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ORIGINAL ARTICLE

Risk–risk governance in a low-carbon future: Exploring institutional, technological, and behavioral tradeoffs in climate geoengineering pathways

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Abstract

Deliberations are underway to utilize increasingly radical technological options to help address climate change and stabilize the climatic system. Collectively, these options are often referred to as “climate geoengineering.” Deployment of such options, however, can create wicked tradeoffs in governance and require adaptive forms of risk management. In this study, we utilize a large and novel set of qualitative expert interview data to more deeply and systematically explore the types of risk–risk tradeoffs that may emerge from the use of 20 different climate geoengineering options, 10 that focus on carbon dioxide or greenhouse gas removal, and 10 that focus on solar radiation management and reflecting sunlight. We specifically consider: What risks does the deployment of these options entail? What types of tradeoffs may emerge through their deployment? We apply a framework that clusters risk–risk tradeoffs into institutional and governance, technological and environmental, and behavioral and temporal dimensions. In doing so, we offer a more complete inventory of risk–risk tradeoffs than those currently available within the respective risk-assessment, energy-systems, and climate-change literatures, and we also point the way toward future research gaps concerning policy, deployment, and risk management.

KEYWORDS

carbon dioxide removal, climate engineering, greenhouse gas removal, negative emissions technologies, solar radiation management

1 | INTRODUCTION

Risk research has long focused on and provided insight into the perceptions, impacts, and management of “dangerous climate change” (Lorenzoni et al., 2005). More recently, deliberations are underway to utilize increasingly radical technological options to help address climate change and stabilize the climatic system. To ensure that global warming does not exceed 2°C temperature levels, cumulative emissions since 1870 must remain under an ultimate budget of 3650 $GtCO_2$ (Pachauri et al., 2014). Following current emission rates and scenarios, this global emissions budget will be used up within the next 20 years (Bui et al., 2018). Some scientists, including those within the Intergovernmental Panel on Climate Change and National Academies in the United States, have come to argue that we must consider sociotechnical options as disparate and revolutionary as direct air capture, enhanced weathering, stratospheric aerosol injection, or marine cloud brightening (Caldeira et al., 2013; Fuss et al., 2018; NASEM, 2021). Collectively, these options have been referred to as “climate geoengineering” (Caldeira et al., 2013; Jinnah & Nicholson, 2019; Sovacool, 2021; Zelli et al., 2017), although they are also increasingly assessed as separate suites of carbon dioxide removal (or greenhouse gas removal) and solar geoengineering (or solar radiation management).

Scholars of risk analysis are beginning to undertake expert- and public-facing, future-oriented assessments of these climate geoengineering approaches, as well as developing frameworks for doing so (Choptiany & Pelot, 2014; Cox et al., 2021; Grieger et al., 2019; Joubin & Siegrist, 2020;

Low & Honegger, 2020; Merk & Pönitzsch, 2017). In this paper, we build upon these existing assessments and risk-analytical efforts and introduce a framework for exploring a frequently referenced but poorly examined dimension of this topic: how deployment of carbon-removal and solar-geoengineering options creates *wicked tradeoffs* in governance, and also requires adaptive forms of risk management. The National Academies of Sciences framed this in terms of *risk–risk* tradeoffs, given that acting to address one set of risks only exacerbates another (NASEM, 2021). While geoengineering approaches pose risks of their own across different types of populations and ecosystems, they also have the (greater) potential to significantly reduce the pending impacts of climate change to humans—the risks of deployment therefore have to be weighed against the risks of counterfactuals in which different measures are taken, or emissions or warming rise unabated (Reynolds, 2014). One study has quantified risk–risk tradeoffs across the dimensions of economic productivity, reliable stabilization of temperatures, damages, and costs (Garner et al., 2016).

However, such a catalog of risks remains incomplete, and drawn from fragmented (and sometimes opaque) sources of data. For the most part, researchers working on carbon-removal and solar-geoengineering options (or even in collective assessment, as climate geoengineering) have treated risk–risk tradeoffs as a truism rather than a framework for empirical assessment (Harrison et al., 2021; Jebari et al., 2021). In turn—and particularly in solar geoengineering—the unnuanced use of the risk–risk framing has the potential to downplay the risks of deploying (combinations of) these novel sociotechnical systems in comparison to simplistic counterfactuals of business-as-usual climate change (Low & Honegger, 2020).

