ¹²¹ Visschers, V. H. M., Shi, J., Siegrist, M., & Arvai, J. (2017). Beliefs and values explain international differences in perception of solar radiation management: Insights from a cross-country survey. *Climatic Change*, 142(3–4), 531–544. <https://doi.org/10.1007/s10584-017-1970-8>
- ¹²² Spence, E., Cox, E., & Pidgeon, N. (2021). Exploring cross-national public support for the use of enhanced weathering as a land-based carbon dioxide removal strategy. *Climatic Change*, 165(1), 23. <https://doi.org/10.1007/s10584-021-03050-y>
- ¹²³ Wibeck, V., Hansson, A., Anshelm, J., Asayama, S., Dilling, L., Feetham, P. M., Hauser, R., Ishii, A., & Sugiyama, M. (2017). Making sense of climate engineering: A focus group study of lay publics in four countries. *Climatic Change*, 145(1), 1–14. <https://doi.org/10.1007/s10584-017-2067-0>
- ¹²⁴ Carr, W. A., & Yung, L. (2018). Perceptions of climate engineering in the South Pacific, Sub-Saharan Africa, and North American Arctic. *Climatic Change*, 147(1), 119–132. <https://doi.org/10.1007/s10584-018-2138-x>
- ¹²⁵ Cox, E., Spence, E., & Pidgeon, N. (2020). Incumbency, Trust and the Monsanto Effect: Stakeholder Discourses on Greenhouse Gas Removal. *Environmental Values*, 29(2), 197–220. <https://doi.org/10.3197/096327119X15678473650947>
- ¹²⁶ Bellamy, R., Fridahl, M., Lezaun, J., Palmer, J., Rodriguez, E., Lefvert, A., Hansson, A., Grönkvist, S., & Haikola, S. (2021). Incentivising bioenergy with carbon capture and storage (BECCS) responsibly: Comparing stakeholder policy preferences in the United Kingdom and Sweden. *Environmental Science & Policy*, 116, 47–55. <https://doi.org/10.1016/j.envsci.2020.09.022>
- ¹²⁷ Veland, S., & Merk, C. (2021). *Lay person perceptions of marine carbon dioxide removal (CDR) – Working paper*. OceanNETs. https://doi.org/10.3289/oceannets_d3.3

-
- ¹²⁸ Wright, M. J., Teagle, D. A. H., & Feetham, P. M. (2014). A quantitative evaluation of the public response to climate engineering. *Nature Climate Change*, 4(2), 106–110. <https://doi.org/10.1038/nclimate2087>
- ¹²⁹ Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (2020). The public remain uninformed and wary of climate engineering. *Climatic Change*, 160(2), 303–322. <https://doi.org/10.1007/s10584-020-02706-5>
- ¹³⁰ Cox, E., Spence, E., & Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nature Climate Change*, 10(8), 744–749. <https://doi.org/10.1038/s41558-020-0823-z>
- ¹³¹ Sugiyama, M., Kosugi, T., Ishii, A., & Asayama, S. (2016). *Public attitudes to climate engineering research and field experiments: Preliminary results of a web survey on students' perception in six Asia-Pacific countries*. 39.
- ¹³² Visschers, V. H. M., Shi, J., Siegrist, M., & Arvai, J. (2017). Beliefs and values explain international differences in perception of solar radiation management: Insights from a cross-country survey. *Climatic Change*, 142(3–4), 531–544. <https://doi.org/10.1007/s10584-017-1970-8>
- ¹³³ Carr, W. A., & Yung, L. (2018). Perceptions of climate engineering in the South Pacific, Sub-Saharan Africa, and North American Arctic. *Climatic Change*, 147(1), 119–132. <https://doi.org/10.1007/s10584-018-2138-x>
- ¹³⁴ Bostrom, A., O'Connor, R. E., Böhm, G., Hanss, D., Bodi, O., Ekström, F., Halder, P., Jeschke, S., Mack, B., Qu, M., Rosentrater, L., Sandve, A., & Sælensminde, I. (2012). Causal thinking and support for climate change policies: International survey findings. *Global Environmental Change*, 22(1), 210–222. <https://doi.org/10.1016/j.gloenvcha.2011.09.012>
- ¹³⁵ Cox, E., Spence, E., & Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nature Climate Change*, 10(8), 744–749. <https://doi.org/10.1038/s41558-020-0823-z>
- ¹³⁶ Mercer, A. M., Keith, D. W., & Sharp, J. D. (2011). Public understanding of solar radiation management. *Environmental Research Letters*, 6(4), 044006. <https://doi.org/10.1088/1748-9326/6/4/044006>
- ¹³⁷ Sugiyama, M., Kosugi, T., Ishii, A., & Asayama, S. (2016). *Public attitudes to climate engineering research and field experiments: Preliminary results of a web survey on students' perception in six Asia-Pacific countries*. 39.
- ¹³⁸ Corner, A., & Pidgeon, N. (2015). Like artificial trees? The effect of framing by natural analogy on public perceptions of geoengineering. *Climatic Change*, 130(3), 425–438. <https://doi.org/10.1007/s10584-014-1148-6>
- ¹³⁹ Pidgeon, N. F., & Spence, E. (2017). Perceptions of enhanced weathering as a biological negative emissions option. *Biology Letters*, 13(4), 20170024. <https://doi.org/10.1098/rsbl.2017.0024>
- ¹⁴⁰ Cummings, C. L., & Rosenthal, S. (2018). Climate change and technology: Examining opinion formation of geoengineering. *Environment Systems and Decisions*, 38(2), 208–215. <https://doi.org/10.1007/s10669-018-9683-8>
- ¹⁴¹ Mahajan, A., Tingley, D., & Wagner, G. (2019). Fast, cheap, and imperfect? US public opinion about solar geoengineering. *Environmental Politics*, 28(3), 523–543. <https://doi.org/10.1080/09644016.2018.1479101>
- ¹⁴² Sweet, S. K., Schuldt, J. P., Lehmann, J., Bossio, D. A., & Woolf, D. (2021). Perceptions of naturalness predict US public support for Soil Carbon Storage as a climate solution. *Climatic Change*, 166(1), 22. <https://doi.org/10.1007/s10584-021-03121-0>

