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Climate protection or privilege? A whole systems justice milieu of twenty negative emissions and solar geoengineering technologies

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ABSTRACT

In this study, we utilize a large and diverse expert interview exercise (N = 125) to critically examine the whole systems justice issues associated with ten negative emissions and ten solar geoengineering technologies. We ask: What equity and justice concerns arise with these 20 options? What particular vulnerable groups could be affected? What risks do these options entail for communities or the climate? Utilizing a “claims making” approach, we examine existing and prospective injustices across a pluralistic whole systems framework analyzing (i) resource extraction issues including minerals, chemicals, and fertilizers (ii) manufacturing, labor and ownership concerns, (iii) transportation-network and land-grabbing dynamics, (iv) unfair and exclusionary policymaking and planning, (v) operational injustices resulting from deployment and use, and (vi) waste flows, liabilities and disposal requirements. We then explore how these potential concerns culminate in a milieu of injustice cutting across the dimensions of distribution (who gets what), recognition (who counts), participation (who gets heard), capabilities (what matters), and responsibility (who does what). We conclude with insights for both policy and future research.

1. Introduction

Negative emissions and solar geoengineering technologies are becoming increasingly justified as urgent and necessary for reducing global temperature change or meeting existing targets embedded in the Paris Accord. For example, many Integrated Assessment Modeling scenarios discuss the widespread use of negative emissions technologies such as bioenergy with carbon capture and storage, suggesting that it could absorb more than 1,000 Gt Co₂ between now and the end of the century, essentially doubling the carbon budget available to human society (Fuss et al., 2014). Other carbon dioxide removal techniques such as afforestation or soil carbon sequestration and management can enhance carbon uptake and be implemented more quickly than some climate mitigation actions such as substituting fossil fuels with nuclear energy (Houghton et al., 2015). Enhanced weathering could even reduce atmospheric levels of carbon to the point where ocean acidification is effectively ameliorated by the end of the century (Taylor et al., 2016). Other researchers have argued that humanity must consider solar geoengineering techniques, such as stratospheric aerosol injection, marine cloud brightening, or cirrus cloud thinning, to reverse the global

warming caused by climate change (Barrett et al., 2014; National Academies of Sciences, Engineering, and Medicine, 2021; Keith, 2013; Sovacool, 2021a).

Despite the increasing importance of both carbon dioxide removal and solar geoengineering in the recent literature, such options are highly contested given that they could entail significant risks for planetary health, for future energy systems, and even for community wellbeing and livelihoods. In the extreme, critics suggest that such options could create a dangerous moral hazard that accelerates emissions (and consequent climate impacts) if policymakers were to foolishly believe they no longer need to mitigate emissions deeply, justly or quickly (Anderson and Peters, 2016; Bellamy, 2018; van Vuuren et al., 2017).

But what global energy justice and equity issues may arise if indeed their future deployment were to occur? In this study, we rely on a large expert-interview exercise (N = 125) to critically examine the whole systems justice issues associated with ten negative emission options (e.g., biochar, direct air capture, enhanced weathering) and ten solar geoengineering options (e.g., stratospheric aerosol injection, ice protection, sun shades). Utilizing a “claims making” approach, we examine existing and prospective injustices across a whole systems framework

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incorporating (i) resource extraction issues including minerals and chemicals, (ii) manufacturing, labor and ownership concerns, (iii) transportation-network and land-grabbing dynamics, (iv) unfair policymaking and planning, (v) operational injustices from deployment and use, and (vi) waste flows, liabilities and disposal requirements. We then explore how these potential injustices culminate in a milieu of injustice cutting across the dimensions of distribution, recognition, participation, capabilities, and responsibility “from below” as well as “from above.” We conclude with insights for both policy and future research.

In doing so, we make multiple contributions. Bellamy and Palmer (2019) write that far too little energy geography work currently engages with geoeconomics, a term inclusive of both negative emissions technologies and solar radiation management techniques. They urge the research community to better utilize geographical approaches to recognize the “heterogeneous spatial contexts” within deployment options and to explore how such technologies can lead to “new modes of geopolitics” and new types of human relations with place-making and earth-scale processes. We tackle this head on by applying a multi-scalar, whole systems environmental and energy justice framework that accounts for injustices from the “top-down” as well as “bottom-up.” In doing so, we reveal multiple place-specific injustices which “span the socio-environment gamut” (Marston and Himley, 2021) as well as how multiple spatial scales can be affected by the deployment of different technologies. We also agree with Mahony’s (2021) request that the geography literature better unpack the “making and unmaking” of boundaries between the deployment of new technologies, especially emergent “high tech” systems, and the prospective, multi-scalar effects of that deployment.

2. Energy justice: tenets, technologies and milieu

Before we explain our specific Research Design, Results, and Discussion, in this Section we introduce readers briefly to the core tenets of environmental and energy justice, and we argue in favor of a multiplicity of justice perspectives. We then explore recurring themes relating to justice (and equity) in the emergent literature on negative emissions and solar geoeconomics technologies. These include issues of procedural justice and inclusion, mitigation deterrence and moral hazard, unfair distribution of risks, and unfair distribution of benefits. There is a larger literature on justice that has been historically coupled to or blended into ethical investigations, but these do not always clearly articulate justice principles or dimensions. We finally identify gaps, and synthesize the literature into a multi-scalar and whole systems milieu, which we return to in Sections 4 and 5.

2.1. Multiplicity: merging core tenets of environmental and energy justice

Environmental justice and energy justice have similar terms and groundings, but are not identical. Jenkins (2018) argues that environmental justice traditionally refers to either the fair or unfair distribution of environmental hazards, or equal or unequal access to natural resources. The environmental justice literature initially placed more emphasis on activist-led, community-level topics of interest, especially the distribution of pollution or exposure to toxicity, often measured at the local scale. Energy justice, by contrast, does not have such an activist history, and focuses instead most generally on providing individuals safe, affordable, and sustainable energy, but within a framework that also respects equal distribution, fair procedure, and the recognition of vulnerable groups (Jenkins, 2018). Energy justice refers broadly to a conceptual approach seeking to investigate the various costs of energy systems or transitions, the fairness (or unfairness) in ownership and benefits, the impartiality and representative of procedures as well as impacts on recognition and vulnerable groups (Sovacool et al., 2016). Energy justice thus combines elements of distributive justice, procedural justice, and free, prior informed consent, but also cosmopolitan concerns of human rights or global externalities and recognitional concerns of

Table 1
Pluralizing the tenets of environmental and energy justice.

Tenet of justice	Critical questions
<i>Distribution</i>	<ul style="list-style-type: none"> • Does a deprived community suffer disproportionately from an environmental burden? • Is it particularly vulnerable to the impact of the environmental burden? • Is it provided with mitigating measures?
<i>Recognition</i>	<ul style="list-style-type: none"> • Does exposure to an environmental burden result in, or add to, misrecognition for a deprived community or stigmatization of a deprived area? • Is the area perceived as a ‘natural’ destination for other environmental burdens and does it suffer from their cumulative impact?
<i>Participation</i>	<ul style="list-style-type: none"> • Is a deprived community excluded from decisions about locating, or strategies to mitigate, an environmental burden?
<i>Responsibility</i>	<ul style="list-style-type: none"> • Is a deprived community the least contributor to the cause of the environmental burden to which it is exposed? • Is it compensated by the benefits that are attendant on the environmental burden? • Can it contribute to mitigation measures?
<i>Capabilities</i>	<ul style="list-style-type: none"> • Does the environmental burden limit the freedom of a deprived community to pursue their valued goals?

Source: Modified from Davoudi and Brooks (2014).

vulnerable groups and dispossessed minorities (McCauley et al., 2019).

The environmental justice literature has existed and grown over the past four decades, whereas the energy justice literature has flourished and grown mostly over the past decade, with the number of publications published in key journals more than doubling for some periods (e.g., 2017 and 2018) (Jenkins et al., 2021).

In this study, we draw from both environmental and energy justice, but in a way that respects a multiplicity of perspectives. We advance a pluralistic framework of justice from Davoudi and Brooks (2014) that combines a more expansive conceptualization of distributive justice but is coupled to important concerns related to recognition, participation, capability, and responsibility. Essentially, this framework deals with:

- Distribution: who gets what?
- Recognition: who counts?
- Participation: who gets heard?
- Capabilities: what matters?
- Responsibility: who does what?

Table 1 offers an overview of these concerns, along with examples of critical research questions.

The multifaceted, pluralistic perspective of environmental and energy justice offered in Table 1 has the benefit of approaching justice well beyond *only* the issue of equity, or how environmental benefits and burdens are distributed (Walker, 2011). It offers what Schlosberg (2004) terms a more complete assessment of justice issues – that extends beyond distribution of benefits to include equity in the distribution of environmental or energy/climate burdens, and it recognizes the diversity of experiences of affected communities, and it calls for participation in political processes that design and govern policy. This more expansive notion of energy justice extends horizontally to a broader range of issues (employment, health, exclusion), vertically into different scales of injustice (local and community, national, global), and even conceptually to how humans treat the non-human world (impacts on other species and the ecosystems, lands, and habitats they depend upon) (Schlosberg, 2013). Environmental and energy justice is conceived as cutting across “spheres of justice” to include issues of distribution (the goods and bads people receive), procedure (the way people are addressed), and recognition (the involvement of people in decision-making) (Martens, 2012, 2016).

Table 2

Exploring twenty different negative emissions and solar geoengineering technologies discussed in the energy and climate literature.

Type	Option	Description	Reference
Negative emissions	<i>Carbon capture and utilization and storage</i>	Employing technologies, processes or solvents that extract, capture, transport, utilize, and/or store carbon dioxide	National Research Council. 2015a; Bruhn et al., 2016; European Academies Science Advisory Council, 2018; Linzenich et al., 2019;
Negative emissions	<i>Afforestation and reforestation</i>	Planting trees or vegetation to absorb carbon dioxide	Royal Society 2009; National Research Council. 2015a; Minx et al., 2018; National Academies of Sciences, Engineering, and Medicine 2019
Negative emissions	<i>Bioenergy with carbon capture and storage</i>	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	Royal Society 2009; Sanchez et al., (2015); Minx et al., 2018; Fridahl and Lehtveer (2018); Harper et al., (2018); National Academies of Sciences, Engineering, and Medicine 2019
Negative emissions	<i>Biochar</i>	Managing the thermal degradation of organic material in the absence of oxygen to increase soil carbon stocks and improve soil fertility	Royal Society 2009; Sohi 2010; Minx et al., 2018
Negative emissions	<i>Soil carbon sequestration or enrichment</i>	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	National Research Council. 2015a; Minx et al., 2018; National Academies of Sciences, Engineering, and Medicine 2019
Negative emissions	<i>Ocean iron fertilization</i>	Utilizing planktonic algae and other microscopic plants to take up CO ₂ and convert it to organic matter, some of which sinks and is sequestered in ocean	Royal Society 2009; Minx et al., 2018
Negative emissions	<i>Enhanced weathering and ocean liming or alkalization</i>	Deploying physical or chemical mechanisms to accelerate the geochemical processes that naturally absorb CO ₂ at slow rates.	Royal Society 2009; Minx et al., 2018; National Academies of Sciences, Engineering, and Medicine 2019
Negative emissions	<i>Direct air capture</i>	Capturing carbon dioxide from the air via engineering or mechanical systems, and then using solvents or other techniques to store it safely	Minx et al., 2018; National Academies of Sciences, Engineering, and Medicine 2019; Hanna et al., (2021)
Negative emissions	<i>Blue carbon and seagrass</i>	Harnessing the ability for coastal mangrove forests, tidal marshes, and seagrass meadows to accelerate their uptake of carbon dioxide	Greiner et al., (2013); Johannessen and Macdonald (2016); National Academies of Sciences, Engineering, and Medicine 2019
Negative emissions	<i>Ecosystem restoration</i>	Managing the restoration of ecosystems (including wetlands, peatlands, and grasslands) to reverse environmental damage and increase their ability to absorb greenhouse gases	Griscom et al., 2017; National Academies of Sciences, Engineering, and Medicine 2019
Solar geoengineering	<i>Space mirrors</i>	Placing scatterers, reflectors, or spacecraft in outer space to reduce the amount of sunlight entering the Earth's atmosphere	Angel (2006); Chandler, 2007; Royal Society 2009; Caldeira et al., (2013); Baum et al., (2022)
Solar geoengineering	<i>High altitude sunshades</i>	Placing scatterers or reflectors in the upper atmosphere (e.g., stratosphere) to reduce the amount of sunlight entering the Earth	Chandler, 2007; Kosugi (2010); Brown and Sovacool (2011)
Solar geoengineering	<i>Stratospheric aerosol injection</i>	Dispersing aerosol particles through high-altitude jets (e.g., sulfur) into the lower stratosphere, where they would reflect a small portion of incoming sunlight back to space, cooling temperatures.	Brown and Sovacool (2011); Royal Society 2009; Caldeira et al., (2013); Keith et al., (2014); National Academies of Sciences, Engineering, and Medicine 2021
Solar geoengineering	<i>Cirrus cloud thinning</i>	Reducing cirrus cloud cover to facilitate the release of outgoing radiation and lower temperature	Duan et al., (2018); National Academies of Sciences, Engineering, and Medicine 2021
Solar geoengineering	<i>Marine sky or cloud brightening</i>	Coordinating fleets of ships to spray sea water into the air below marine clouds, thereby increasing their reflectivity and longevity	National Research Council 2015b; Caldeira et al., (2013); National Academies of Sciences, Engineering, and Medicine 2021
Solar geoengineering	<i>Albedo modification via human settlements</i>	Enhancing the reflectivity of buildings, roads, or other structures to cool the global temperature	Brown and Sovacool (2011); Caldeira et al., (2013)
Solar geoengineering	<i>Albedo modification via grasslands and crops</i>	Enhancing the reflectivity of grasslands, crops, and land to cool the global temperature	Caldeira et al., (2013); National Research Council 2015b
Solar geoengineering	<i>Albedo modification via deserts</i>	Enhancing the reflectivity of deserts to cool the global temperature	Caldeira et al., (2013); Royal Society 2009
Solar geoengineering	<i>Albedo modification via clouds</i>	Creating new clouds or reflecting more sunlight from the surface to increase the heating of the lower atmosphere, improving cloudy-sky shortwave climate forcing	Caldeira et al., (2013); Royal Society 2009; Zhao et al., (2021)
Solar geoengineering	<i>Ice protection</i>	Protecting glaciers and ice sheets by either slowing their melting or reflecting solar radiation via tarpaulins	Desch et al. (2016)

Source: Authors

2.2. Technologies: justice, negative emissions, and solar geoengineering

The specific focus of our application of environmental and energy justice is the collection of climate geoengineering technologies, a broad

term that refers to “prospective large-scale interventions in the Earth’s climate system that seek to either remove greenhouse gases from the atmosphere or reflect sunlight back into space” (Bellamy and Palmer, 2019). One other novel feature of our study is that it explores a broad

diversity of negative emissions and solar geoengineering options. As Table 2 summarizes, this includes ten distinct options (drawn from the literature) including nature-based or terrestrial negative emissions technologies such as soil sequestration and management, ecosystem restoration, and forestry along with engineered options such as direct air capture and enhanced weathering. We also examine ten solar geoengineering options including various forms of albedo management and ice protection.

One justice issue mentioned in the literature on negative emissions centers on *procedural justice*, notably the failure of advocates to adequately consult with communities or recognize vulnerable groups in planning and permitting processes (O'Beirne et al., 2020). A related critique argues that too much negative emissions discussions (and knowledge) remain concentrated on the Global North, and excludes technology transfer as well as knowledge and modeling input from the Global South (Delina, 2020). Members of indigenous groups have also expressed concern that they believe carbon dioxide removal experiments are morally wrong because they are imposed by elites onto vulnerable First Nations populations without their informed consent (Bertram and Merk, 2020).