In this study, we utilize a large and novel set of qualitative expert interview data to more deeply and systematically explore the types of risk–risk tradeoffs that may emerge with 10 different carbon dioxide or greenhouse gas removal approaches, and another 10 that focus on solar radiation management. We apply a framework informed by the notion of path dependence that clusters risk–risk tradeoffs into institutional and governance, technological and environmental, and behavioral and temporal dimensions. We therefore offer a more complete inventory of risk–risk tradeoffs than those currently available within the risk-assessment, energy-systems, and climate-change literatures (Honegger, 2020; Lofstedt & Schlag, 2017; Vaino et al., 2016), and we also point the way toward future research gaps concerning policy and risk management.

2 | CONCEPTUAL APPROACH: PATH DEPENDENCE AND RISK

This section sets up the study by summarizing our conceptual linkages to notion of path dependence and lock-in (Section 2.1) followed by our conceptualization of risk (Section 2.2).

2.1 | Path dependence and lock-in

To guide our analysis, we employ the notion of path dependence in low-carbon transitions, a term that refers to how large-scale sociotechnical systems become embedded in society. Energy systems are paradigmatic of the ways in which massive volumes of labor, capital, and effort become “sunk” into particular institutional configurations (Scrase & Mackerron, 2009). Such strong path dependencies—which can emerge even in the early formative stages of technology development—can exercise lasting impacts on sociotechnical systems, producing inertia (Vadén et al., 2019). Hence, it can become very difficult to reorient such path-dependent development, or indeed to undo any unintended consequences after they have emerged (Knox-Hayes, 2012).

However, while much literature emphasizes the ability for path dependence to occur on the “supply side,” via the sunk costs and legacies of material-transport or energy-supply systems, Kanger et al. (2019) emphasize that it can occur on the “demand side” as well, across user, business, cultural, regulatory, and transnational dimensions, for instance. Drawing from the example of the historical transition to automobiles in the Netherlands and the United States, they argue that path dependence (also referred to as embedding) in user environments extends far beyond purchase activities and can involve the integration of new technologies into user practices and the development of new preferences, routines, habits, and even values. Embedding or path dependence in the business environment can moreover shape the development of industries, business models, supply and distribution chains, and repair facilities, while embedding in culture can encompass the articulation of positive discourses, narratives, and visions that enhance the cultural legitimacy and societal acceptance of new technologies. Regulatory embedding, meanwhile, can capture the variety of policies that shape production, markets, and use of new technologies, for example, safety regulations, reliability standards, adoption subsidies, demonstration projects, and infrastructure-investment programs. Embedding in the transnational community can reflect a shared understanding in a community of global experts related to new technologies that transcends the borders of a single place, often taken at the country level. These diverse dimensions of path dependence suggest that technological diffusion is ultimately an active and contested process, full of choices, debates, and struggles across a variety of domains and scales. What is more, the diverse elements of path dependence can all co-evolve to reinforce particular socioinstitutional structures and constituencies, thereby resulting in a still greater level of complexity (Brown et al., 2007). Seto et al. (2016) visualize these intersecting layers of lock-in and path dependence in Figure 1.

Crucially, these different elements of path dependence (or embedding) can shape technology and infrastructure as well as institutions and collective behavior (see Table 1, Kotilainen et al., 2020). This underscores and explains the existence (and dynamics) of mechanisms on the technological level (such as economies of scale), institutional level (such as vested