- ¹⁴³ Pidgeon, N., Corner, A., Parkhill, K., Spence, A., Butler, C., & Poortinga, W. (2012). Exploring early public responses to geoengineering. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1974), 4176–4196. <https://doi.org/10.1098/rsta.2012.0099>
- ¹⁴⁴ Bellamy, R., Lezaun, J., & Palmer, J. (2019). Perceptions of bioenergy with carbon capture and storage in different policy scenarios. *Nature Communications*, 10(1), 743. <https://doi.org/10.1038/s41467-019-08592-5>
- ¹⁴⁵ Visschers, V. H. M., Shi, J., Siegrist, M., & Arvai, J. (2017). Beliefs and values explain international differences in perception of solar radiation management: Insights from a cross-country survey. *Climatic Change*, 142(3–4), 531–544. <https://doi.org/10.1007/s10584-017-1970-8>
- ¹⁴⁶ Spence, E., Cox, E., & Pidgeon, N. (2021). Exploring cross-national public support for the use of enhanced weathering as a land-based carbon dioxide removal strategy. *Climatic Change*, 165(1), 23. <https://doi.org/10.1007/s10584-021-03050-y>
- ¹⁴⁷ Corner, A., & Pidgeon, N. (2015). Like artificial trees? The effect of framing by natural analogy on public perceptions of geoengineering. *Climatic Change*, 130(3), 425–438. <https://doi.org/10.1007/s10584-014-1148-6>
- ¹⁴⁸ Borick, C., & Rabe, B. (2012). Americans Cool on Geoengineering Approaches to Addressing Climate Change. *Issues in Governance Studies*, 46, 7.
- ¹⁴⁹ Corner, A., & Pidgeon, N. (2014). Geoengineering, climate change scepticism and the ‘moral hazard’ argument: An experimental study of UK public perceptions. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2031), 20140063. <https://doi.org/10.1098/rsta.2014.0063>
- ¹⁵⁰ Merk, C., Pönitzsch, G., Kniebes, C., Rehdanz, K., & Schmidt, U. (2015). Exploring public perceptions of stratospheric sulfate injection. *Climatic Change*, 130(2), 299–312. <https://doi.org/10.1007/s10584-014-1317-7>
- ¹⁵¹ Campbell-Arvai, V., Hart, P. S., Raimi, K. T., & Wolske, K. S. (2017). The influence of learning about carbon dioxide removal (CDR) on support for mitigation policies. *Climatic Change*, 143(3), 321–336. <https://doi.org/10.1007/s10584-017-2005-1>
- ¹⁵² Raimi, K. T., Maki, A., Dana, D., & Vandenberg, M. P. (2019). Framing of Geoengineering Affects Support for Climate Change Mitigation. *Environmental Communication*, 13(3), 300–319. <https://doi.org/10.1080/17524032.2019.1575258>
- ¹⁵³ Jobin, M., & Siegrist, M. (2020). Support for the Deployment of Climate Engineering: A Comparison of Ten Different Technologies. *Risk Analysis*, 40(5), 1058–1078. <https://doi.org/10.1111/risa.13462>
- ¹⁵⁴ Schwartz, S.H. (1994). Are there universal aspects in the structure and contents of human values? *Journal of Social Issues*, 50(4), 19–45.
- ¹⁵⁵ De Groot, I., & Steg, L. (2008). Value orientations to explain beliefs related to environmental significant behavior: How to measure egoistic, altruistic, and biospheric value orientations. *Environment and behavior*, 40(3), 330–354.
- ¹⁵⁶ Kahan, D. M., Jenkins-Smith, H., Tarantola, T., Silva, C. L., & Braman, D. (2015). Geoengineering and Climate Change Polarization: Testing a Two-Channel Model of Science Communication. *The ANNALS of the American Academy of Political and Social Science*, 658(1), 192–222. <https://doi.org/10.1177/0002716214559002>
- ¹⁵⁷ Visschers, V. H. M., Shi, J., Siegrist, M., & Arvai, J. (2017). Beliefs and values explain international differences in perception of solar radiation management: Insights from a cross-country survey. *Climatic Change*, 142(3–4), 531–544. <https://doi.org/10.1007/s10584-017-1970-8>