Similar to negative emissions, one justice concern for solar geoengineering is *procedural justice* and lack of representative decision-making and planning. Efforts to integrate Global South actors into solar radiation management research initiatives remain constrained (Rahman et al., 2018; Winickoff et al., 2015). Svoboda et al. (2011) write about how solar engineering options could be deployed unilaterally by elites or actors in the Global North, imposing them unfairly on the Global South without their consent. Low and Buck (2020) also write about how climate engineering options often fail to tap into truly inclusive or responsible forms of innovation or technology design. McLaren (2018) argues that the knowledge systems of technocratic, Northern-based global cockpit modeling that produce idealized stratospheric aerosol injection scenarios have a consequentialist and utilitarian reading of justice that shuts out participation from more marginalized societies and constituencies. The National Academies of Sciences, Engineering, and Medicine (2021) has highlighted the salience of procedural issues as well, noting that the concentration of research in wealthy countries, and limited participation by some actors, has served to marginalize diverse voices and raised concerns about “recognition justice.”

A second justice issue relates to the *moral hazard* or *mitigation deterrence* that arises from (the promise of) deploying negative emissions options. This encompasses the ethical appropriateness of slowing mitigation (and failing to immediately lower emissions) because negative emissions technologies can offset them at a later date. This involves a potential moral hazard against acting immediately to fight climate change and relies on an implicit, unproven, and potentially hubristic bet that we can indeed deploy negative emissions technologies at scale in the future (Minx et al., 2018; Lamb et al., 2020; Low and Boettcher, 2020). There is even a concern that researching negative emissions technologies can create path dependencies that lock in a requirement that we *have* to deploy such options even if they come to possess considerable risks for future generations. Buck (2019) frames this as a matter of intergenerational injustice, given negative emissions options can allow for continued emissions in the Global North on the assumption that the Global South can be exploited for negative emissions adoptions later. Such a trend could exacerbate a “decarbonization divide” between North and South, where the North becomes cleaner and less carbon intensive only at the expense of the South becoming dirtier and more carbon intensive (Sovacool et al., 2020), perpetuating patterns of “pollution offshoring” (Brunel, 2017; Cole et al., 2021; Levinson, 2010).

Claims of *moral hazard* and *mitigation deterrence* also arise in the literature on solar geoengineering (Gardiner and McKinnon, 2020). In their review of the solar geoengineering literature, Pamplany et al. (2020) even noted that this challenge came up in 33 separate studies, making it one of the most frequently-used justice arguments in the field.

This included claims of “moral corruption” (the subversion of moral arguments to immoral ends) as well as variants of “moral hazard” (including “technical dependence hazard,” “governance hazard,” “snowball hazard,” and “ethical” and “life-style consolidation” hazards.” Sapinski et al. (2020) also add, based on a summary of a special issue on the topic, that some options are ethically questionable given these concerns.

Another justice issue, one extensively discussed, concerns distributional justice and the unfair *distribution of risks* within negative emissions options. Carton et al. (2020) note that many negative emissions options are land-intensive and can thus perpetuate land-based exploitation of the Global South by the Global North, something that has already occurred with carbon-emissions trading and forestry initiatives; they can also induce severe negative social and environmental impacts including the use of fertilizers and pesticides or the exclusion of local groups. Other studies mention equity or distributional concerns over storage disposal constraints (Honegger and Reiner, 2017), social acceptance and public perceptions (Cox et al., 2021; Shrum et al., 2020; Wibeck et al., 2015), and risks to the environment or planetary health (Anderson and Peters, 2016; Buck, 2016; Obersteiner et al., 2018).

Moreover, the solar geoengineering literature also discusses distributional justice issues related to the *unfair distribution of risks*. Russell et al. (2012) mention how stratospheric aerosol injection could induce regional cooling with differentiated impacts on rainfall, forest quality, and marine ecosystems that could see some actors benefit at the expense of others. The National Research Council (2015b) also noted potential risks with both aerosol injection and albedo modification that include the worsening of ozone depletion, changes in soil moisture, and increases in acid rain across different ecosystems. McLaren (2018) argues that the distributional effects of solar radiation management via clouds would not be experienced evenly or fairly, as they would differ across latitudes. Koremenos (2020) and Horton, 2020 caution that solar geoengineering could induce significant changes to regional climates beyond those areas deploying the technology, especially if done by non-state actors. The National Academies of Sciences, Engineering, and Medicine (2021) summarized “justice, fairness, and equity concerns” in their recent report on solar geoengineering, cautioning that distributive injustices could decrease the likelihood of fair outcomes and also exacerbate vulnerabilities. In addition, they noted that deployment raises significant issues over intergenerational equity as it merely postpones climate action to future generations. Preston (2013) also identified the existence of temporal and intergenerational aspects to distributive justice concerns connected to solar geoengineering, suggesting that some ethical issues arise now, when actors contemplate prospective action; some appear only in the near-term future as research gets underway or the technologies are tested; some appear with the full implementation of solar geoengineering technologies; and a final set only occur when actors plan for the elimination and closure of geoengineering projects.

A final justice issue documented by the literature relates to the *distribution of benefits* arising from projects. Buck (2018) notes that rural communities could come to resent negative emissions projects that concentrate financial and energy flows to urban areas or that have benefits flow out of a community—not directly enriching local actors. McLaren et al. (2016) add that such justice concerns over the fairness of the distribution of project benefits can also strongly shape public reactions and acceptance (or rejection), with excluded publics often coming to oppose projects they feel to be exclusionary. Others discuss potential distributive justice issues connected with the design and creation of carbon offsets, and mechanisms of monitoring, reporting, verification, and trading (Bellassen et al., 2015), all of which will almost certainly implicate many of the negative emissions systems either presently in operation or being developed.

2.3. Research gaps: synthesis towards a multi-scalar milieu

Even though procedural and distributive justice issues are beginning to be rigorously documented within the corpus of energy and climate research (and some, such as Heyward, 2019, setting aside notions of rectifactory justice to focus only on distributive and procedural justice), notable lacunae remain. Multiple studies caution that ethical concerns are still seen as peripheral, rather than central, in most extant research (Bellamy, 2018; Lenzi, 2018; Lenzi et al., 2018), even in discussions within or among countries in the Global South (Sugiyama et al., 2017). Gardiner and McKinnon (2020) discuss the need to adopt a broader approach to justice and ethics in existing research and policy; and Pamplany et al. (2020: 3110) go even further in their critique of the literature, documenting “semantic diversity and ethical ambiguity, the academic lop-sidedness of the debate, missing contextual setting, need for interdisciplinary approaches, public engagement, and region-specific assessment of ethical issues.” Buck (2016: 157) adds that while a substantial justice and equity literature addresses particular options such as afforestation or land use, there is “virtually no social science literature” on the potential injustices of direct air capture or enhanced weathering. In later work, Buck (2018) argues that environmental justice concerns around negative emissions technologies are almost always viewed in local, “not-in-my-backward-ism” terms, rather than grappling with a broader scope of justice issues at a greater number of scales. Markusson et al. (2020) also criticized the broad body of work on negative emissions for subscribing to narrow, technoeconomic framings and for focusing intently on instrumental outcomes, rather than subscribing to broader, more inclusive equity framings that would focus on ethical and moral outcomes. Finally, Pamplany et al. (2020) caution that many of the Integrated Assessment Models behind negative emissions and solar radiation management options make inherent arguments about distributive notions of justice, but miss other important ones, including procedure, recognition, and even restorative or corrective justice.

It is with these shortcomings in mind that we designed our study to address a more comprehensive list of justice concerns, across a broader set of scales and systems, based on more inclusive and representative data. Energy justice through a “whole systems” lens seeks to reveal the potential justice impacts that result not only from the use of a

technology, but the often hidden “sacrifice zones” or “embodied injustices” within its lifecycle or supply chain (Healy et al., 2019). As Fig. 1 summarizes, a whole systems approach suggests that one examines a given energy technology across six scales (Brock et al., 2021; Sovacool, 2021b; Sovacool et al., 2019):

- Resource extraction, including mineral supply chains and the extractive industries, which often involve the displacement of workers or generate community hazards;
- Manufacturing and ownership, which can also involve occupational hazards and impacts on labor and employment and concentrations of ownership and intellectual property;
- Transport and construction, including accidents during the building of systems as well as the embodied environmental footprints of materials or the grabbing of land needed to build facilities;
- Policymaking and planning, including licensing, permitting, standards and regulation;
- Operation and use, including the provision of energy services (or in this case the capture and storage of carbon dioxide, or the performance of technologies at changing temperature) or the risk of onsite accidents;
- Disposal and waste, including issues of recycling, waste incineration and electronic waste flows as well as accidents at storage facilities.

Such an approach situates justice concerns across not only a multiplicity of scales but also temporalities of a technology’s lifecycle. It enables one to assess injustices across the entire system – not just use and deployment or policymaking, which is where most studies focus. It also captures past or recurring injustices alongside future ones, covering experienced injustices but also anticipated or prospective ones.

Furthermore, the multifaceted notion of environmental and energy justice elaborated on in Section 2.1 was intended to expressly address these deficiencies, and it approaches justice from the vantage point of what Elden (2021) and Campbell (2019) term a *milieu*. This term is meant to capture how justice issues are not static, but emergent and dynamically evolving; and also relational, where they interact and intersect in ways that anchor different socio-spatial and socio-material relations as well as mediate a critical dialogue that can disrupt them.

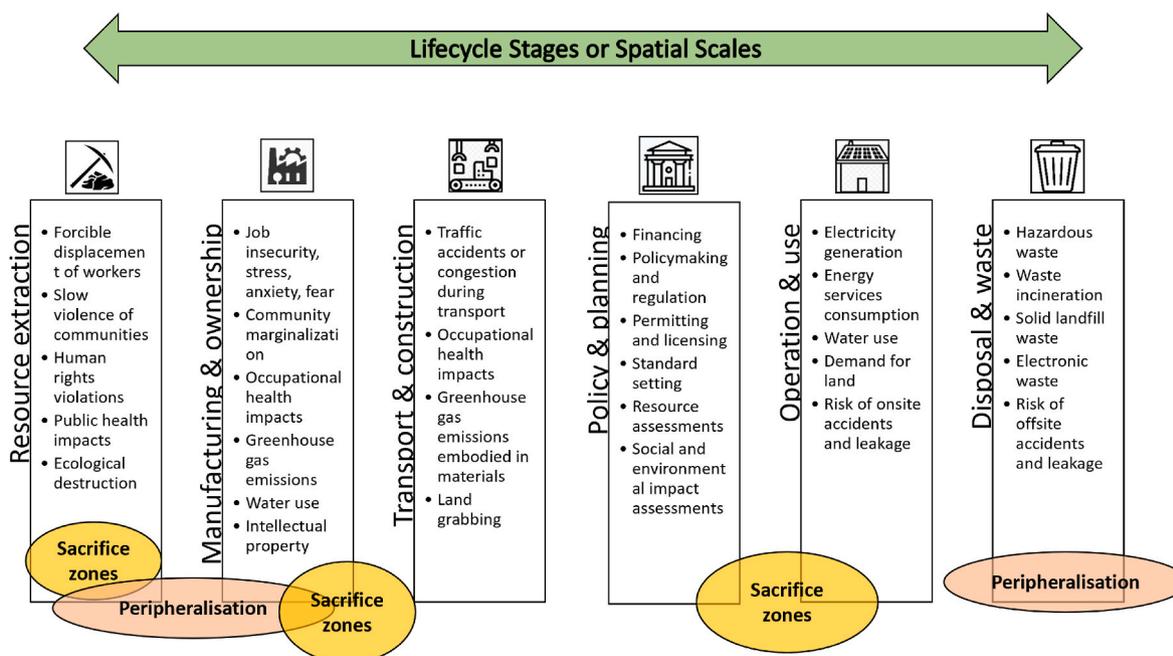


Fig. 1. Conceptualizing a whole systems approach to environmental and energy justice. Source: Authors, modified from Brock et al. (2021) and Sovacool (2021).

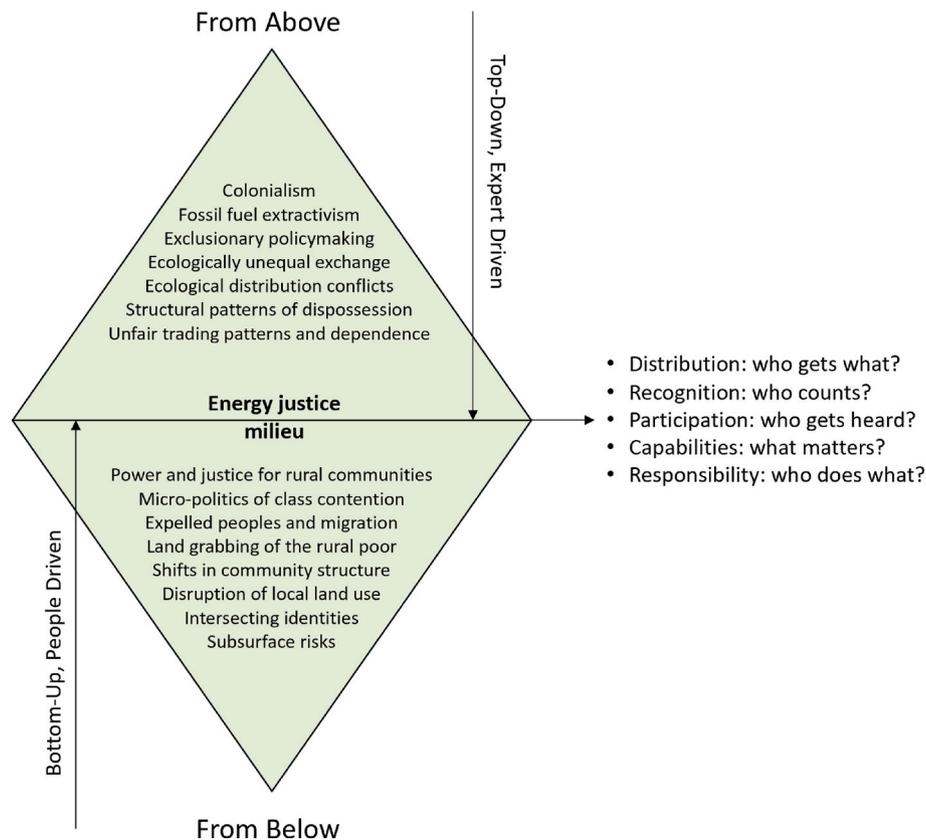


Fig. 2. Integrating “from below” and “from above” environmental and energy justice perspectives.
Source: Authors

Employing justice as a milieu enables one to capture injustices *from below* or *bottom-up* (or even *subsurface*) as well as *from above* or *top-down*. On the one hand, Huber and McCarthy (2017) write that environmental injustices “from below” include local impacts on land use, shifts in power and justice for rural communities, and changes to community structure. Borras and Franco (2013) also identify local or “from below” issues including land grabbing for energy projects, especially among poor, vulnerable, and marginalized peoples, leading to expelled populations and mass migration. Hall et al. (2015) add that a bottom-up perspective can capture the micro-politics of class contention, and exhibit how intersecting identities such as gender, generation, race, caste, or nationality can perpetuate inequality. On the other hand, looking at actions and reactions “from above” enables one to identify broader socio-environmental conflicts and struggles for justice (Verweijen and Dunlap, 2021). This includes ecological distribution conflicts resulting from unequal access to natural resources to unfair burdens and patterns of exploitation, as well as exclusionary policymaking, colonialism and unfair trading patterns and dependence (Sovacool et al., 2022). It can also include macro or structural patterns of dispossession, ecologically unequal exchange, and global patterns of extractivism (Hornborg and Martinez-Alier, 2016).