- ¹⁵⁸ Corner, A., & Pidgeon, N. (2014). Geoengineering, climate change scepticism and the ‘moral hazard’ argument: An experimental study of UK public perceptions. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2031), 20140063. <https://doi.org/10.1098/rsta.2014.0063>
- ¹⁵⁹ Merk, C., & Pönitzsch, G. (2017). The Role of Affect in Attitude Formation toward New Technologies: The Case of Stratospheric Aerosol Injection. *Risk Analysis*, 37(12), 2289–2304. <https://doi.org/10.1111/risa.12780>
- ¹⁶⁰ Braun, C., Merk, C., Pönitzsch, G., Rehdanz, K., & Schmidt, U. (2018). Public perception of climate engineering and carbon capture and storage in Germany: Survey evidence. *Climate Policy*, 18(4), 471–484. <https://doi.org/10.1080/14693062.2017.1304888>
- ¹⁶¹ Braun, C., Rehdanz, K., & Schmidt, U. (2018). Exploring public perception of environmental technology over time. *Journal of Environmental Planning and Management*, 61(1), 143–160. <https://doi.org/10.1080/09640568.2017.1291414>
- ¹⁶² Raimi, K. T., Wolske, K. S., Hart, P. S., & Campbell-Arvai, V. (2020). The Aversion to Tampering with Nature (ATN) Scale: Individual Differences in (Dis)comfort with Altering the Natural World. *Risk Analysis*, 40(3), 638–656. <https://doi.org/10.1111/risa.13414>
- ¹⁶³ Dunlap, R. E., Van Liere, K. D., Mertig, A. G., & Jones, R. E. (2000). New trends in measuring environmental attitudes: measuring endorsement of the new ecological paradigm: a revised NEP scale. *Journal of social issues*, 56(3), 425–442.
- ¹⁶⁴ Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (2020). The public remain uninformed and wary of climate engineering. *Climatic Change*, 160(2), 303–322. <https://doi.org/10.1007/s10584-020-02706-5>
- ¹⁶⁵ Merk, C., Pönitzsch, G., Kniebes, C., Rehdanz, K., & Schmidt, U. (2015). Exploring public perceptions of stratospheric sulfate injection. *Climatic Change*, 130(2), 299–312. <https://doi.org/10.1007/s10584-014-1317-7>
- ¹⁶⁶ Merk, C., & Pönitzsch, G. (2017). The Role of Affect in Attitude Formation toward New Technologies: The Case of Stratospheric Aerosol Injection. *Risk Analysis*, 37(12), 2289–2304. <https://doi.org/10.1111/risa.12780>
- ¹⁶⁷ Raimi, K. T., Wolske, K. S., Hart, P. S., & Campbell-Arvai, V. (2020). The Aversion to Tampering with Nature (ATN) Scale: Individual Differences in (Dis)comfort with Altering the Natural World. *Risk Analysis*, 40(3), 638–656. <https://doi.org/10.1111/risa.13414>
- ¹⁶⁸ Braun, C., Merk, C., Pönitzsch, G., Rehdanz, K., & Schmidt, U. (2018). Public perception of climate engineering and carbon capture and storage in Germany: Survey evidence. *Climate Policy*, 18(4), 471–484. <https://doi.org/10.1080/14693062.2017.1304888>
- ¹⁶⁹ Braun, C., Rehdanz, K., & Schmidt, U. (2018). Exploring public perception of environmental technology over time. *Journal of Environmental Planning and Management*, 61(1), 143–160. <https://doi.org/10.1080/09640568.2017.1291414>
- ¹⁷⁰ Mercer, A. M., Keith, D. W., & Sharp, J. D. (2011). Public understanding of solar radiation management. *Environmental Research Letters*, 6(4), 044006. <https://doi.org/10.1088/1748-9326/6/4/044006>
- ¹⁷¹ Pidgeon, N. F., & Spence, E. (2017). Perceptions of enhanced weathering as a biological negative emissions option. *Biology Letters*, 13(4), 20170024. <https://doi.org/10.1098/rsbl.2017.0024>
- ¹⁷² Merk, C., Pönitzsch, G., Kniebes, C., Rehdanz, K., & Schmidt, U. (2015). Exploring public perceptions of stratospheric sulfate injection. *Climatic Change*, 130(2), 299–312. <https://doi.org/10.1007/s10584-014-1317-7>