Fig. 2 situates our pluralistic conception of justice (from Section 2.1) within a milieu shaped by factors “from below” and “from above”. The resulting framework is inherently multi-scalar, and Givens et al. (2019) write that such a combination of spatial perspectives can provide “deeper understandings of, and more nuanced theoretical developments about, socioenvironmental injustices at various scales.” It recognizes and appreciates the relational view of space and even multiple “types” or “scales” and “levels” of space (Bellamy and Palmer, 2019), and facilitates what Davoudi and Brooks (2014: 2699) call a “radically different take on environmental justice studies” that “combines the positivist, top-down, and expert driven approaches with the interpretive,

bottom-up, and people-driven approaches.” The emphasis on top-down patterns of injustice can help overcome structural factors that constrain behavior and habituate people into restrictive and unjust conditions (Nussbaum, 2003), whereas the emphasis on bottom-up patterns enables one to capture more localized narratives of place and peoples’ perceptions of the meaning and values they attach to the environment or technology. Mattioli (2016) affirms the value of justice frames that are able to account for the agency of actors but also the constraints set by structuration theory. In addition, the figure and its orienting approach recognize that injustice and justice are transitive; issues can move readily up and down the diamond, and across scales “from above” and “from below.” Another implication is that injustice can be rerouted to other parts of the diamond, by other actions or the interventions of elites as power is redistributed (Sovacool and Brisbois, 2019). We will return to many of these themes in Section 5.

3. Research design: research interviews and justice claims-making

With our pluralistic conception of justice across a whole-systems lens established, our research design involved the use of qualitative research interviews where specific claims were made about energy and environmental justice.

3.1. Research interviews

To determine the whole systems injustices that may arise within negative emissions and solar geoengineering options, we relied on a large pool of semi-structured interviews, the asking of semi-structured questions to respondents, sometimes referred to as “guided introspection,” “intensive interviewing” or “responsive interviewing” (Hancké, 2009; O’Sullivan et al., 2010; Yin, 2003). This technique asks

participants a set of standard inquiries but then allows the conversation to build and deviate to explore new directions and areas. Such interviews are most appropriate when the goal of research is to understand the meaning that individuals assign to their actions, when the research objective is to comprehend complicated programs or events and how they intersect with one's perceptions, beliefs, and values. The interview process facilitates a more targeted discussion on and around a given topic, and can provide insightful knowledge related to complex events, especially since most case studies and projects are about human affairs, and best discussed by humans. Lastly, interviews were chosen because, unlike documents which can take months or even years to be published, they enabled the collection of recent data which (at the time of the interview) was not yet available in other formats.

We proceeded to interview prominent experts who had expertise about the ten different negative emissions options (grounded in the literature) as well as ten different solar engineering options (grounded in the literature) for a total of twenty options (already introduced in Section 2.2). Our recruitment and sampling of experts focused on a mix of advocates and critics of both negative emissions technologies and solar geoengineering options. We invited only those who have published high-quality peer-reviewed research papers on the topic, or published patents and intellectual property, within the past ten years (from 2011 to 2020). This does have a particular screening effect, especially likely to have reduced our sampling of voices from NGO or activist groups, and our sampling of voices from the Global South.

We conducted 125 individual interviews with experts closely associated with negative emissions and/or solar geoengineering research or commercialization over the course of May to August 2021. We explicitly asked, among other questions, "What equity and justice concerns arise with negative emissions or solar geoengineering options", "What particular vulnerable groups could be affected" as well as "What risks do these options entail for communities or the climate?" Informants were asked only about their self-declared areas of expertise, meaning many did not discuss all of the 20 techniques, and some focused only on one (e. g., biochar, or direct air capture, or BECCS). Table 3 shows an overview of the demographics of our sample, and Annex I lists all 125 experts who participated (although it does not match them with respondent numbers, to protect the anonymity of their statements). Although we did secure some interviews with members of civil society and nongovernmental organizations, governments, and commercial entities in the private sector, the sample is still strongly concentrated towards experts at universities and research institutes. That said, the sample does include scholars from more than 30 disciplines as well as a dozen participants from the Global South, here determined by either the country of origin of the participant and/or their current location.

Given that interviewees were speaking on their own behalf, and also given the sensitivity of the topic, the data from these interviews is presented here as anonymous with a generic respondent number (e.g., R10 for respondent 10, or R110 for respondent 110). First, anonymity was mutually agreed upon at the beginning of each interview to adhere to

Table 3
Summary of the demographics of experts who took part in our study.

Summary information	No.
No. of experts	125
No. of organizations represented	104
No. of countries represented	21
No. of academic disciplines represented	34
Cumulative years spent in the geoeengineering industry or research community	881
Average years spent in the geoeengineering industry or research community	7.8
No. of experts whose current position falls into the following areas:	
Civil society and nongovernmental organizations	12
Government and intergovernmental organizations	8
Private sector and industrial associations	12
Universities and research institutes	94
No. of experts from the Global South	12

Source: Authors.

institutional review board guidelines at authors' university. Second, anonymity protects respondents from retaliation over divulging potentially controversial information. Third, it can encourage candor, as people often speak their minds if they no longer have to worry about their statements coming back to haunt them. Fourth, individuals were not speaking on behalf of their institutions and were instead giving their personal opinion, making institutional affiliation less relevant (though still important for sampling purposes).

3.2. Claims-making in environmental and energy justice

Because our data is inherently qualitative, it captures the different meanings and values that our experts assigned to natural ecosystems and the environment and the real or potential perturbations which negative emissions and solar geoengineering technologies can have on those systems. It thus presents a relational view of justice insofar as each of our experts will have been influenced by culturally or spatially specific ideas about what justice is, what is worth protecting, and how particular technologies may interfere with those ideas. Our approach thus inherently respects the justice principle of recognition—treating all experts equal in dignity and respect to each other—and by emphasizing the crucial importance of togetherness rather than otherness (Coolsaet and Néron, 2020).

One helpful approach to navigating this complexity or relativity of justice perspectives is offered by Walker (2011), who utilizes the lens of "claims-making." Claims-making is a way of respecting the multi-dimensionality of justice issues and adequately accommodating the different justice statements made by researchers, activists, policy-makers or affected communities. Such claims share the common goal of typically linking evidence of a condition of inequality or unfairness with a normative position of what is considered just or unjust. A claims-making approach treats *all* perspectives as valid: this has the benefit of "heightening" the concerns of non-experts and also "lowering" the claims of experts so that they are seen as claims, rather "than assertions of absolute truth based on their 'better', 'more expert' grasp of what is at stake" (Walker, 2011, p. 184). Claims are not objective truths, but intersubjective attempts to capture a justice issue from one's personal lived experience. Expert statements are not to be privileged above other statements, nor are some statements to be interpreted as "more true" or "less true" than others.

Similar to Walker's work, Barnett (2018) argues against critical social science or geography work that assumes injustice becomes visible by comparing patterns of disadvantage with prominent academic theories or concepts. This only serves, as Barnett (2018: 320) writes, to reify some forms of exclusion and inequity: "... by continuing to think of injustice and justice as lying on either side of a division between practice and theory, spatial theorists inadvertently reproduce the form of authoritative third-person reasoning that is the most problematic feature of normative political philosophies of justice." Instead, Barnett argues in favor of starting justice analysis from claims of harm, suffering and injustice, rather than normative formulations. And a critical part of conducting such an analysis is respecting claims-making "as the dynamic through which relations of domination are challenged" (Barnett, 2018, p. 322). This avoids grounding justice claims with any predetermined notion of what justice is, and instead opens up justice discussion to contested notions of power and the voicing of disagreement and objections—justice norms come to be entangled in controversy and intersubjective interaction. As Barnett (2018: 323) concludes:

"giving conceptual priority to injustice involves, instead, thinking of the sense of injustice as arising from and being processed through intersubjectively mediated, shared inquiry. Injustice is, in short, a thoroughly public phenomenon."

We interpret this line of thinking within claims-making research to mean that energy justice statements are not only a matter of recognition, but also of empowerment, of treating respondents as individuals with

their own unique experiences as well as equally justifiable justice claims, even if they sometimes contradict each other or challenge established assumptions. Our approach reveals that justice, like democracy, remains a contested concept and a perpetually “unfinished business” (Davoudi and Brooks, 2014). Our goal is not to provide a universal set of consistent normative principles, but rather an illustration of important justice factors deemed relevant by our diverse respondents, even when there are tensions within those statements, and maybe even especially in such cases, insofar as these reflect distinct contexts and scales of experience and analysis. The resulting analysis is not meant to be conceived as an all-encompassing, definitive answer to what justice concerns are relevant, applicable to all situations and peoples; instead, it envisions justice work as a starting point to develop a fuller account of how multiple factors (cutting across social, spatial, technological, and other categories) can intersect to turn distributional unevenness into injustice and unfairness.

3.3. Limitations

Although we believe our large and diverse sample of expert interviews facilitates triangulation and has methodological merit, our research design does have some shortcomings. One is that while we respect a pluralistic notion of justice that captures “from below” and “from above” reflections, our sample is limited to only experts. These experts often spoke about impacts “from below” at the local and community level, but our study did not attempt to confirm these views through other forms of data collection such as household surveys, community interviews, or site visits. We nevertheless believed the topic well suited to expert interviews because general knowledge of geo-engineering among the lay public is quite low as well as malleable to the framing and presentation of information. This signals that attitudes are not yet stable or well-formed.

Even though we targeted those with expertise in one or several of these technologies, the knowledge of interviewees about geoengineering in general is necessarily limited, and the methodology may have encouraged them to comment outside of their experience or knowledge, and any such misconceptions may come to have political impact regardless of factual inaccuracy. That said, we also wanted to avoid imposing our own view on the expertise and experience of our respondents, and to avoid artificially forcing them to only comment on those areas where we deemed them competent, instead relying on where they themselves determined their own competency.

Additionally, a drawback to providing anonymity is that there is no guarantee this study can be replicated, given the difficulty for future authors to correlate the identity of respondents with particular interviewee statements.

Moreover, the paper is critical in nature, exploring only injustices and not positive justices or co-benefits (which we plan to explore in future research). In simple terms: we explore the prospective injustices from deploying negative emissions and solar geoengineering options, but not the injustices from *not* deploying them. Finally, line with the points about “claims making” above, we took an ethnographic approach that did not correct or problematize responses, so we present the data unfiltered (adhering to the justice principle of recognition), even if our respondents may have had misperceptions on specific points.

4. Results: competing justice claims across a whole-systems perspective

Our results from the interviews provide strong evidence for the applicability of our whole systems framework presented in Section 2.3, with a multiplicity of claims being advanced by our interview respondents across multiple spatial dimensions “from below” and “from above.”

4.1. Resource extraction, chemicals and fertilizers

Resource-extraction injustices from our data revolve around expert claims and perceptions of the growth of mining and material extraction needed to build future negative emissions and solar geoengineering options, the expansion of chemical use (and resulting pollution), and the dependence on large-scale fertilizer production.

4.1.1. Growth of mining and material extraction

The sustained expansion of many negative emissions options, especially enhanced weathering, direct air capture, and ocean alkalization, would likely necessitate the widespread development of new mining operations, while deployment of some sunshade options would also rely on mining operations in outer space, i.e., the development of a “Moon economy”.

For instance, our experts stated that enhanced weathering would require both large supplies of rocks for capturing and sequestering carbon that might then need to be stored in underground mines or aquifers. As R002 explained:

Enhanced weathering would involve shifting such large amounts of mass that it would rival mining operations and general land moving. So, enhanced weathering could become highly connected to a whole bunch of extractive industry systems with impacts on a planetary scale.

R026 picked up on this theme as well noting that:

With enhanced weathering, you have a very strong coupling to mining. Its dependence on geotechnical systems would lead to constraints on mining material to be used for enhanced weathering processes, but opening loads of new mines all over the place would certainly give rise to local siting issues and environmental pressures.

R036 also agreed and supposed that:

For both enhanced weathering and ocean alkalinity enhancement, you would need to do massive new mining operations.

Moving to direct air capture, R087 spoke about how direct air capture facilities would need “a substantial fraction of industrial emissions for mining” given that “you’re talking order of magnitude scale-up of limestone or of these kind of mining operations, which my understanding is very similar to mountaintop coal mining in terms of the scale of mass handling in that they’re removing these whole mountaintops, you know, to get at this coal.” R099 also confirmed that direct air capture and ocean fertilization options would require “huge mining operations” with “a huge number of risks.”

Our experts also perceived that space mirrors and sunshades would similarly require the use of “hundreds to millions of tons of materials in space” which could even necessitate “strip mining asteroids or colonizing Mars” (R002). R031 explained that:

One plan for a functioning space mirror would be to place it at the Lagrange point between Earth and the Sun (SEL1). But this thing would be huge, it would be 1 million square km, three times the size of Germany ... You would need to build the whole system from resources on the moon, or on an asteroid ... Call it in-space manufacturing, the idea is that in the end you need giga-factories in space. We will need a whole moon economy to do in-source resource utilization, a mining process to get moon regolith and metal, aluminium, titanium, helium-3, whatever is there.

This approach would see the establishment of entirely new mining operations and giga-factories in outer space, to fuel the material requirements of building effective space mirrors.

4.1.2. Expansion of chemical use and pollution

Global growth in the use of negative emissions options, or the deployment of stratospheric aerosol injection, would entail the creation of multiple potential exposure pathways for chemicals and chemical pollution. Our respondents claimed this could include solvents used for

direct air capture, pesticides for energy crops or to protect forests, iron used for ocean iron fertilization, and various solvents, amines, and treatments for carbon capture utilization and storage as well as leachates from enhanced weathering and biochar, and chemicals used for aerosol injection or cloud brightening.

For instance, focusing on negative emissions, R002 worried about “what’s leaking into the soil from enhanced weathering, what chemicals are coming out of the rocks we’ve ground up.” R010 added that:

Direct air capture could create multiple wicked problems ... it uses a lot of different types of chemicals, so if you don’t process the chemicals well, then you create an environmental pollution problem. If you create a direct air capture plant in the wrong manner, they can spit chemicals into the environment.

R042 concurred and added that “direct air capture will involve the deployment of large volumes of chemicals to the point where chemical demand is high.” R036 also contended that with ocean fertilization or alkalization:

I am very skeptical of dumping anything that seems like chemicals into the ocean, that’s going to constrain ocean-based options. There are even environmental governance issues associated with ocean alkalization because you’re adding something in the ocean that’s not going to stay within your territorial waters, so there are cross-boundary effects.

R125 spoke about how carbon-reduction efforts depend on “processes like the caustic soda chloralkaline industry” but that “major innovation gaps exist to using these chemicals safely or within system boundaries.” In terms of biochar and enhanced weathering, R026 clarified that:

There are always risks of chemical contamination [from biochar and enhanced weathering] ... there is great concern about what contaminants will be in the rocks when you grind them up. If you’re spreading them on agricultural land, they’re either, maybe, potentially contaminating the food, certainly you might get run-off into the local rivers, what are the implications of that?

These statements all depict multiple exposure points for chemical pollution involving releases across urban spaces, forests, oceans, and watersheds.

Solar-geoengineering connections to chemicals involved both stratospheric aerosol injection, cirrus cloud thinning, and marine cloud brightening. R011 commented that:

Techniques like aerosol injection or cloud thinning have limits because they need airborne spraying of chemicals or specially designed particles. Once you get rid of all the cirrus or sprinkle too many aerosols, then you’re stuck. Even if you could do it, would you want to be in an airplane flying through cirrus where, ahead of you, an airplane was spraying these chemicals to get rid of them?