-
- ¹⁷³ Merk, C., & Pönitzsch, G. (2017). The Role of Affect in Attitude Formation toward New Technologies: The Case of Stratospheric Aerosol Injection. *Risk Analysis*, 37(12), 2289–2304. <https://doi.org/10.1111/risa.12780>
- ¹⁷⁴ Jobin, M., & Siegrist, M. (2020). Support for the Deployment of Climate Engineering: A Comparison of Ten Different Technologies. *Risk Analysis*, 40(5), 1058–1078. <https://doi.org/10.1111/risa.13462>
- ¹⁷⁵ Braun, C., Merk, C., Pönitzsch, G., Rehdanz, K., & Schmidt, U. (2018). Public perception of climate engineering and carbon capture and storage in Germany: Survey evidence. *Climate Policy*, 18(4), 471–484. <https://doi.org/10.1080/14693062.2017.1304888>
- ¹⁷⁶ Braun, C., Rehdanz, K., & Schmidt, U. (2018). Exploring public perception of environmental technology over time. *Journal of Environmental Planning and Management*, 61(1), 143–160. <https://doi.org/10.1080/09640568.2017.1291414>
- ¹⁷⁷ Fairbrother, M. (2016). Geoengineering, moral hazard, and trust in climate science: Evidence from a survey experiment in Britain. *Climatic Change*, 139(3), 477–489. <https://doi.org/10.1007/s10584-016-1818-7>
- ¹⁷⁸ Klaus, G., Ernst, A., & Oswald, L. (2020). Psychological factors influencing laypersons' acceptance of climate engineering, climate change mitigation and business as usual scenarios. *Technology in Society*, 60, 101222. <https://doi.org/10.1016/j.techsoc.2019.101222>
- ¹⁷⁹ Wenger, A., Stauffacher, M., & Dallo, I. (2021). Public perception and acceptance of negative emission technologies – framing effects in Switzerland. *Climatic Change*, 167(3), 53. <https://doi.org/10.1007/s10584-021-03150-9>
- ¹⁸⁰ Corner, A., Parkhill, K., Pidgeon, N., & Vaughan, N. E. (2013). Messing with nature? Exploring public perceptions of geoengineering in the UK. *Global Environmental Change*, 23(5), 938–947.
- ¹⁸¹ Osaka, S., Bellamy, R., & Castree, N. (2021). Framing “nature-based” solutions to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, 12(5), e729.
- ¹⁸² Corner, A., & Pidgeon, N. (2015). Like artificial trees? The effect of framing by natural analogy on public perceptions of geoengineering. *Climatic Change*, 130(3), 425–438. <https://doi.org/10.1007/s10584-014-1148-6>
- ¹⁸³ Shrum, T. R., Markowitz, E., Buck, H., Gregory, R., van der Linden, S., Attari, S. Z., & Van Boven, L. (2020). Behavioural frameworks to understand public perceptions of and risk response to carbon dioxide removal. *Interface Focus*, 10(5), 20200002. <https://doi.org/10.1098/rsfs.2020.0002>
- ¹⁸⁴ Visschers, V. H. M., Shi, J., Siegrist, M., & Arvai, J. (2017). Beliefs and values explain international differences in perception of solar radiation management: Insights from a cross-country survey. *Climatic Change*, 142(3–4), 531–544. <https://doi.org/10.1007/s10584-017-1970-8>
- ¹⁸⁵ Jobin, M., & Siegrist, M. (2020). Support for the Deployment of Climate Engineering: A Comparison of Ten Different Technologies. *Risk Analysis*, 40(5), 1058–1078. <https://doi.org/10.1111/risa.13462>
- ¹⁸⁶ Klaus, G., Ernst, A., & Oswald, L. (2020). Psychological factors influencing laypersons' acceptance of climate engineering, climate change mitigation and business as usual scenarios. *Technology in Society*, 60, 101222. <https://doi.org/10.1016/j.techsoc.2019.101222>
- ¹⁸⁷ Sweet, S. K., Schuldt, J. P., Lehmann, J., Bossio, D. A., & Woolf, D. (2021). Perceptions of naturalness predict US public support for Soil Carbon Storage as a climate solution. *Climatic Change*, 166(1), 22. <https://doi.org/10.1007/s10584-021-03121-0>

- ¹⁸⁸ Wenger, A., Stauffacher, M., & Dallo, I. (2021). Public perception and acceptance of negative emission technologies – framing effects in Switzerland. *Climatic Change*, 167(3), 53. <https://doi.org/10.1007/s10584-021-03150-9>
- ¹⁸⁹ Wolske, K. S., Raimi, K. T., Campbell-Arvai, V., & Hart, P. S. (2019). Public support for carbon dioxide removal strategies: The role of tampering with nature perceptions. *Climatic Change*, 152(3), 345–361. <https://doi.org/10.1007/s10584-019-02375-z>
- ¹⁹⁰ Sweet, S. K., Schuldt, J. P., Lehmann, J., Bossio, D. A., & Woolf, D. (2021). Perceptions of naturalness predict US public support for Soil Carbon Storage as a climate solution. *Climatic Change*, 166(1), 22. <https://doi.org/10.1007/s10584-021-03121-0>
- ¹⁹¹ Wolske, K. S., Raimi, K. T., Campbell-Arvai, V., & Hart, P. S. (2019). Public support for carbon dioxide removal strategies: The role of tampering with nature perceptions. *Climatic Change*, 152(3), 345–361. <https://doi.org/10.1007/s10584-019-02375-z>
- ¹⁹² Raimi, K. T., Wolske, K. S., Hart, P. S., & Campbell-Arvai, V. (2020). The Aversion to Tampering with Nature (ATN) Scale: Individual Differences in (Dis)comfort with Altering the Natural World. *Risk Analysis*, 40(3), 638–656. <https://doi.org/10.1111/risa.13414>
- ¹⁹³ Merk, C., Klaus, G., Pohlers, J., Ernst, A., Ott, K., & Rehdanz, K. (2019). Public perceptions of climate engineering: Laypersons’ acceptance at different levels of knowledge and intensities of deliberation. *GAIA - Ecological Perspectives for Science and Society*, 28(4), 348–355. <https://doi.org/10.14512/gaia.28.4.6>
- ¹⁹⁴ Pidgeon, N. F., & Spence, E. (2017). Perceptions of enhanced weathering as a biological negative emissions option. *Biology Letters*, 13(4), 20170024. <https://doi.org/10.1098/rsbl.2017.0024>
- ¹⁹⁵ Jobin, M., & Siegrist, M. (2020). Support for the Deployment of Climate Engineering: A Comparison of Ten Different Technologies. *Risk Analysis*, 40(5), 1058–1078. <https://doi.org/10.1111/risa.13462>
- ¹⁹⁶ Merk, C., & Pönitzsch, G. (2017). The Role of Affect in Attitude Formation toward New Technologies: The Case of Stratospheric Aerosol Injection. *Risk Analysis*, 37(12), 2289–2304. <https://doi.org/10.1111/risa.12780>
- ¹⁹⁷ Braun, C., Rehdanz, K., & Schmidt, U. (2018). Exploring public perception of environmental technology over time. *Journal of Environmental Planning and Management*, 61(1), 143–160. <https://doi.org/10.1080/09640568.2017.1291414>
- ¹⁹⁸ Klaus, G., Ernst, A., & Oswald, L. (2020). Psychological factors influencing laypersons’ acceptance of climate engineering, climate change mitigation and business as usual scenarios. *Technology in Society*, 60, 101222. <https://doi.org/10.1016/j.techsoc.2019.101222>
- ¹⁹⁹ Wenger, A., Stauffacher, M., & Dallo, I. (2021). Public perception and acceptance of negative emission technologies – framing effects in Switzerland. *Climatic Change*, 167(3), 53. <https://doi.org/10.1007/s10584-021-03150-9>
- ²⁰⁰ Klaus, G., Ernst, A., & Oswald, L. (2020). Psychological factors influencing laypersons’ acceptance of climate engineering, climate change mitigation and business as usual scenarios. *Technology in Society*, 60, 101222. <https://doi.org/10.1016/j.techsoc.2019.101222>
- ²⁰¹ Klaus, G., Oswald, L., Ernst, A., & Merk, C. (2021). Effects of opinion statements on laypeople’s acceptance of a climate engineering technology. Comparing the source credibility of researchers, politicians and a citizens’ jury. *Journal of Science Communication*, 20(1), A03. <https://doi.org/10.22323/2.20010203>
- ²⁰² Merk, C., Pönitzsch, G., & Rehdanz, K. (2016). Knowledge about aerosol injection does not reduce individual mitigation efforts. *Environmental Research Letters*, 11(5), 054009. <https://doi.org/10.1088/1748-9326/11/5/054009>