R076 believed that such techniques could chemically pollute oceans and waters as well, given that “they all require putting chemicals into clouds or the air that will obviously and eventually have negative effects on plankton growth or life below water.”

4.1.3. Dependence on large-scale fertilizer production

A final source of environmental injustice according to our data involves claims and speculation about the fertilizers needed for bioenergy with carbon capture and storage as well as biochar, ocean iron fertilization, and enhanced weathering. R036 articulated that “If you grow lots of bioenergy crops, you will need extremely large amounts of water and industrial fertilizer.” Buck (2016) calculated that bioenergy with carbon capture and storage could come to consume up to 75% of global annual nitrogen fertilizer production if scaled up globally. R061 added that the sustainability challenges with fertilizers and bioenergy with carbon capture and storage are “huge” given that “its deployment requires phosphate fertilizer which is very damaging and can even result in cadmium pollution.” R014 spoke about how “ocean fertilization requires that you

grow something quickly so then it dies and falls to the bottom of the ocean and stays there ... I find it scary because of the scale you would need to deploy the chemicals to make it happen.” R015 added that you could even need fertilizer for enhanced weathering, because:

You use enhanced weathering to optimize the soil, and also because in the rocks like basalt you have important nutrients like phosphorous or potassium – this is needed. If you remove plant material from the field, you need to replace the nutrient. Normally we use industrial fertilizer, and industrial fertilizer is a fast-dissolving, inexpensive thing.

Some respondents (R014, R055, R112) added that afforestation and reforestation could depend on fertilizers or monocultures intended to accelerate carbon sinks, while others mentioned similar risks for albedo management techniques using grasslands or ecosystems (R066, R071, R101). Dependence on fertilizers is not only problematic due to costs and environmental risks; it also serves as a major limiting factor to expansion given that about 30% of global soils are already overly acidic due to the overuse of ammonia-based nitrogen fertilizers, making them potentially unsuitable for current use by plants or crops (Kantola et al., 2017).

4.2. Manufacturing, labor and ownership

Manufacturing, labor, and ownership injustices involved harmful employment patterns, negative effects on unemployment and poverty, and a concentration of ownership and patents in the Global North.

4.2.1. Harmful employment patterns

Given the coupling of some negative emissions and solar geoengineering options to resource extraction, mining, and chemical flows mentioned in Section 4.1, our experts made claims about how the jobs generated by these options would involve occupational hazards or be very similar to the employment problems with fossil fuels. R118 explained it this way:

The kind of employment offered by bioenergy crops, enhanced weathering, or direct air capture would be very similar to the kind of employment for fossil fuels or mineral economies, which is not necessarily good for workers or communities. Indeed, in many existing mineral economies there is a huge amount of economic problems, social problems, and a lot of them are related to employment difficulties. Communities have, more or less, been forced to sell off the mineral rights or sign unfair concessions for land use. In my view, that does not lead to very sustainable, very good quality, long-term jobs and employment, or, for that matter, equality and all of those kinds of sustainable development goals or objectives that we would like to see.

R006 also mentioned couplings to fossil fuel employment patterns, noting that direct air capture could “provide more positive job opportunities for fossil fuel workers ... to continue to have employment,” especially in areas already known for things like shale gas production or areas rich in petroleum, potassium and natural gas such as the Permian Basin in Texas. This could embed and entrench fossil fuel use, and all of its consequent impacts on the environment and climate. R059 elaborated on this theme as well, commenting that carbon dioxide removal and direct air capture could both “reduce the stranding of fossil-fuel intensive assets” and offer a greater opportunity for “millions of workers in coal mines and plants.” R064 believed that these employment dynamics of negative emissions mean that rather than transforming sociotechnical systems, they merely make incremental changes:

Basically, with carbon dioxide removal, you’re moving carbon from the air, in this case, into the ocean, rather than from geological reservoirs into the air, but it’s worth noting, or even emphasizing the fact, that a lot of things stay the same in that sociotechnical system. Direct air capture becomes coupled to oil and gas, or bioenergy with carbon capture and

storage becomes coupled to oil, gas, and coal. They prolong jobs and investment in fossil fuels.

Indeed, we will return more to other aspects of extending fossil fuels (beyond jobs) in Section 4.3.3.

4.2.2. Unemployment and poverty among the rural poor

Although adoption patterns for negative emissions could generate new jobs in fossil fuel sectors or hazardous jobs in mineral economies, it (along with solar geoengineering) also threatens to create new patterns of unemployment or the exacerbation of rural poverty. R120 argued that natural solutions to negative emissions portend the greatest risk in this regard, with the real potential to create net unemployment:

Nature-based carbon dioxide removal techniques or even albedo management via grasslands are often believed to create economies of scale as you eliminate inefficiencies, so that the costs would actually go down and therefore the prices would go down. However, the biggest tradeoff with this process is actually with rural poverty and rural employment. So, this is a major problem with nature-based solutions. You deploy large machines that otherwise do the work of people. Sure, there are some marginal jobs: you can have park rangers, you could have people who are guarding the fence in bioenergy and carbon capture and storage supply chains or whatever. So, there is some opportunity, but the scale of people released from their jobs is just so much, much higher than those who could be rehired by the nature-based solution sector. So, in the long run, I really think we have a rural-poverty problem with these options, which is probably intensified by subsidizing nature-based solutions.

R064 expressed concerns that afforestation or bioenergy options will “drive up global food prices, hurting the rural poor”, and R042 cautioned that “afforestation and bioenergy projects could displace many workers from rural areas and force migration to urban ones.”

4.2.3. Concentration of ownership and intellectual property

A final justice subtheme relates to ownership and intellectual property. R086 argued that a transition to negative emissions technologies would merely benefit the same incumbent actors (and communities) that have owned and benefitted from fossil fuels. As they remarked:

Because of this colocation thing, where's the best place to store carbon dioxide? Where the oil or gas was stored originally. Those global companies or communities that are producing oil and gas, with carbon dioxide removal or carbon capture and storage, now those places enjoy the economic benefits of it again, so that's unjust.

R081 was even more critical, suggesting that the only sectors to really benefit from negative emissions were incumbents, and also that such options could come to represent the “blood diamonds” of our time:

All the dirtiest fossil fuels, tar sands, oil shale, lignite, and biomass will benefit. It's the same evil, with a different kind of green hat on it. This sort of action supports all the technologies we don't want to have, as well as systems that are hyper-centralized, that possess enormous geological risks, that have produced the resource curse or monopoly profits. Negative emissions are like the blood diamonds of our era, they reinforce dictators from Venezuela to Saudi Arabia to Russia ... these evil technologies are the natural partners and bad bed fellows for negative emissions, sort of like how fleas and lice are drawn to rot.

R006 even spoke about how “I can envision a natural gas company or an oil company saying they are doing direct air capture, and mining natural gas, but in truth their supply chain is leaky and it's just a cover for venting methane.”

Although the ownership of physical assets is one issue, ownership and concentration of intellectual property and patents could be even more significant. R034 spoke about how emerging regimes of property rights were both inhibiting innovation trends and also concentrating intellectual property among a few firms; as they went on to note:

Certainly, current intellectual property rights are benefitting only a very small number of firms ... As it gets more real, as there are more patents out there in the world, we will start running into roadblocks in places. There are some real intellectual-property concerns over having longer control over an invention that could then be spun out into the real world. Alternatively, people can dress something up as a non-geoengineering concern, lock it in, and then, suddenly, it becomes necessary for geoengineering. These could slow innovation and learning.

R062 spoke about lack of transparency in patenting processes, and how this makes effective governance (and determining ownership) exceedingly difficult.

4.3. Transportation, construction and land grabbing

Justice issues in this theme involve environmentally destructive transport networks and pipelines, land grabbing and dispossession, along with building more fossil-fuel facilities (and infrastructure) to satisfy the energy or material requirements of negative emissions or solar geoengineering options.

4.3.1. Environmentally destructive transport networks and pipelines

One core infrastructural challenge identified by our evidence relates to the extensive transport networks that would need to be created to deliver energy crops or residues (for bioenergy with carbon capture and storage) or forest outputs (for afforestation and reforestation), pipelines and reservoirs for stored carbon dioxide (for multiple options), and large scale fleets of ships (for ocean fertilization or marine albedo modification) or aircraft (for aerosol injection), or even rocket launches (for space mirrors).

In terms of negative emissions options, R081 asserted that bioenergy crops and even afforestation and soil management techniques, done at a large enough scale, would amount to “terraforming” the planet and would be connected to significant logistics and transport network challenges:

For negative emissions to reach the scale required for climate stabilization, we will need very super continental-scale managed plantations that are harvested on a short rotation cycle, and this would need catchment areas of thousands of square kilometers. Transport alone would be daunting, even if you build monorails in the forests to transport trees to the unit, or micro carbon dioxide removal or storage units to bring to the forest, or invent carbon capture and storage units on wheels or drones, it becomes almost impossible. Think only about the pilot projects already, those at 1 MW, not thinking about scaling up to GW. Even those pilot projects require trains, boats, lots of trucks for just an 80-MW biomass boiler, something like that, bringing it from forests to the Danube and to Vienna, infrastructure doesn't exist or the costs are too prohibitive and nobody wants to pay for it.

R032 added that all of the options requiring carbon storage would necessitate “massive pipelines”, many of them interstate:

So if you want to store captured CO2 under the North Sea, whether that is through enhanced oil recovery or simply at the seafloor, then Switzerland and Czechia and Hungary need to move their waste product in massive pipes through Germany. Think of the energy needs for pumping. Think of the needed infrastructure!

R034 elaborated on this theme as well, commenting that the risk of infrastructural trade-offs is also high within deployment options:

Wherever you put a BECCS energy-producing plant, you need to sequester the carbon that's captured – Is it in the same location? Does it require a pipeline to go tens or hundreds of miles down the road? All of those things, typically, will require some sort of land approval.

Then there are also trade-offs for infrastructure use. So if you think about all the gas pipelines that we are using currently, are we transporting synthetic energy carriers, like bio-methane or hydrogen

in those pipelines, or are we going to use it for CO₂ transport? Where the CO₂ transport maybe just precedes us looking at whether the pipeline system can be optimized for CO₂ transport because point sources and sinks in Germany might need storage in the north, so we would have to erect an entire efficient network for those new pipelines.

R041 spoke about how ocean fertilization efforts also need complex transport networks, as you would need “fleets of thousands of ships to create and maintain algal blooms,” and enhanced weathering would need to find spaces on land to “grind the material, mill it into small particles, which is also extremely energy consuming, and transport it either by pipeline or by ship into the ocean.”

Even solar geoengineering options could involve significant justice issues concerning transport and logistics. R088 cautioned that aerosol injection would require “whole new fleets of high-altitude aircraft, something an order of magnitude never done before, with a good chance it would fail before you even build commercially the aircraft, it would require three times weight of the aircraft in terms of the paperwork and approval needed alone.” Transport options become even more daunting for high-altitude sunshades or space mirrors. R70 stated that these would require more launched spacecraft in a year than have been launched in the history of spaceflight:

If taken seriously, these options would require a complete overhaul of the space industry, a scale up to a level we have never seen before, nothing compared to Space X or even the Apollo Mission. A completely different ballgame, an increase in launches and launch schedules for rockets. Our current launch schedule is, give or take, 100 launches now per year, for a total of about 20,000 launches for the history of space flight. Space mirrors would require launches orders of magnitude greater than what we've done before, we would need between 30,000 and 2.7 million spacecraft! That's launching more in a year than we've done in human history.

These would entail significant pollution, and carbon emissions, with rocket launches and space infrastructure, with R031 believing that “you could need millions of rocket-starts to bring up the pure mass of needed materials and components, and each of those would consume rocket fuel or hydrogen.” R081 agreed, and stated that:

I don't see the feasibility of high-altitude sunshades or space mirrors. When you think about the payload you have to shoot into outer space, you realize it is insane. A typical rocket is a few hundred tons, but its payload is only a few tons. Even if you take all of the rockets and missiles, every single one shot out to space, and calculate the cumulative tons in history, it won't come close to the weight of one of these sunshades.

Such logistical challenges could both limit the ability to deploy these options and contribute directly to environmental destruction.

4.3.2. Land grabbing and dispossession

As significant as they may seem, issues of transport and logistics may pale in comparison to the risk of negative emissions options—especially land-based ones such as forestry, soil management, biochar, enhanced weathering, albedo modification via grasslands, and bioenergy with carbon capture and storage—displacing communities from their land or perpetuating patterns of land grabbing. For example, R064 argued that:

The big question for bioenergy and carbon storage options is the extent that they require arable land, same for afforestation and reforestation. Can you take over the land, or share the land? Is it crowding out, or co-locating? Indigenous people are already losing control over land or getting pushed off their land. Outside actors buying up large land to get to net-zero in their own countries will worsen this trend, I believe the impact of land grabs on local people and sovereignty can be severe.

R042 agreed and pointed out that such actions could negatively impact more than one billion people:

I see the highest risk of injustice in bioenergy, these occur via the dimension of land use. Land use is the main driver of anthropogenic mass extinction which we are currently witnessing. Any option that demands further land is a problem and high-risk strategy, think about biodiversity loss, ecosystem-service loss. This is why I see some negative emissions options as highly problematic technologies. Bioenergy with carbon capture and storage has already been historically connected to land enclosures and land grabbing, with extremely negative impacts on the poor. It's not only about biodiversity, either, but the livelihoods of people especially in traditional societies, of smallholder farmers that are still there at the scale of at least one billion people who make their livelihood from land.

R036 stressed that land-use competition could even lock in these patterns into the foreseeable future:

If you're afforesting large regions, then you also have land-use competition issues. Once you grow a forest for carbon storage, you probably don't want to cut the whole thing down and build a city there or anything like that, or you turn it back into farmland. You want that carbon to stay locked up, so there are certainly trade-offs.

R003 echoed this point when they asked “where are we going to get

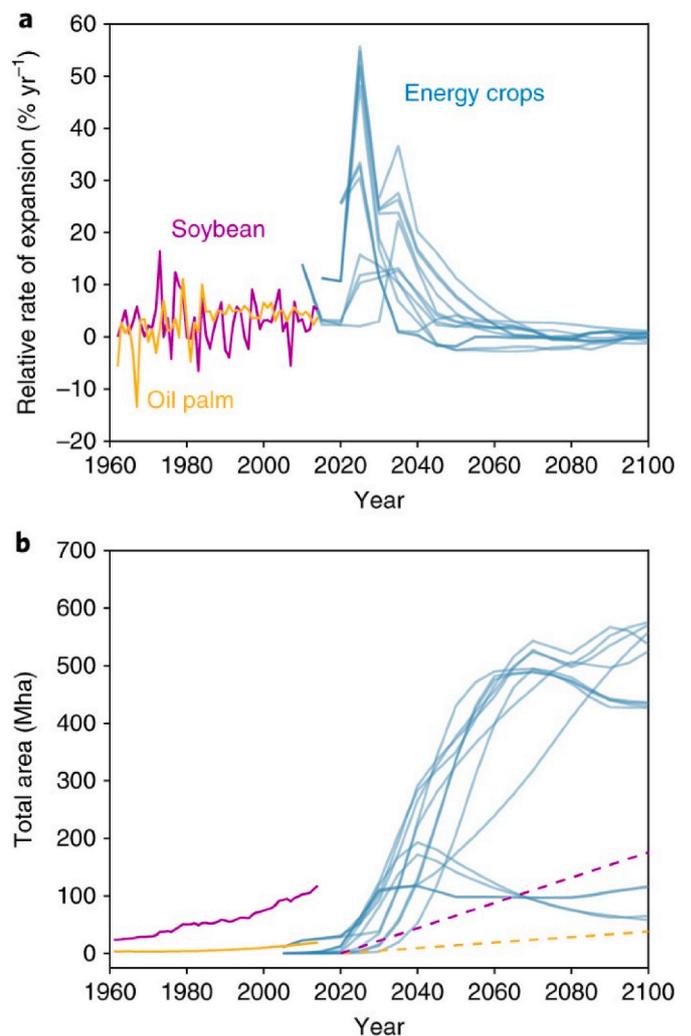


Fig. 3. Projected rates of expansion and land-use impacts associated with the extension of energy crops for bioenergy-based, negative-emissions pathways. Source: Turner et al. (2018). Note: Panel A depicts the relative rate of expansion observed in soybean and oil palm acreage data and relative rate of energy crop expansion implied in the <2 °C scenarios. Panel B depicts the total area of energy crops in the <2 °C scenarios relative to the total acreage of soybean and oil palm.

another India-size continent to grow the forest necessary, the fertilizers, and the water needed to meet our climate targets with bioenergy carbon capture and storage?"

Although these statements may sound hyperbolic, they are supported by studies referred to by our respondents. Two interviewees pointed us to Turner et al. (2018), who examined the scenarios and climate pathways likely required to limit global warming to 2 °C by 2100. Our experts noted that the Turner et al. study means the rate of energy cropland expansion supporting bioenergy with carbon capture and storage proceeds at a median rate of 8.8 Mha yr⁻¹ and 8.4% yr⁻¹ (see Fig. 3). This rate exceeds, by more than three times, the observed expansion of soybean cultivation, the most rapidly expanding crop in commodity markets, and it exceeds by 1.8 times the historical expansion of oil palm acreage over the past 50 years. They conclude that such an expansion of energy crops would dramatically change land-use patterns, even in some cases reversing rates of global deforestation.

Respondents also spoke about how deployment patterns for negative emissions options could dispossess particularly vulnerable groups such as indigenous peoples or minorities. R081 worried that climate action via these technologies could "steamroll" the rights of vulnerable groups:

I mean, who wants to live close to a CO2 pipeline? Who wants to live on top of a CO2 reservoir? Marginalized groups will suffer because they are weak, they're vulnerable and so they cannot fight against this. Remember, when we talk about very large-scale technologies, these require very large mobilization of capital and of political power. Together this is basically a steamroller over the rights of indigenous people or vulnerable groups.

R007 added that deployment on tribal lands will also both face resistance and likely harm local groups:

There won't be any trust for deployment of these options in tribal lands, people will doubt that it will help them ... These options could even be seen as a colonial enterprise to displace local groups from their assets.

R102 espoused this point as well, noting that:

If there is some sort of huge, great industrial development for negative emissions or solar geoengineering, then it is probably going to be closer to less well-off communities than say in downtown Manhattan, right? Such industrial facilities tend to be sited at the margins of society, among migrant communities, persons of color, Native American territories, that kind of thing.

These statements all support the contention that low-carbon systems have immense potential to shift and redistribute pollution flows to vulnerable groups or regions.

4.3.3. Construction of additional fossil fuel infrastructure

A final construction-related sub-theme centers on the need to build more fossil fuel infrastructure to help support the expansion of either negative emissions or solar geoengineering options. R079 explained that:

If you were to actually roll out carbon capture and sequestration you'd be able to maintain the current distribution of fossil plants. The communities that have been built around coal and gas plants would be able to continue to prosper, but it would also imply continued or even additional use of fossil fuels.

R047 picked up this theme as well, noting that strong couplings with storage sites and natural gas would likely see a net expansion of fossil fuels to undergird a shift to negative emissions:

From an engineering view, negative emissions or direct air capture only works with achieving scale and volume. I believe it will lead to more natural gas power plants running 24/7 to help make hydrogen or feed into our carbon dioxide removal machines. In my mind, the backbone of this future system is not renewables, it would be Russian gas fields or Middle

Eastern liquified natural gas, or some cheap source of gas in the Algerian desert.

Both these statements imply negative emissions are coupled positively with fossil fuels, not negatively, at least in the near to mid-term. Indeed, a whole series of linkage mechanisms are laid out in McLaren (2020).

4.4. Policymaking and planning

Procedural-justice issues of governance, policymaking, and planning were a frequent point of discussion among our experts, emphasizing aspects such as exclusionary and elitist decision-making, challenges over accountability, and the shifting of policy risks to future generations.

4.4.1. Exclusionary and elitist policymaking and planning

Our interviews broadly suggested that patterns of current policy-making and research tend to benefit actors in the Global North, and not the Global South; this can even be perceived by some as a new wave of "climate colonialism" (R064) related to negative emissions or the "domination of the Global South, where a small group of elites decide what's best for everyone" (R084) for geoengineering. R026 insisted that "some of these technologies may have to be deployed in Global South countries who do not have responsibility for the emissions in the first place, where they are bearing the risks of our climate protection, but without any input into actual deployment decisions." These statements all reveal issues of representativeness and inclusion in contemporary decision-making.

4.4.2. Accountability, liability, and governance challenges

A second procedural concern relates to accountability, liability, and responsibility, issues that enable attribution of responsibility for the ownership of stored carbon or determine who is accountable for accidents (a theme we explore in greater depth in Section 4.6.3), as well as issues of accounting and attribution, notably, whether it is possible to correlate deployment of one option (e.g., afforestation project in Namibia) to a particular reduced risk of a climate impact (e.g., a flood in India).

For example, R043 believed that the climate community "must get better at monitoring, verifying, accounting ... we have an important gap in monitoring and accountability, and it is very difficult to close that gap." R062 added that in order for carbon dioxide removal to work, we need a system of "carbon accounting at a scale that has never been managed before;" R064 spoke about "huge challenges related to monitoring, verification, and reporting;" R071 mentioned the "tremendous need for better transparency and accountability." Respondents commented that these accountability issues are only compounded by lack of transparency over solar geoengineering. R020 asserted that "no country has a solar geoengineering strategy that is transparent and public, it's all discussed behind closed doors." R027 claimed that, for negative emissions technologies, "current deployment for carbon dioxide removal options are not always trackable, traceable, controllable or reversible."

4.4.3. Shifting policy risks to future generations

A final policy and planning concern arising from our data is the shifting of policy risks to the future. R071 spoke about how deployment of these options now could only lead to more risky behavior that compromises future generations, affirming previous work on moral hazard and mitigation deterrence. R071 asserted that "people drive more dangerously with seat belts, or eat more cheese when they have cholesterol medicine; there is a risk these climate options can lead to more dangerous, unsustainable behavior that hurts future generations." R026 was even more explicit in this critique, comparing negative emissions and solar geoengineering options to a "unicorn:"

Consider the policy risks to future generations. Let's suppose the mitigation-deterrence argument is right, that would mean these options are shortchanging future generations. This generation of policymakers are

not getting on with what they should be solving: overconsumption, overpopulation, high use of energy, mega-consumption in our cities and urban areas. Instead, we're depending on a unicorn, and that leaves future generations with the problem of cleaning up the mess, even assuming they can clean up the mess.

R042 also expressed worry that deployment of carbon dioxide removal would merely amount to “loss of freedom for future generations”, and R096 spoke about how solar geoengineering will commit “who knows how many future generations” to “the ultimate lock in, one cannot stop these technologies from happening once you start them, it could take future generations centuries to shift away from them.” These statements all pinpoint the ability of deployment to merely transfer climate policy risks to future generations, rather than eliminate them now.

4.5. Deployment, operation and use

Energy-justice issues arising from deployment, operation and use include intensive energy consumption (for most, if not all options), a suite of environmental and planetary risks, and the termination effect.

4.5.1. Intensive and aggravated energy use

The most direct operational justice concern relates to the energy needed to actually run, deploy, or use various negative emissions and geoengineering options, especially direct air capture, enhanced weathering, and carbon capture and storage.

For example, R020 noted that “carbon dioxide removal techniques are major energy consumers” and that their widespread utilization would necessitate “massive amounts of nuclear or renewable energy”, also commenting that the energy needs for enhanced weathering and crushing rocks would be “quite significant.” R023 agreed and underscored that “greenhouse gas removal needs large energy inputs to work, these could be coupled with renewables or hydrogen, but whatever happens it will require an obscene amount of energy to take carbon out of the air.” R071 called these options “energy hogs”, and R096 did note that many are “extremely energy intensive”.

Indeed, our respondents did refer to some of the literature offering different scenarios for future energy use. Fig. 4 charts the ranges offered by a synthetic review of literature and finds that enhanced weathering and bioenergy with carbon capture and storage could grow to constitute 12% of total global energy consumption to achieve significant carbon

reductions; ocean liming could grow to almost 40% of global energy consumption, and direct air capture a staggering 380% of global energy consumption. Looking not at extremes, but more reasonable estimates for deployment, Hanna and colleagues (2021) calculated that the total energy consumed to attain that removal for various direct air capture configurations would most likely reach 9–14% of global electricity use in 2075 (median; 5–30%, 15th/85th percentiles) and 53–83% of global gas use in 2100 (median; 0–470%, 15th/85th percentiles).

4.5.2. Degraded environmental and planetary health

The operation and use of negative emissions and solar geoengineering options not only involve direct (and indirect) energy use; they also present sophisticated and at times sobering environmental and planetary risks. R026 captured a sample of these risks when they stated that:

There are real and compelling tensions with negative emissions and planting loads of trees or energy crops and therefore degrading peat lands, other forests, or habitats. With biochar and enhanced weathering, if you take the wrong rocks or wrong materials, what pollution do they have in them, spread them on agricultural land, can contaminate food, pollute local rivers. They are also linked to ocean pollution. Done inappropriately, I could see these options as even more controversial than genetically modified crops.

R026 noted that the environmental risks with solar radiation management are often seen as even more significant, and these could include changes in rainfall, changes in regional temperature, and even pollution from things like sulfur particles or manufactured aerosols released into the environment. As R026 explained:

Solar geoengineering is potentially very controversial, given the environmental risks involved. Serious proposals will meet serious objections from international nongovernmental organizations. It will always face extreme opposition ... to most people, it just looks crazy, tampering with the planet, not fixing the crux of the problem. It could even become the next big thing that environmentalists come to fight.

R077 cautioned that:

You can imagine this multi-axial space where it's just all trade-offs. It's all horrible trade-offs between risks, rather than the elimination of risk.

Sovacool (2021a) recently reviewed the potential environmental and

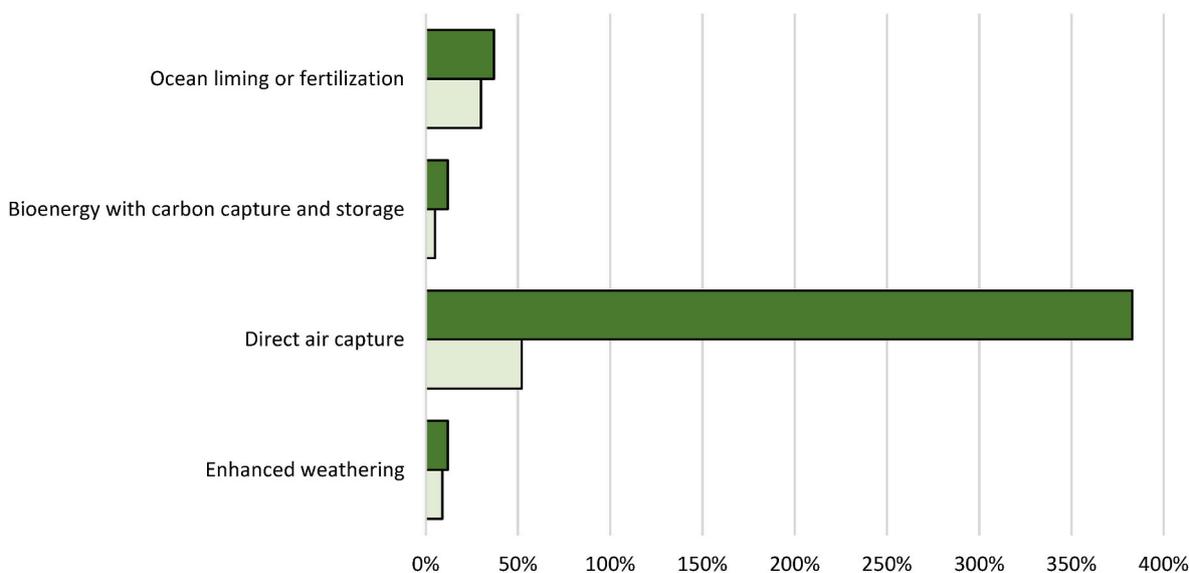


Fig. 4. Projected proportion of total final energy consumption (as a % of global consumption, minimum and maximum ranges) needed for four negative emissions technologies to achieve 24 Gigatons of annual carbon dioxide reduction.

Source: Data plotted from Table 6 in Sovacool (2021a) but derived from McLaren (2012).

planetary risks from the deployment of 12 negative emissions or solar geoengineering options, and evidenced a large corpus of literature concerned about (i) accelerated rates of deforestation as well as land use, biodiversity loss and species extinction, and water consumption; (ii) the inability to address ocean acidification (especially among solar geoengineering options); (iii) major perturbations to existing land uses around the world as well as potential soil degradation; and (iv) the disruption or pollution of marine habitats, changes in precipitation patterns, or contributions to ozone depletion and acid rain.

4.5.3. Impermanence, termination effects and shocks

The “termination effect” is a final injustice issue within our material, a term that relates to the sudden reversal, or impermanence, of the emissions reductions achieved or the stabilization of global temperatures. R011 framed it in these words:

The termination effect is a massive justice issue. If we did any sort of direct air capture, or solar geoengineering for a while, and then stopped, we would be at risk to much more rapid climate change than if you would have done nothing, or let nature on its course of gradual changes. The impacts of termination could be devastating to ecosystems.

R034 agreed, stating that “termination-effect issues could be severe, and involve sudden shutdowns and the climate snapping back to wherever it was in a radically fast process.” R003 contended that:

Stratospheric aerosol injection has got some huge downsides. It needs to go on forever because, whenever you stop it you end up with a really savage increase in temperature which can undo all the good work which you've done cooling beforehand. That's really bad ... Marine cloud brightening ends after a week or two. If you want to keep it going, you will need to be perpetually modifying clouds for centuries.

R011 even remarked that due to the termination effect, there was a risk “you get rapid climate change much faster than if you hadn't done anything.”

Permanence issues and termination threats also exist for ocean options or afforestation. R036 said that:

There's artificial ocean upwelling, similar to fertilization. It has some nasty side effects, like once you start it at a large scale, you couldn't stop it without having to get warmer than if you'd never done it in the first place ... Or if, in the future, climate change gets worse and it kills off your seagrass meadow, all the carbon you've captured could be released, so that's a big risk.

R008 added that:

With afforestation you have standing biomass which can burn up, that's potentially a risk. Its non-permanence is a risk for public acceptance. When people get the feeling what you're doing is not really sustainable in that sense. You're basically just greenwashing and not removing carbon.

R064 remarked that modifications made to forests or energy crops could even make them more vulnerable to impermanence:

The physical risk that spans all of carbon dioxide removal options is reversibility, the unexpected loss of sequestered carbon. Soil carbon and forests are easily reversible. In fact, for forests, it could become hard to prevent reversal, depending on how climate change proceeds and on how it's done. A monoculture tree farm is going to be much more vulnerable to loss of carbon from beetle infestation or some kind of disease than a real forest.

R012 agreed and said that:

Some methods of storage turn out to be more leaky or impermanent. Doing lots of the nature-based stuff badly means you can essentially lose stored carbon quite quickly if you get that wrong, so pests, disease, wildfires, human intervention, changes of policy can all reverse our carbon gains.