-
- ²⁰³ IPCC 2022 Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change ed P R Shukla (Cambridge: Cambridge University Press) (<https://doi.org/10.1017/9781009157926>)
- ²⁰⁴ Shrum TR, Markowitz E, Buck H, Gregory R, van der Linden S, Attari SZ, Van Boven L. 2020 Behavioural frameworks to understand public perceptions of and risk response to carbon dioxide removal. *Interface Focus* 10: 20200002.
- ²⁰⁵ Christine Bertram and Christine Merk, Perceptions of Ocean-Based Carbon Dioxide Removal: The Nature-Engineering Divide? *Front. Clim.* 2:594194.
- ²⁰⁶ Low, S, C Baum, and BK Sovacool. "Taking it outside: Exploring social opposition to 21 early-stage experiments in radical climate interventions," *Energy Research & Social Science* 90 (August, 2022), 102594, pp. 1-21.
- ²⁰⁷ Cox E, Boettcher M, Spence E and Bellamy R (2021) Casting a Wider Net on Ocean NETs. 2021. *Front. Clim.* 3:576294. doi: 10.3389/fclim.2021.576294
- ²⁰⁸ Buck HJ (2018). The politics of negative emissions technologies and decarbonization in rural communities. *Global Sustainability* 1, e2, 1–7. <https://doi.org/10.1017/sus.2018.2>
- ²⁰⁹ Bellamy, Rob, Javier Lezaun, and James Palmer. "Perceptions of bioenergy with carbon capture and storage in different policy scenarios." *Nature communications* 10, no. 1 (2019): 1-9.
- ²¹⁰ Bellamy, R., 2018. Incentivize negative emissions responsibly. *Nature Energy*, 3(7), pp.532-534.
- ²¹¹ Shrum TR, Markowitz E, Buck H, Gregory R, van der Linden S, Attari SZ, Van Boven L. 2020 Behavioural frameworks to understand public perceptions of and risk response to carbon dioxide removal. *Interface Focus* 10: 20200002.
- ²¹² National Research Council 2015. *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/18805>.
- ²¹³ Edward A. Parson and Holly J. Buck, Large-Scale Carbon Dioxide Removal: The Problem of Phasedown, *Global Environmental Politics* 20:3, August 2020, https://doi.org/10.1162/glep_a_00575
- ²¹⁴ IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926
- ²¹⁵ GESAMP (2019). "High level review of a wide range of proposed marine geoengineering techniques". (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p.
- ²¹⁶ Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., ... Smith, P. (2018a). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, 13(6), 063003. <https://doi.org/10.1088/1748-9326/aabff4>
- ²¹⁷ Nemet, G. F. (2019). *How solar became cheap: a model for low-carbon innovation*. Routledge.
- ²¹⁸ Grübler, A., & Wilson, C. (2014). *Energy Technology Innovation: Learning from Historical Successes and Failures*. Cambridge University Press, Cambridge, UK.
- ²¹⁹ Creutzig, Felix, Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., ... Masera, O. (2015). Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*. <https://doi.org/10.1111/gcbb.12205>