R023 concurred by adding that:

If people actually plant a massive forest, it could get burnt down by climate change and re-release all the gases. And even if it doesn't, the timescale of the storage is much, much shorter than it is compared to the more geological-based approaches. That is not to say that we shouldn't be doing them. It is just to say we should be very cautious about promoting these things over and above anything else.

Our respondents did refer us to the [National Academies of Sciences, Engineering, and Medicine \(2019\)](#) report, which validated some of these statements in their review, noting that even land-based negative emissions options like forestry, soil management or ecosystem restoration were always at risk of being terminated, or reversed, by wildfires, illegal logging or deforestation, or even pests. Respondents also referenced the [Asayama and Hulme \(2019\)](#) study, which cautions against the use of solar radiation management techniques, as once begun, they must operate on a robust to heroic scale in perpetuity if society were to fail to otherwise cut emissions.

4.6. Disposal and waste

Our final class of justice concerns involve disposal and waste, including accidents and leakage, earthquakes, and the generation of hazardous waste streams.

4.6.1. Accidents and leakage

Although our existing industrial and infrastructural systems have some experience storing carbon dioxide, our respondents noted a slew of risks regarding accidents, venting, and leakage, even in some instances at amounts that can harm or kill local residents. R003 expanded on this topic as follows:

The entire system of direct air capture or storage of carbon presents geological risks. You're essentially trying to mine air, a very low-grade, low-value product: not gold, but CO2. And once you've got it, you've got to compress it, you've got to pump it maybe hundreds or thousands of kilometers, and you've got to compress it down into rock strata which doesn't want to accept anything more, so you've got to use huge amounts of energy. Once it's down there, you're never quite sure whether a fault is going to happen and it's going to vent again and you're going to kill lots of people around about where it's venting because CO2, you know, if you remember those lakes in Africa which vented their CO2 and they wiped out five villages worth of livestock and people.

R011 added that:

Right now, almost all of our carbon-capture efforts are used for enhanced oil recovery, pushing more oil up: not such a good idea in terms of climate change. For a couple of hundred dollars a ton you can make things out of carbon or bury it underground; there are enough places to do so. But leakage is a real issue. What if it leaks? Grandma Smith's farm lake turns into Perrier. Then who is responsible, especially if it slowly happens over decades, who is responsible for it? I worry about that.

R026 said that the risks of leakage could not only undo climatic gains but also require more energy or result in a rebound effect in order to pump escaped gases back into the earth:

What happens if this stuff leaks from a major storage site in the North Sea? Will that affect any people in the area, or will it undermine the whole process because the stuff's got out and, therefore, you've spent loads of money just to pump it back into the atmosphere indirectly or worse, recapture it again?

R019 mentioned that biochar also had some handling and disposal risks, that it needs to be “packaged the right way” or else it can catch fire. Soil amendments employing both biochar and rock dust for enhanced weathering also have particulate pollution risks at the handling stage.

4.6.2. Subsurface seismicity and earthquakes

A second subsurface disposal risk identified by our experts were earthquakes. R067 explained that:

There are some unique risks related to direct air capture ... there is seismic activity and stuff that makes some parts of the world more unstable than others. You would need to have very reliable monitoring, I think, of the reservoirs where you store the captured CO2.

R036 added that many carbon capture and storage methods pump carbon underground at high pressure and thus give rise to “earthquakes or subsidence or things like that, which already occur sometimes with enhanced oil recovery or fracking.” R075 framed these as both recurring engineering risks as well as risks that would face hosting sites and communities:

The risk of direct air capture is always that you put the stuff on the ground, and then it bubbles up and you’ll have a big burst and some earthquake, and five houses fall into a ditch and so on. So, there is always the engineering risk of solutions like this.

R026 lastly picked up on this theme as well, noting that the “sub-surface risks for negative emissions are largely unseen and unknown, they are not entirely understood.” They went on to remark how such risks are not only physical, but social:

All carbon dioxide removal brings to the fore our use of the underground, either storing stuff underground, similar to fracking in a way, or underground storage of carbon, which is similar to the storage of radioactive waste or geothermal energy. Everyone gets upset about the analogy to radioactive waste, but the social and organizational processes are common to both, and planners are likely to get the same response if they don’t do the right social response.

In this way, even the perceived risk of earthquakes (rather than their actual incidence) could forestall permitting or complicate social acceptance and any license to operate.

4.6.3. Hazardous waste streams

The last injustice issue mentioned by respondents involved the burdens of waste and hazardous waste that negative emissions and geo-engineering options entail. R041 claimed that due to the energy penalty of having to capture carbon (via processes for capture, transport, storage and sequestration), you will need more fuel (more coal) and also generate more waste. As they remarked:

For every three power plants you wish to equip with carbon capture and storage, you must build a fourth power plant to generate the energy to treat all four of them. It’s an incredible amount of energy you would waste that way ... you would increase the burning of fuels by a quarter, and generate large amounts of extra waste streams.

R008 added that widespread use of bioenergy with carbon capture and storage would generate extremely large volumes of “waste residues and bioproducts.” R035 mentioned that due to this, new advances are needed for “how to reduce waste across the lifecycles of negative emissions options”, and R039 mentioned their concern with dealing with “waste treatment as well as solid and liquid waste streams” from all potential options. R109 lastly noted that while carbon dioxide removal techniques are meant to be essentially a solution to waste management (long-term storage of the pollutant carbon), they also generate their own wastes, especially biomass and electronic waste, meaning we “need a step change in our mentality in terms of thinking about waste.”

5. Discussion: multifarious injustice in a net-zero future

The justice claims advanced by experts in Section 4 not only map onto our whole systems framework; they connect with our multifarious notion of justice and injustice. As Table 4 indicates, and this section

Table 4

Pluralizing environmental and energy justice for negative emissions and solar geoengineering technologies.

Tenet of justice	Burdens related to negative emissions and solar geoengineering technologies
Distribution	<ul style="list-style-type: none"> Land use impacts among communities hosting infrastructure Shifting pollution flows from fertilizers for new energy crops Uneven climatic protection from aerosol injection or cloud brightening Creation of “pollution havens” near mining or disposal sites and “sacrifice zones” among the world’s poor Hidden future and unknown risks
Recognition	<ul style="list-style-type: none"> Increased vulnerability among demographic or cultural groups (rural farmers, indigenous peoples) near infrastructure Entrenchment of preexisting patterns of spatial, economic, or political peripheralization Impacts on non-human species (forest loss, water use, habitat change, land degradation) Threat of real or potential termination shocks and risks to future generations
Participation	<ul style="list-style-type: none"> Inadequate attention to and respect for social acceptance and community well-being, lack of adequate compensation for benefits Unfair or non-representative energy or climate planning and policymaking at local, national, and global levels
Responsibility	<ul style="list-style-type: none"> Threat of “mitigation deterrence” and rebounds in fossil fuel consumption and profiteering that interfere with decarbonization Perpetual risk of accidents or carbon leakage Creating a “Pandora’s Box” of liability
Capabilities	<ul style="list-style-type: none"> Concentration of profits, wealth, resources or intellectual property among elites with risks distributed to communities Constraints arising from deployment related to local employment, capacity building, gender equality, or other Sustainable Development Goals

Source: Authors.

elaborates upon, they intersect with notions of distribution, recognition, participation, capabilities, and responsibilities, and in ways that cut across “from above” and “from below” concerns.

5.1. Distribution: who gets what?

Distributive justice issues are wide-ranging, including land use impacts and dispossession and shifting pollution flows (from below), as well as uneven climate protection, sacrifice zones and very significant unknown future risks (from above). For instance, our experts made claims about how negative emissions and solar geoengineering technologies could create entirely new pollution havens. Respondents noted how this could include solvents used for direct air capture, pesticides for energy crops or to protect forests, iron for ocean iron fertilization, and various solvents, amines, and treatments for carbon capture utilization and storage as well as leachates from enhanced weathering and biochar, and chemicals used for aerosol injection or cloud brightening. R018 expressed concern that deployment could lead to more “sacrifice zones” among the poor:

I worry that solar geoengineering or negative emissions could lead to the emergence of a new set of sacrifice zones. This refers to areas essentially treated simply as resource areas that can be pulled out or exploited to feed whatever the global goal is. Most sacrifice zones at the moment are areas of high fossil fuel extraction, like the Niger Delta or Alaskan tar sands, but future sacrifice zones could be coastal communities near ocean fertilization sites or mountain communities living under heightened acid rain from aerosol injection. We must ensure deployment does not create severe transgressions of ecological rights, of human rights.

Their comment reveals how solar geoengineering options could also entail justice risks alongside those related to negative emissions options.

A final distributive concern relates to hidden and future unknown risks that the community could not anticipate as of 2021 (when the data

was collected). R009 asserted that there may be “hidden risks” even with “proven” or nature-based options, and very high degrees of uncertainty:

There are real and often hidden environmental risks with many of the technologies. We're not entirely sure what the broader impacts are going to be of large-scale deployment. So, even when we start looking at blue carbon or some of the natural, ocean-based ones, there are some really interesting opportunities, and potentially very cheap, but being able to evaluate their environmental impact is all but impossible. If you're growing sea kelp and then sinking it to the ocean floor, which sounds a fantastic option, but how on earth can we ever measure whether it's going to stay there and for how long? You cannot talk about one thing without really understanding the implications elsewhere. That's one of the complexities of this and because it's all emergent, a lot of the issues we haven't necessarily come across or been aware of.

5.2. Recognition: who counts?

Recognitional justice concerns involve increased vulnerability among very specific communities of identity and place (e.g., rural farmers, indigenous peoples, mining towns) as well as localized negative impacts on the environment, including deforestation or water use (all from below) as well as the risk of ecological distribution conflicts and the broader entrenchment of preexisting patterns of spatial, economic, or political peripheralization (from above). R040 agreed that “there is more potential for negative emissions and solar geoengineering options to harm vulnerable groups, because the moment markets are established, then land becomes more valuable and this could harm certain indigenous groups, making the more exposed to potential injustice.”

Apart from the risk of under recognizing vulnerable groups, our data also indicated that future generations are misrecognized and do not “count” in current discussions given the prevalent risk of termination shocks. R025 added that, similar to the land-grabbing dynamics mentioned in Section 4.3.2, the impacts of a termination effect would likely affect vulnerable groups and future generations the most:

The risks of terminating these options would not be felt equally, it would be senior people, people with disabilities, or vulnerable groups most impacted well into the future ... With greenhouse gas removal and solar radiation management, the possible impacts of sudden termination would be to make those populations more vulnerable ... Same with people with disabilities, who don't have access to resources unlike other segments of the population. Most of them are unemployed, so they have low resilience. They would be hit differently by changes in weather, or drought, or land-use issues created by termination.

R022 mentioned the potential for actors to even trigger termination shocks if they wish, remarking that:

Termination shock also raises serious governance issues, especially if you have multiple actors capable of deploying solar radiation management, then it cannot be terminated unilaterally. You can't be deploying it and saying, “Screw this. I'm stopping,” because I could just send up my planes to keep it going. Or someone else could. Any capable actor could. That means solar radiation management can't be terminated unilaterally, even if we wanted to. The corollary to that is you can't easily turn the system off if people want to keep it on. So, that's a very real form of lock-in once it's up and running, because of termination shock.

5.3. Participation: who gets heard?

Issues of participation center on unfair or non-representative energy or climate planning and policymaking at local and regional levels (from below) but also national and global levels (from above). These often begin with an inability to appreciate or hear concerns about local and community acceptance. R054 speculated on the problem of social acceptance for carbon transport networks, questioning whether:

Do people really want to see these carbon dioxide removal devices all over the place? Do people want the pipelines bringing them to the storage facilities etc.? Already, there's a lot of resistance to the pipeline infrastructure for oil and gas. There's going to be a lot of similar pushback because this is just huge infrastructure that could end up being put in place.

R047 spoke about how solar radiation management options would likely be viewed as high risk, and would create immense social opposition near airports and deployment sites:

With solar radiation management, the number one thing I am worried about is the lack of field trials. Deployment will risk children and Mother Theresa showing up to bolt or superglue themselves to your airplane taking off. It's an “understandable nightmare” that could very well unfold.

These local issues of acceptance intersect with the exclusion of particular stakeholders from policy discussions. R025 put it as follows, noting that current discussion and decisions essentially silence the Global South:

The entire debate over these options makes me ask: Where is the voice of the Global South, where most of the impacts of climate change are occurring already? They are not contributing to policy decisions or decisions in terms of knowledge production. They are silenced, they don't have a standing, they aren't shaping policy, they are not brokering innovation or patents, they are not facilitating research trends, they are seen not to have the expertise to do the modelling or risk assessment. This is compounded by the fact that there is no support from national governments in these regions anyway. The focus in the Global South is almost always on adaptation and mitigation, not geoengineering.

5.4. Responsibility: who does what?

Negative emissions and solar geoengineering will complicate climate responsibility actions. This includes the perpetual risks of accidents, leakage and even death (from below) but also the threat of mitigation deterrence and rebounds in fossil fuel consumption and creating a “Pandora's Box” of liability (from above). Local communities for example must confront perpetual risks from carbon leakage and even death. As R016 explained:

For carbon capture utilization and storage, the main risk to the technology is carbon dioxide leaking up and killing people. A storage facility near a town leaks and within a village a bunch of people die when it leaks, which is not an insignificant risk. Storage could also become useless.

Multiple respondents spoke about the real risk of mitigation deterrence where deployment of the technologies reduces the incentives for countries and other actors to stop climate change or reduce greenhouse gas emissions. Experts made claims about the increased incentives for fossil fuel use as well within technological options. R074 claimed that “negative emissions are tricky, because the fossil fuel industry could benefit greatly from carbon dioxide removal options because it gives them a trajectory for surviving a bit longer.” R099 added that they believed solar geoengineering options were also primed to be “developed or even co-opted by fossil fuel industries and interests.”

R034 identified liability as an important governance concern, noting that:

Liability issues regarding ownership of the carbon dioxide will be mind boggling. Ownership of the captured CO₂. Liability for burial and for long-term storage of it. Issues of whether or not the liability transfers to the government, which is a procedure that's been used in a number of states, meaning more nations. Possible physical effects from the sequestration of carbon dioxide, such as seismic activity, possible contamination of water resources. It's like opening a Pandora's box of liability.

Elaborating further on these themes, R009 stated that:

The complexities that these options introduce in terms of governance and procedural justice are fiendish. They present real and serious governance problems. We have already seen it with the Kyoto Protocol and mitigation-offsetting processes. The problems of proving additionality, the problems of technology transfer, the problems of transboundary responsibility, the goal is in sight, but the guardrails for achieving it aren't put in place.

5.5. Capabilities: what matters?

Lastly, deployment of negative emissions and solar geoengineering technologies will shape future capabilities, and contribute towards a future world where mineral extraction, mining and managed forestry plantations grow (from below) and wealth and assets are concentrated among elites (from above). These could collectively create severe constraints arising from deployment related to local employment, capacity building, gender equality, or other Sustainable Development Goals. The capability to manage lands and forests, to provide fertilizers for bio-energy with carbon capture and storage as well as biochar, or to manage the pollution flows or chemical aspects of ocean iron fertilization and enhanced weathering all become highly valuable in a net-zero world. R041 even calculated the potential scope for mining expansion, calculating that:

Rock weathering and marine alkalization required to reach the scale which the IPCC has discussed would demand a doubling of global mining activities. Have you ever thought about the land use with that? Already, now, about 80% of biodiversity loss is caused by mining and extraction or processing of mining goods. What is the water demand? What is the land demand? What is the energy demand for all that? It could be astronomical.