-
- ²²⁰ Creutzig, F., Popp, A., Plevin, R., Luderer, G., Minx, J., & Edenhofer, O. (2012). Reconciling top-down and bottom-up modelling on future bioenergy deployment. *Nature Climate Change*, 2(5). <https://doi.org/10.1038/nclimate1416>
- ²²¹ Nemet, G. F. (2019). *How solar became cheap: a model for low-carbon innovation*. Routledge.
- ²²² Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., ... Smith, P. (2018a). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, 13(6), 063003. <https://doi.org/10.1088/1748-9326/aabff4>
- ²²³ Nemet, G. F. (2019). *How solar became cheap: a model for low-carbon innovation*. Routledge.
- ²²⁴ Mankins, J.C. (1995). *Technology Readiness Levels: A White Paper*. Advanced Concepts Office, Office of Space Access and Technology, NASA.
- ²²⁵ Innovation Fund Denmark (n.d.) Societal Readiness Levels (SRL) defined according to Innovation Fund Denmark. Available online at: https://innovationsfonden.dk/sites/default/files/2019-03/societal_readiness_levels_-_srl.pdf (accessed January 20, 2022).
- ²²⁶ Bruno, I., Donarelli, A., Marchetti, V. Panni, A.S. & Covino, B.V. (2020). Technology Readiness revisited: A proposal for extending the scope of impact assessment of European public services. *ICEGOV 2020*, 369-380. Available online at: https://ec.europa.eu/isa2/sites/default/files/technology_readiness_revisited_-_icegov2020.pdf (accessed January 20, 2022).
- ²²⁷ Industrial Decarbonization Research and Innovation Centre. (2022). Research and Innovation. January 3. Available online at <https://idric.org/research-innovation/> (accessed January 21, 2022).
- ²²⁸ International Energy Agency (2019). *Innovation Gaps*. Paris, France: IEA, Paris. Available online at: <https://www.iea.org/reports/innovation-gaps> (accessed January 20, 2022).
- ²²⁹ Sovacool, BK, CM Baum, S Low, C Roberts, and J Steinhauser. “Climate Policy for a Net-Zero Future: Ten Recommendations for Direct Air Capture,” *Environmental Research Letters* (in press)
- ²³⁰ Low, S, C Baum, and BK Sovacool. “Taking it outside: Exploring social opposition to 21 early-stage experiments in radical climate interventions,” *Energy Research & Social Science* 90 (August, 2022), 102594, pp. 1-21.
- ²³¹ GESAMP (2019). “High level review of a wide range of proposed marine geoengineering techniques”. (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p.
- ²³² Sargoni, J. (2016). The Best of Both Worlds: Maximising the Legitimacy of the EU's Regulation of Geoengineering Research. *European Journal of Risk Regulation*, 7(1), 87-108. doi:10.1017/S1867299X00005420
- ²³³ Holly Jean Buck, *Challenges and Opportunities of Bioenergy With Carbon Capture and Storage (BECCS) for Communities*, Current Sustainable/Renewable Energy Reports 2019.
- ²³⁴ Felix Creutzig et al., The mutual dependence of negative emission technologies and energy systems, *Energy Environ. Sci.*, 2019, 12, 1805
- ²³⁵ National Academies of Sciences, Engineering, and Medicine 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/25259>

²³⁶ Cambridge Economics, E4Tech and Element Energy. Policy Mechanisms for First-Of-A-Kind Direct Air Capture and Other Engineered Greenhouse Gas Removal. June, 2022, available at <http://www.element-energy.co.uk/wordpress/wp-content/uploads/2022/06/BEIS-Engineered-GGR-policies-FINAL-REPORT.pdf>.

²³⁷ European Commission (2021). Sustainable carbon cycles. Communication from the Commission to the European Parliament and the Council. COM(2021) 800 final.

²³⁸ 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’, *Frontiers in Climate*, 3, 638805.

²³⁹ Schenuit, F., Boettcher, M., and Geden, O. (2022). Carbon Dioxide Removal as an Integral Building Block of the European Green Deal. Stiftung Wissenschaft und Politik (SWP) Comment 2022/C 40, doi:10.18449/2022C40

²⁴⁰ Bright, M. (2022). *The Inflation Reduction Act creates a whole new market for carbon capture*. Clean Air Task Force: Boston, MA. <https://www.catf.us/2022/08/the-inflation-reduction-act-creates-a-whole-new-market-for-carbon-capture/>

²⁴¹ Carbon Capture Coalition. (2022). The *Inflation Reduction Act* (IRA) of 2022. Carbon Capture Coalition. <https://carboncapturecoalition.org/wp-content/uploads/2022/08/IRA-2022-Fact-Sheet-8.16.pdf>

²⁴² Spaargaren, G. and Mol, A.P., 2013. Carbon flows, carbon markets, and low-carbon lifestyles: reflecting on the role of markets in climate governance. *Environmental Politics*, 22(1), pp.174-193.

²⁴³ 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’, *Frontiers in Climate*, 3, 638805.

²⁴⁴ Honegger M, Poralla M, Michaelowa A and Ahonen H-M (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

²⁴⁵ Amelie Carver, How Stripe Is Building Up the Carbon Capture Market, Illumination, July 22, 2022, available at <https://medium.com/illumination/how-stripe-is-building-up-the-carbon-capture-market-3421a7ab1b79>

²⁴⁶ Kremer, M., Levin, J., & Snyder, C. M. (2020, May). Advance market commitments: insights from theory and experience. In *AEA Papers and Proceedings* (Vol. 110, pp. 269-73).

²⁴⁷ Meyer, R. (2022, April 13). We’ve Never Seen a Carbon-Removal Plan Like This Before. *The Atlantic*. <https://www.theatlantic.com/science/archive/2022/04/big-tech-investment-carbon-removal/629545/>

²⁴⁸ Louise Jeffery, Niklas Höhne, Mia Moisio, Thomas Day, Benjamin Lawless, Options for supporting Carbon Dioxide Removal, New Climate Institute, July, 2020.

²⁴⁹ Buck HJ (2018). The politics of negative emissions technologies and decarbonization in rural communities. *Global Sustainability* 1, e2, 1–7. <https://doi.org/10.1017/sus.2018.2>

²⁵⁰ Rickels Wilfried, Proelß Alexander, Geden Oliver, Burhenne Julian, Fridahl Mathias, Integrating Carbon Dioxide Removal Into European Emissions Trading, *Frontiers in Climate* 3 (2021), <https://www.frontiersin.org/articles/10.3389/fclim.2021.690023>.

²⁵¹ La Hoz Theuer, S., Doda, B., Kellner, K. and Acworth, W. (2021). *Emission Trading Systems and Net Zero: Trading Removals*. Berlin: ICAP

- ²⁵² 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. *Philosophical Transactions of the Royal Society A* 376: 20160447
- ²⁵³ Honegger, M.A. and Reiner, D. (2018) The political economy of negative emissions technologies: consequences for international policy design. *Climate Policy* 18:3, 306-321.
- ²⁵⁴ Torvanger, A. (2019). Governance of bioenergy with carbon capture and storage (BECCS): Accounting, rewarding, and the Paris agreement. *Climate Policy*, 19(3), 329–341. <https://doi.org/10.1080/14693062.2018.1509044>
- ²⁵⁵ Tamme, E. and Beck L.L. (2021). European Carbon Dioxide Removal Policy: Current Status and Future Opportunities. *Front. Clim.* 3:682882. doi: 10.3389/fclim.2021.682882
- ²⁵⁶ Carton, W., Asiyambi, A., Beck, S., Buck, H.J. and Lund, J.F. (2020). Negative emissions and the long history of carbon removal. *Wiley Interdisciplinary Reviews Climate Change*, doi:10.1002/wcc.671.
- ²⁵⁷ Song, L., and Temple, J. (2021). A nonprofit promised to preserve wildlife. Then it made millions claiming it could cut down trees. *Propublica*. <https://www.propublica.org/article/a-nonprofit-promised-to-preserve-wildlife-then-it-made-millions-claiming-it-could-cut-down-trees#:~:text=The%20Air%20Resources%20Board%20accepted,in%20exchange%20for%20its%20promise.>
- ²⁵⁸ Carton, W., Lund, J.F., and Dooley, K. (2021). Undoing Equivalence: Rethinking Carbon Accounting for Just Carbon Removal. *Frontiers in Climate* DOI:10.3389/fclim.2021.664130.
- ²⁵⁹ Rogelj, J., Geden, O., Cowie, A. and Reisinger, A. (2021) ‘Three ways to improve net zero emissions targets’, *Nature*, 591, p365-368.
- ²⁶⁰ Buck, H. J. (2021). *Ending Fossil Fuels: Why Net Zero Is Not Enough*; Verso Books.
- ²⁶¹ Asayama, S. (2021). The Oxymoron of Carbon Dioxide Removal: Escaping Carbon Lock-In and yet Perpetuating the Fossil Status Quo? *Front. Clim.* 3:673515. doi: 10.3389/fclim.2021.673515
- ²⁶² Battersby, F, Heap, RJ, Gray, AC, Workman, M and Strivens, F. (2022). The Role of Corporates in Governing Carbon Dioxide Removal: Outlining a Research Agenda. *Front. Clim.* 4:686762. doi: 10.3389/fclim.2022.686762
- ²⁶³ IEA (2021). *Net Zero by 2050: A road map for the global energy sector*, International Energy Agency.
- ²⁶⁴ 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. *Frontiers in Climate*. DOI: 10.3389/fclim.2021.664456
- ²⁶⁵ McLaren, D.P., Tyfield, D.P., Willis, R., Szerszynski, B. and Markusson, N. (2019) ‘Beyond ‘Net Zero’: A case for separate targets for emissions reduction and negative emissions’, *Frontiers in Climate*, 1(4), doi: 10.3389/fclim.2019.00004
- ²⁶⁶ Smith, Joyotee, Kalemani Mulongoy, Reidar Persson, and Jeffrey Sayer. "Harnessing carbon markets for tropical forest conservation: towards a more realistic assessment." *Environmental Conservation* 27, no. 3 (2000): 300-311.
- ²⁶⁷ Fiona Downs. *Forest carbon rights and corruption: What donors can do to minimize the risks*. U4 Brief. January 2015. 1.
- ²⁶⁸ Schneider L, Kollmuss A. Perverse effects of carbon markets on HFC-23 and SF6 abatement projects in Russia. *Nature Climate Change*. 2015 Dec;5(12):1061-3.
- ²⁶⁹ Honegger, M, Poralla, M, Michaelowa, A and Ahonen, H-M (2021b). 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