R054 spoke about profiteering and the hoarding of intellectual property, noting that:

If someone takes a patent out then you have potential for slowing down development and research, if someone claims an exclusive right, or the fear that someone is going to assert the patent against others. You have legitimate public-perception concerns about profiteering off of the technologies.

R102 agreed, and went on to say that:

In terms of the innovation process, the more that we are talking about co-production of knowledge and co-production of technologies and all these kinds of things, I think generally, the issues of ownership are one of the biggest ones that are left undressed. We have seen these kinds of issues arise before and I just can't help thinking that is going to be one that is going to raise its head again in the not too distant future ... the intellectual property barriers are not getting enough attention at the moment and could be significant.

6. Conclusion: towards a more holistic multi-scalar milieu of justice impacts

Employing a whole systems energy justice lens to the analysis of our large sample of expert interview statements and claims reveals a comprehensive list of injustices associated with twenty negative emissions options and solar geoengineering technologies. Our approach offers greater granularity regarding the material and site-specific ways that injustices can arise from rebound effects and opportunity costs, including the mitigation deterrence and moral hazard issues highlighted in the literature. If geoengineering slows mitigation, extending our reliance on coal mining and oil production, the environmental and social impacts of those processes become part of the overall calculus. Similarly, if by slowing mitigation it sustains car-based transport systems, the health impacts from particulate pollution to community severance must also be considered. Taken together these might well outweigh the direct and material implications of geoengineering. With this in mind, we offer four conclusions.

First, our material focuses on prospective and anticipated injustices as well as more definitive historical or retrospective injustices; we do not explore the potential positive justices from deployment, and we are limited given our desire to focus on the original qualitative data collected for the study. Our material also arises from claims-making from a large sample of experts, with different types of background knowledge as well as assumptions (and preferred frameworks and forms of analysis) which they bring to bear on the topic.

That said, and second, the perceived injustices of negative emissions and solar geoengineering transcend well beyond their mere deployment and use (where risks such as energy consumption, environmental destruction, and termination shocks arise). As Fig. 5 notes, resource-extraction issues include a potential doubling of global mining operations, some of them with impacts similar to mountaintop removal and valley-fill operations for coal, and the risk that capture and storage

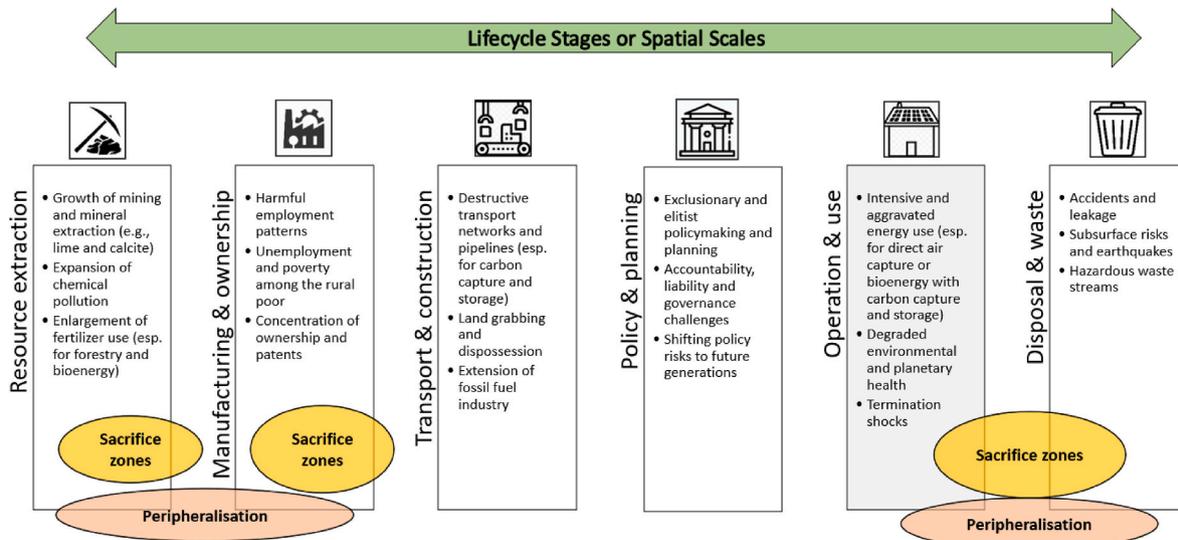


Fig. 5. The whole systems justice impacts of negative emissions and solar geoengineering. Source: Authors

Table 5
Summarizing the whole systems justice impacts of negative emissions and solar geoengineering.

	Resource extraction, chemicals, and fertilizers	Manufacturing, labor and ownership	Transportation, construction and land grabbing	Policymaking and planning	Deployment, operation and use	Disposal and waste
Nature-based carbon dioxide removal (e.g., afforestation and reforestation, biochar, soil sequestration, blue carbon and seagrass, ecosystem restoration)	Possible dependence on fertilizers or pesticides or monoculture plantations	Resource-curse risks for workers and communities	Extensive transport networks needed harvest forest outputs, competition with other land-uses	Climate colonialism, poor monitoring, verification, and accounting, loss of freedom for future generations	Pollution of agricultural land or food, hidden or unknown environmental risks, impermanence and reversibility of carbon storage	Generation of agricultural residues and biomass wastes
Engineered carbon dioxide removal (e.g., carbon capture and utilization and storage, bioenergy with carbon capture and storage, ocean iron fertilization, enhanced weathering, direct air capture)	Large-scale mining operations, chemical pollution from solvents and treatments, dependence on fertilizers	Resource-curse risks for workers and communities, creation of sacrifice zones near deployment, strengthening of fossil-fuel incumbents	Extensive transport networks needed to deliver energy crops or residues, creation of pipelines and storage reservoirs, fleets of ships for ocean iron fertilization, competition with other land-uses, displacement of vulnerable groups, increases in fossil fuel consumption	Irresponsible distribution of risks between Global North and Global South, a “Pandora’s Box” of liability concerns over stored carbon, loss of freedom for future generations	Immediate increases in energy consumption, risk of sudden termination shocks or effects	Accidents at storage sites including suffocation of host communities, impermanence of long-term storage, earthquakes, energy penalties and increased resource waste
Nature-based solar geoengineering (albedo modification via grasslands and crops, albedo modification via deserts, albedo modification via cloud formation, ice protection)	Possible dependence on fertilizers or pesticides or monoculture plantations	Displacement of rural workers, exacerbation of rural poverty	Fleets of ships for marine albedo modification, competition with other land uses	Elite domination of the Global South, liability concerns over deployment risks	Hidden or unknown environmental risks, impermanence and reversibility	Generation of biomass waste
Engineered solar geoengineering (space mirrors, high-altitude shades, stratospheric aerosol injection, cirrus cloud thinning, marine cloud brightening, albedo modification via human settlements)	Large-scale mining operations (in outer space or on the moon!), chemical spraying and alteration of clouds	Resource-curse risks for workers and communities, creation of sacrifice zones near deployment, strengthening of fossil-fuel incumbents, risk of malign innovation	Creation of pipelines and storage reservoirs, fleets of aircraft or rockets for aerosols and mirrors, displacement of vulnerable groups	Silencing of Global South concerns, irresponsible distribution of risks between Global North and Global South, liability concerns over deployment risks, risk of lock-in	Hidden or unknown environmental risks, acid rain, changing precipitation patterns, risk of both accidental and intentional termination shocks or effects	Generation of solid or liquid waste, electronic waste

Source: Authors

facilities “spit chemicals” into watersheds or landscapes. Manufacturing and ownership injustices include occupational hazards within the supply chains for negative emissions and geoengineering options, exacerbating rural poverty, or concentrating physical assets or patents among incumbent fossil fuel firms. Transportation and construction dilemmas involve the need to erect monumental new infrastructural channels and pipelines, occupying extremely large tracts of land (land use as large as the size of India or patterns that could negatively impact 1 billion farmers), and building additional fossil fuel capacity to steer deployment. Policymaking and planning risks remind us of the procedural and due process issues surrounding these options, including patterns of exclusionary and elitist planning, daunting challenges of accountability and liability, and a very real risk of shifting burdens to future generations and future policymakers. Disposal and waste issues include the omnipresent risk of accidents and leakage, seismic disturbances and earthquakes, and the generation of new hazardous waste streams.

Third, potential injustices arise across many different types of both negative emissions and solar geoengineering. As Table 5 summarizes, natural based solutions for both negative emissions and albedo modification possess their own systematic risks alongside the more often critiqued human engineered ones. Interestingly, prospective injustices were *not* just dominated by engineered solutions (such as direct air capture or enhanced weathering) or solar radiation management options (such as space mirrors or stratospheric aerosol injection); we also see

them arise with multiple natural solutions including blue carbon and seagrass, ecosystem restoration, afforestation and reforestation, and soil management, especially negative impacts on land grabbing and dispossession, new environmental risks, or aggravated risks of impermanence and termination shocks.

Fourth, our analysis reveals the wicked, multi-scalar, and likely-systemic injustices that can arise, or worsen, due to the commercialization or deployment of many net-zero or solar geoengineering technologies presumed to play a pivotal role in future decarbonization scenarios. As Fig. 6 visualizes, some injustices arise “from below” and others “from above,” with consequent impacts on distribution, recognition, participation, responsibility, and capabilities. One troubling implication is that net-zero transitions may not be net beneficial for all, even themselves entrenching toxic pollution, exploitative labor practices, the worsening of vulnerability among minorities and indigenous peoples, and patently unjust patterns of policymaking for some disaffected groups. In future research, we must both consider how to design net-zero options that minimize these justice concerns and also avoid conceptual approaches or research designs that obscure or mask them by focusing only on deployment and use.

Nevertheless, there is also hope, given the iterative and “unfinished business” nature of our expert claims, in that they are meant to open up a discussion of these justice issues, rather than close it down. For as Gordillo (2021) has written, the power of whole-systems, multi-scalar

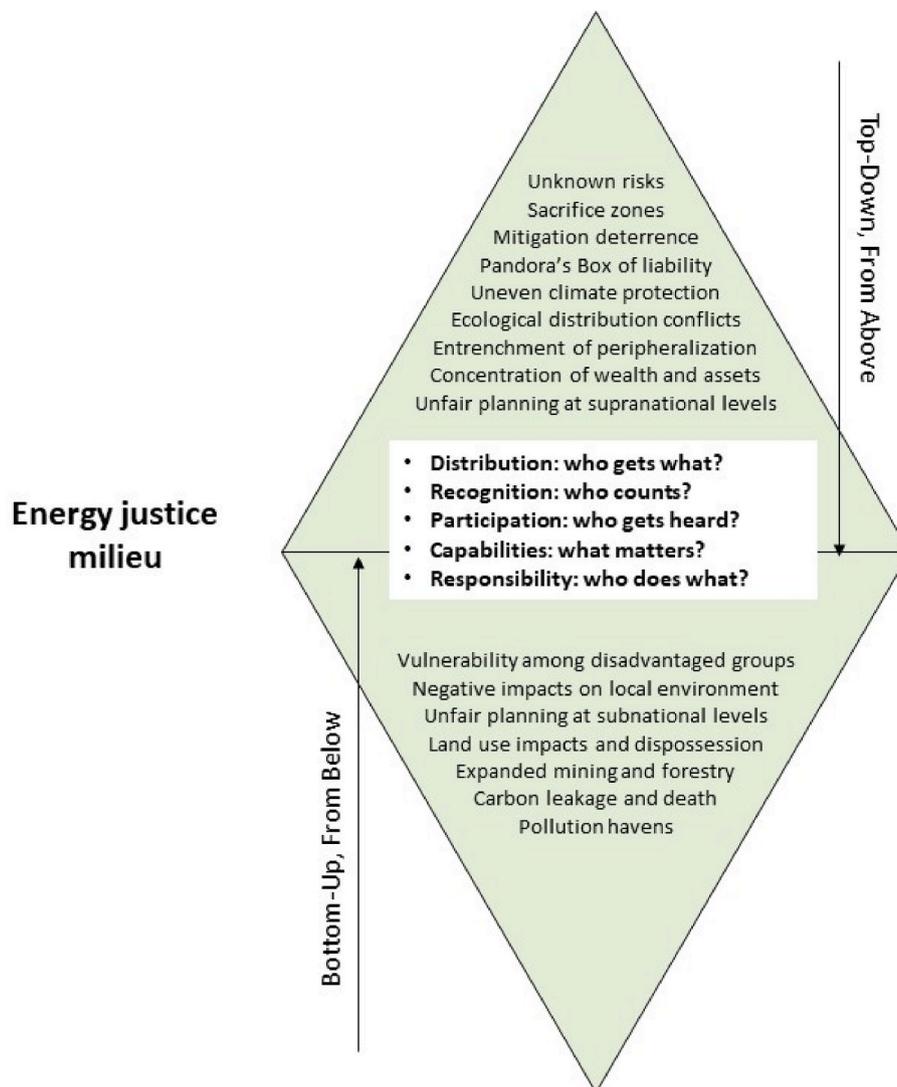


Fig. 6. Visualizing the “from below” and “from above” milieu of justice concerns with negative emissions and solar geoengineering technologies. Source: Authors.

analysis such as ours is that it can identify not only the negative aspects of terrain and space as disrupting human practices, but can motivate and facilitate action. Perhaps this dualistic role of space and justice can inspire all of us to resist the patterns of injustice that are emerging with negative emissions and solar geoengineering technologies, and imagine a better future that is more just in its distribution of benefits, recognizable of vulnerable groups, inclusive in participation, effective in its responsibility, and empowering in the capabilities it provides.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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References

- Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science*, 354, 182–183, 14 October.
- Angel, R. (2006). Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proceedings of the National Academy of Sciences Nov*, 103(46), 17184–17189. <https://doi.org/10.1073/pnas.0608163103>
- Asayama, S., & Hulme, M. (2019). Engineering climate debt: Temperature overshoot and peak-shaving as risky subprime mortgage lending clim. *Pol*, 19(8), 937–946.
- Barnett, C. (2018). Geography and the priority of injustice. *Annals of the Association of American Geographers*, 108(2), 317–326.
- Barrett, S., Lenton, T. M., Millner, A., Tavoni, A., et al. (2014). Climate engineering reconsidered. *Nature Climate Change*, 4, 527–529.