-
- ²⁷⁰ 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
- ²⁷¹ Benjamin K Sovacool et al “Climate policy for a net-zero future: ten recommendations for Direct Air Capture” 2022 *Environ. Res. Lett.* 17 074014
- ²⁷² Meckling, J. and Biber, E. (2021). A policy roadmap for negative emissions using direct air capture. *Nature Communications* 12: 2051.
- ²⁷³ Cox, E. and Edwards, N.R. (2019). Beyond carbon pricing: policy levers for negative emissions technologies. *Climate Policy*. DOI: 10.1080/14693062.2019.1634509
- ²⁷⁴ Brack, D., and King, R. (2021). Managing Land-based CDR: BECCS, Forests and Carbon Sequestration. *Global Policy* 12(1): 45-56.
- ²⁷⁵ Low, S., Baum, C.M., and Sovacool, B.K. (2022). Rethinking Net Zero Systems, Spaces, and Societies: Hard vs. soft alternatives for engineered and nature-based carbon removal. *Global Environmental Change* 75, 102530. DOI: 10.1016/j.gloenvcha.2022.102530
- ²⁷⁶ Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nature Energy*, 3, 532–534.
- ²⁷⁷ Mace, M.J., Fyson, C.L., Schaeffer, M., and Hare, W.L. (2021). Large-Scale Carbon Dioxide Removal to Meet the 1.5°C Limit: Key Governance Gaps, Challenges and Priority Responses. *Global Policy* 12(1): 67-81.
- ²⁷⁸ Low, S., Baum, C.M., and Sovacool, B.K. (2022). Rethinking Net Zero Systems, Spaces, and Societies: Hard vs. soft alternatives for engineered and nature-based carbon removal. *Global Environmental Change* 75, 102530. DOI: 10.1016/j.gloenvcha.2022.102530
- ²⁷⁹ Borth, A.C. and Nicholson, S. (2021). A Deliberative Orientation to Governing Carbon Dioxide Removal: Actionable Recommendations for National-Level Action. *Front. Clim.* 3:684209. doi: 10.3389/fclim.2021.684209
- ²⁸⁰ Healey, P., Scholes, R., Lefale, P. and Yanda, P. (2021) Governing Net Zero Carbon Removals to Avoid Entrenching Inequities. *Front. Clim.* 3:672357. doi: 10.3389/fclim.2021.672357
- ²⁸¹ Sovacool, BK, C Baum, and S Low. “Climate protection or privilege? A whole systems justice milieu of twenty negative emissions and solar geoengineering technologies ” *Political Geography* (in press)97, 102702. DOI: 10.1016/j.polgeo.2022.102702
- ²⁸² Vincent, K., Carter, S., Steynor, A. et al. Addressing power imbalances in co-production. *Nat. Clim. Chang.* 10, 877–878 (2020). <https://doi.org/10.1038/s41558-020-00910-w>
- ²⁸³ Gerber, J.-F. (2011). Conflicts over industrial tree plantations in the South: Who, how and why? *Global Environmental Change*, 21(1), p165-176.
- ²⁸⁴ Ericksen, P.J. (2008). Conceptualizing food systems for global environmental change research. *Global Environmental Change*, 18(1), p234-245.
- ²⁸⁵ Lovera-Bilderbeek, S. and Lahiri, S. (2021). Addressing Power Imbalances in Biosequestration Governance. *Global Policy* 12(1): 57-66.
- ²⁸⁶ Cox, E., Boettcher, M., Spence, E., Bellamy, R. (2021). Casting a wider net on Ocean NETs. *Frontiers in Climate* <https://doi.org/10.3389/fclim.2021.576294>
- ²⁸⁷ Lezaun, J. (2021). Hugging the shore: Tackling marine carbon dioxide removal as a local governance problem. *Frontiers in Climate* 3:684063.
- ²⁸⁸ Hilser, H., Cox, E., Draiby, A., Moreau, C., Hiraldo, L., Walworth, N.G. and Winks, L. (2022). Localized governance of carbon dioxide removal in Small Island Developing States. <https://ssrn.com/abstract=4114319>
- ²⁸⁹ Pozo, C., Galán-Martín, Á., Reiner, D.M. Mac Dowell, N., and Guillén-Gosálbez, G. (2020). Equity in allocating carbon dioxide removal quotas. *Nature Climate Change* 10, 640–

646. Mohan, A., Geden, O., Fridahl, M., Buck, H.J., and Peters, G.P. (2021). UNFCCC must confront the political economy of net-negative emissions. *One Earth* 4: 1348-1351.

²⁹⁰ Pozo, C., Galán-Martín, Á., Reiner, D.M. Mac Dowell, N., and Guillén-Gosálbez, G. (2020). Equity in allocating carbon dioxide removal quotas. *Nature Climate Change* 10, 640–646.

²⁹¹ Fuss, S., Canadell, J.G., Ciais, P., Jackson, R.B., Jones, C.D., Lyngfelt, A., Peters, G.P., and van Vuuren, D.P. (2020). Moving toward Net-Zero Emissions Requires New Alliances for Carbon Dioxide Removal. *One Earth* 3: 145-149.

²⁹² Rogelj, J., Forster, P.M., Kriegler, E. et al. Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* 571, 335–342 (2019).

²⁹³ Gambhir, A., Butnar, I., Li P. H., Smith, P., & Srachan, N. (2019). A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS. *Energies*, 12, 1747; doi:10.3390/en12091747.

²⁹⁴ van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D. & Cassen. C. (2020). Anticipating futures through models: Integrated Assessment Modeling in the climate science-policy interface since 1970. *Global Environmental Change* 65: 102191.

²⁹⁵ Boettcher Miranda, Brent Kerry, Buck Holly Jean, Low Sean, McLaren Duncan, Mengis Nadine, Navigating Potential Hype and Opportunity in Governing Marine Carbon Removal, *Frontiers in Climate* 3 (2021), <https://www.frontiersin.org/article/10.3389/fclim.2021.664456>

²⁹⁶ Boettcher Miranda, Brent Kerry, Buck Holly Jean, Low Sean, McLaren Duncan, Mengis Nadine, Navigating Potential Hype and Opportunity in Governing Marine Carbon Removal, *Frontiers in Climate* 3 (2021), <https://www.frontiersin.org/article/10.3389/fclim.2021.664456>

²⁹⁷ Sabine Fuss et al., Negative emissions—Part 2: Costs, potentials and side effects, *Environ. Res. Lett.* 13 (2018) 063002