- Baum, C. M., Low, S., & Sovacool, B. K. (2022). Between the Sun and Us: Expert perceptions on the innovation, policy, and deep uncertainties of space-based solar geoeengineering. *Renewable and Sustainable Energy Reviews*, 158, 1–22, 112179.
- Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nature Energy*, 3, 532–534.
- Bellamy, R., & Palmer, J. (2019). Geoengineering and geographers: Rewriting the earth in what image? *Area*, 51, 524–531.
- Bellassen, V., Stephan, N., Afriat, M., et al. (2015). Monitoring, reporting and verifying emissions in the climate economy. *Nature Climate Change*, 5, 319–328.
- Bertram, C., & Merk, C. (2020). Perceptions of ocean-based carbon dioxide removal: The nature-engineering divide? *Front Climate*, 2, Article 594194.
- Borras, S. M., & Franco, J. (2013). *Global land grabbing and political reactions “from below” Third World Quarterly*. 34 pp. 1723–1747 (9) (2013).
- Brock, A., Sovacool, B. K., & Hook, A. (2021). Volatile Photovoltaics: Green industrialization, sacrifice zones, and the political ecology of solar energy in Germany. *Annals of the Association of American Geographers*, 111(6), 1756–1778 (November/December).
- Brown, M. A., & Sovacool, B. K. (2011). *Climate change and global energy Security: Technology and policy options*. Cambridge: MIT Press.
- Bruhn, T., & Naims, H. (2016). Barbara Olfe-Krättelein Separating the debate on CO2 utilisation from carbon capture and storage. *Environmental Science & Policy*, 60, 38–43.
- Brunel, C. (2017). Pollution offshoring and emission reductions in EU and US manufacturing. *Environmental and Resource Economics*, 68, 621–641.
- Buck, H. J. (2016). Rapid scale-up of negative emissions technologies: Social barriers and social implications. *Climatic Change*, 139, 155–167.
- Buck, H. J. (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>
- Buck, H. J. (2019). *Challenges and opportunities of bioenergy with carbon capture and storage (BECCS) for communities*. Current Sustainable/Renewable Energy Reports, 2019.
- Caldeira, K., et al. (2013). The science of geoengineering. *Annual Review of Earth and Planetary Sciences*, 41, 231–256.
- Campbell, E. (2019). Three-dimensional security: Layers, spheres, volumes, milieus. *Political Geography*, 69, 10–21.
- Carton, W., et al. (2020). Negative emissions and the long history of carbon removal. *WIREs Clim Change*, e671.
- Chandler, D. L. (2007). A sunshade for the planet. *New Scientist*, 195(2613), 42–45.
- Cole, M. A., Elliott, R. J., Okubo, T., & Zhang, L. (2021). Importing, outsourcing and pollution offshoring. *Energy Economics*, 103, Article 105562.
- Coolsaet, B., & Néron, P.-Y. (2020). *Recognition and environmental justice*. London: Routledge.
- Cox, E., Boettcher, M., Spence, E., & Bellamy, R. (2021). Casting a wider net on ocean NETS, 2021 *Front Climate*, 3, Article 576294. <https://doi.org/10.3389/fclim.2021.576294>.
- Davoudi, S., & Brooks, E. (2014). When does unequal become unfair? *Judging claims of environmental injustice*. *Environment and Planning A*, 46(11), 2686–2702.
- Delina, L. L. (2020). Potentials and critiques of building a Southeast Asian interdisciplinary knowledge community on critical geoeengineering studies. *Climatic Change*, 163, 973–987.
- Desch, S. J., et al. (2016). Arctic ice management. *Earth's Future*, 5(December), 107–127.
- Duan, L., Cao, L., Bala, G., & Caldeira, K. (2018). Comparison of the fast and slow climate response to three radiation management geoeengineering schemes. *Journal of Geophysical Research: Atmospheres*, 123, 11,980–12,001.
- Elden, S. (2021). Terrain, politics, history. *Dialogues in Human Geography*, 11(2), 170–189.
- 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>
- National Academies of Sciences, Engineering, and Medicine. (2021). *Reflecting sunlight: Recommendations for solar geoeengineering research and research governance*. Washington, DC: The National Academies Press.
- European Academies Science Advisory Council. (2018). *Negative emission technologies: What role in meeting Paris Agreement targets? February*.
- Fridahl, M., & Lehtveer, M. (August 2018). Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers. *Energy Research & Social Science*, 42, 155–165.
- Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., et al. (2014). Betting on negative emissions. *Nature Climate Change*, 4, 850–853.
- Gardiner, S., & McKinnon, C. (2020). The justice and legitimacy of geoeengineering. *Critical Review of International Social and Political Philosophy*, 23(5), 557–563.
- Givens, J. E., Huang, X., & Jorgenson, A. K. (2019). Ecologically unequal exchange: A theory of global environmental injustice. *Sociology Compass*, 13, Article e12693.
- Gordillo, G. (2021). The power of terrain: The affective materiality of planet Earth in the age of revolution. *Dialogues in Human Geography*, 11(2), 190–194.
- Greiner, J. T., McGlathery, K. J., Gunnell, J., & McKee, B. A. (2013). Seagrass restoration enhances “blue carbon” sequestration in coastal waters. *PLoS One*, 8(8), Article e72469.
- Griscom, B. W., et al. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, 114(44), 11645–11650. October 31.
- Hall, R., et al. (2015). Resistance, acquiescence or incorporation? An introduction to land grabbing and political reactions ‘from below’. *Journal of Peasant Studies*, 42(3–4), 467–488.
- Hancké, B. (2009). *Intelligent research design: A guide for beginning researchers in the social sciences*. Oxford: Oxford University Press.
- Hanna, R., Abdulla, A., Xu, Y., et al. (2021). Emergency deployment of direct air capture as a response to the climate crisis. *Nature Communications*, 12, 36.
- Harper, A. B., et al. (2018 Aug 7). Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature Communications*, 9(1), 2938.
- Healy, N., Stephens, J. C., & Malin, S. A. (2019). Embodied energy injustices: Unveiling and politicizing the transboundary harms of fossil fuel extractivism and fossil fuel supply chains. *Energy Research & Social Science*, 48, 219–234.
- Heyward, C. (2019). Normative issues of geoeengineering technologies. In s), & T. M. Letcher (Eds.), *Managing global warming* (pp. 639–657). Academic Press.
- Honegger, M., & Reiner, D. (2017). The political economy of negative emissions technologies: Consequences for international policy design. *Climate Policy*, 18(3), 306–321.
- Ecologically unequal exchange and ecological debtHornborg, A., & Martinez-Alier, J. (Eds.). *Special Section of the Journal of Political Ecology*, 23, (2016), 328–491.
- Horton, J. B. (2020). Barbara Koremenos, steering and influence in transnational climate governance: Nonstate engagement in solar geoeengineering research. *Global Environmental Politics*, 20, 93–111. Number 3, August.
- Houghton, R. A., Byers, B., & Nassikas, A. A. (2015). A role for tropical forests in stabilizing atmospheric CO2. *Nature Climate Change*, 5, 1022, 01023.
- Huber, M. T., & McCarthy, J. (2017). Beyond the subterranean energy regime? Fuel, land use and the production of space. *Transactions of the Institute of British Geographers*, 42 (4), 655–668.
- Jenkins, K. (2018). Setting energy justice apart from the crowd: Lessons from environmental and climate justice. *Energy Research & Social Science*, 39(2018), 117–121.
- Jenkins, K., Sovacool, B. K., Mouter, N., Hacking, N., & McCauley, D. (2021). The methodologies, geographies, and technologies of energy justice: A systematic and comprehensive review. April, *Environmental Research Letters*, 16(4), Article 043009, 1–25.
- Johannessen, S. C., & Macdonald, R. W. (2016). Geoeengineering with seagrasses: Is credit due where credit is given? *Environmental Research Letters*, 11, Article 113001.
- Kantola Ilsa, B., Masters Michael, D., Beerling David, J., Long Stephen, P., & DeLucia Evan, H. (2017). Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. *Biological Letters*, 132016071420160714.
- Keith, D. (2013). *A case for climate engineering*. MIT Press.
- Keith, D. W., Duren, R., & MacMartin, D. G. (2014). *Field experiments on solar geoeengineering: Report of a workshop exploring a representative research portfolio*. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences.
- Kosugi, T. (2010). Role of sunshades in space as a climate control option. *Acta Astronautica*, 67(1–2), 241–253, 2010.
- Lamb, W. L., Mattioli, G., Levi, S., Roberts, J. T., Capstick, S., Creutzig, F., Minx, J. C., Müller-Hansen, F., Culhane, T., & Steinberger, J. K. (2020). Discourses of climate delay. *Global Sustainability*, 3(e17), 1–5. <https://doi.org/10.1017/sus.2020.13>
- Lenzi, D. (2018). The ethics of negative emissions. *Global Sustainability*, 1(e7), 1–8.
- Lenzi, D., et al. (2018). Don't deploy negative emissions technologies without ethical analysis. *Nature*, 561, 303–305.
- Levinson, A. (2010). Offshoring pollution: Is the United States increasingly importing polluting goods? *Review of Environmental Economics and Policy*, 4(1), 63–83.
- Low, S., & Boettcher, M. (2020). Delaying decarbonization: Climate government alities and sociotechnical strategies from Copenhagen to Paris. *Earth System Governance*. <https://doi.org/10.1016/j.esg.2020.100073>
- Low, S., & Buck, H. J. (2020). The practice of responsible research and innovation in “climate engineering”. *WIREs Clim Change*, 11, e644.
- Mahony, M. (2021). Geographies of science and technology 1: Boundaries and crossings. *Progress in Human Geography*, 45(3), 586–595.
- Markusson, N., Balta-Ozkan, N., Chilvers, J., Healey, P., Reiner, D., & McLaren, D. (2020). Social science sequestered. *Front Climate*, 2, 2. <https://doi.org/10.3389/fclim.2020.00002>
- Marston, Andrea, & Himley, M. (2021). Earth politics: Territory and the subterranean – introduction to the special issue. *Political Geography*, 88, 102407.
- Martens, K. (2012). Justice in transport as justice in accessibility: Applying Walzer's ‘spheres of justice’ to the transport sector. *Transportation*, 39(6), 1035–1053.
- Martens, K. (2016). *Transport justice: Designing fair transportation systems*. London: Routledge.
- Mattioli, G. (2016). Transport needs in a climate-constrained world. A novel framework to reconcile social and environmental sustainability in transport. *Energy Research & Social Science*, 18, 118–128, 2016.
- McCauley, D., Ramasar, V., Heffron, R. J., Sovacool, B. K., Mebratu, D., & Mundaca, L. (2019). Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research. *Applied Energy*, 233(January), 916–921.
- McLaren, D. (2012). A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection*, 90, 489–500.
- McLaren, D. P. (2018). Whose climate and whose ethics? Conceptions of justice in solar geoeengineering modelling. *Energy Research & Social Science*, 44, 209–221.
- McLaren, D. (2020). Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. *Climatic Change*, 162, 2411–2428.
- McLaren, D., et al. (2016). Public conceptions of justice in climate engineering: Evidence from secondary analysis of public deliberation. *Global Environmental Change*, 41, 64–73.
- Minx, Jan, C., et al. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, 13, Article 063001.
- National Research Council. (2015a). *Climate intervention: Carbon dioxide removal and reliable sequestration* (Washington, DC: Committee on geoeengineering climate: Technical

- evaluation and discussion of impacts; board on atmospheric sciences and climate. Ocean Studies Board; Division on Earth and Life Studies, 2015.
- National Research Council. (2015b). *Climate intervention: Reflecting sunlight to cool earth*. Washington, DC: National Academies Press.
- Nussbaum, M. (2003). Capabilities as fundamental entitlements: Sen and social justice. *Feminist Economics*, 9(2–3), 33–59.
- O’Beirne, P., et al. (2020). The UK net-zero target: Insights into procedural justice for greenhouse gas removal. *Environmental Science & Policy*, 112, 264–274.
- Obersteiner, M., et al. (2018). How to spend a dwindling greenhouse gas budget. *Nature Climate Change*, 8(January), 2–12.
- O’Sullivan, E., Rassel, G. R., & Berner, M. (2010). *Research methods for public administrators*. New York: Pearson Longman.
- Pamplany, A., Gordijn, B., & Brereton, P. (2020). The ethics of geoengineering: A literature review. *Science and Engineering Ethics*, 26, 3069–3119.
- Preston, C. J. (2013). Ethics and geoengineering: Reviewing the moral issues raised by solar radiation management and carbon dioxide removal. *WIREs Clim Change*, 4, 23–37.
- Rahman, A. A., et al. (2018). Developing countries must lead on solar geoengineering research. *Nature*, 556, 22–24.
- Royal Society. (2009). *Geoengineering the climate Science, governance and uncertainty*. London: September.
- Russell, L. M., et al. (2012). Ecosystem impacts of geoengineering: A review for developing a science plan. *Ambio*, 41, 350–369.
- Sanchez, D. L., Nelson, J. H., Johnston, J., Mileva, A., & Kammen, D. M. (2015). Biomass enables the transition to a carbon-negative power system across western North America. *Nature Climate Change*, 5, 230–234.
- Holly Jean Buck. (2020). In J. P. Sapinski, & Andreas Malm (Eds.), *Has it come to this? The promises and perils of geoengineering on the brink*. Rutgers University Press.
- Schlosberg, D. (2004). Reconceiving environmental justice: Global movements and political theories. *Environmental Politics*, 13(3), 517–540.
- Schlosberg, D. (2013). Theorising environmental justice: The expanding sphere of a discourse. *Environmental Politics*, 22(1), 37–55.
- 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, Article 20200002.
- Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A review of biochar and its use and function in soil. *Advances in Agronomy*, 105, 47–82.
- Sovacool, B. K. (2019). Marie-claire Brisbois, elite power in low-carbon transitions: A critical and interdisciplinary review. *Energy Research & Social Science*, 57, Article 101242.
- Sovacool, B. K. (2021a). Reckless or righteous? Reviewing the sociotechnical benefits and risks of climate change geoengineering. *Energy Strategy Reviews*, 35, Article 100656, 2021.
- Sovacool, B. K. (2021b). Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation. March, 2021 *Energy Research & Social Science*, 73, Article 101916, 1–16.
- Sovacool, B. K., Hook, A., Martiskainen, M., & Baker, L. H. (2019). The whole systems energy injustice of four European low-carbon transitions. September *Global Environmental Change*, 58, 1–15, 101958.
- Sovacool, B. K., Hook, A., Martiskainen, M., Brock, A., & Turnheim, B. (2020). The decarbonisation divide: Contextualizing landscapes of low-carbon exploitation and toxicity in Africa. January *Global Environmental Change*, 60, 102028, 1–19.
- Sovacool, B. K., Newell, P., Carley, S., et al. (2022). Equity, technological innovation and sustainable behaviour in a low-carbon future. *Nature Human Behaviour*. <https://doi.org/10.1038/s41562-021-01257-8>
- Sovacool, B. K., Rj Heffron, D. M. C., & Goldthau, A. (2016). Energy decisions reframed as justice and ethical concerns. May *Nature Energy*, 16024, 1–6.
- Sugiyama, M., et al. (2017). Transdisciplinary co-design of scientific research agendas: 40 research questions for socially relevant climate engineering research. *Sustainability Science*, 12, 31–44.
- Svoboda, T., & Keller, K. (JULY 2011). Marlos goes and Nancy tuana, sulfate aerosol geoengineering: The question of justice. *Public Affairs Quarterly*, 25(No. 3), 157–179.
- Taylor, L. L., Quirk, J., Thorley, R. M., Kharecha, P. A., et al. (2016). Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nature Climate Change*, 6, 402–406.
- Turner, P. A., Field, C. B., Lobell, D. B., et al. (2018). Unprecedented rates of land-use transformation in modelled climate change mitigation pathways. *Nature Sustainability*, 1, 240–245.
- Van Vuuren, D. P., Hof, A. F., van Sluisveld, M. A. E., & Riahi, K. (2017). Open discussion of negative emissions is urgently needed. *Nature Energy*, 2(December), 902–904.
- Verweijen, J., & Dunlap, A. (2021). The evolving techniques of the social engineering of extraction: Introducing political (re)actions ‘from above’ in large-scale mining and energy projects. *Political Geography*, 88, Article 102342.
- Walker, G. (2011). *Environmental justice: Concepts, evidence and politics*. London: Routledge.
- Wibeck, V., et al. (2015). Questioning the technological fix to climate change – lay sense-making of geoengineering in Sweden. *Energy Research & Social Science*, 7, 23–30.
- Winickoff, D. E., et al. (2015). Engaging the Global South on climate engineering research. *Nature Climate Change*, 5, 627–634.
- Yin, R. K. (2003). *Case study research: Design and methods*. London: Sage.
- Zhao, M., Cao, L., Duan, L., Bala, G., & Caldeira, K. (2021). Climate more responsive to marine cloud brightening than ocean albedo modification: A model study. *Journal of Geophysical Research: Atmospheres*, 126, Article e2020JD033256.