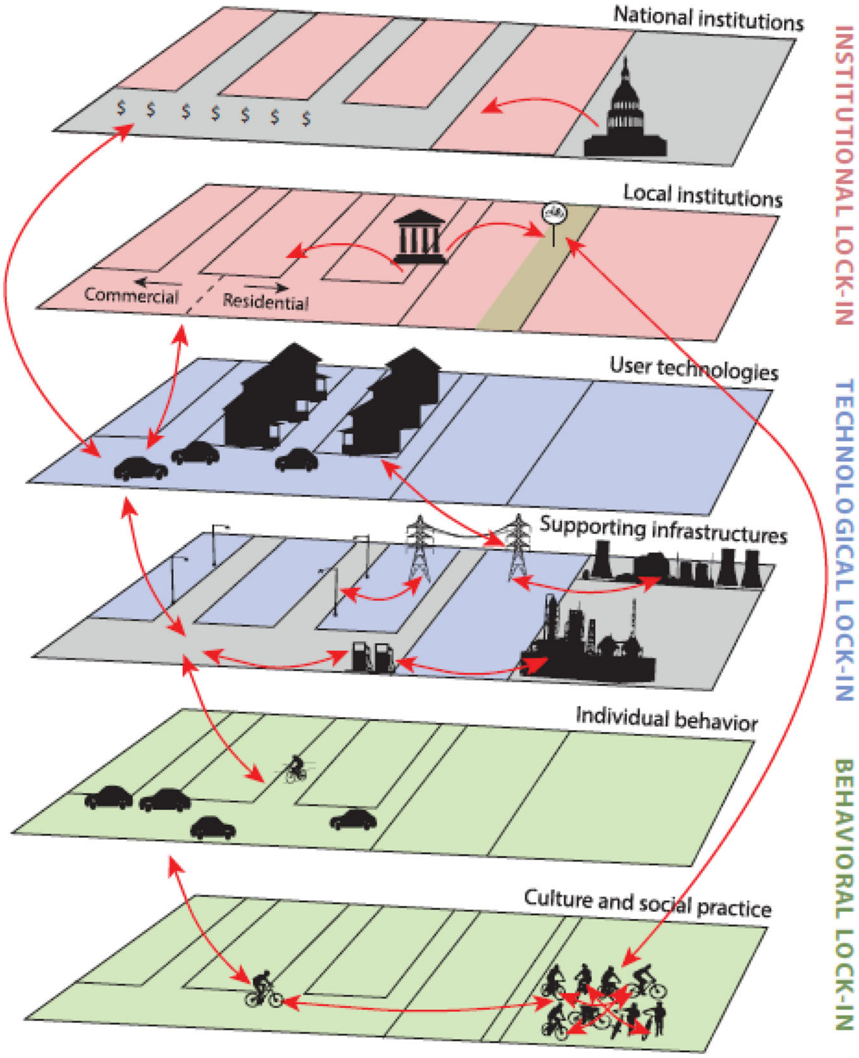

FIGURE 1 Path dependence across institutional, technological, and behavioral dimensions. *Source*: Seto et al. (2016) Interconnections and interactions (arrows) among and within different levels of carbon lock-in. Carbon lock-in can occur in multiple dimensions (institutional, technological, behavioral), at multiple scales (local to national or individual to structural), and with multidirectional causation between and among the levels

interests), and behavioral level (such as habituation), which we extend in our paper to examine climate geoengineering techniques.

2.2 | The social construction of risk

We couple our focus on the heuristics of path dependence and lock-in with the social construction of risk. Following convention, we envision risks as the perceived potential for undesired and unintended consequences of events and activities (Renn et al., 1992; SRA, 2015). This encompasses four distinct types of risk:

- Risk as the possibility of an unfortunate occurrence;
- Risk as the potential for realization of unwanted, negative consequences of an event;
- Risk as the consequences of an activity and its associated uncertainties;
- Risk as uncertainty itself about and severity of the consequences of an activity with respect to something that humans value.

Part of the risk management conundrum is that new emerging technologies (like climate geoengineering) tend not to eliminate risk; because they are introduced on top of or coupled to existing sociotechnical systems, they tend to merely redistribute risk, or at times even obscure risk. Luhmann (1993) cautioned almost three decades ago that high-technology societies tend to mask the existence of social risk redistribution for two core reasons: complexity, given that a multiplicity of interactions and side effects makes it difficult to isolate causes; and accumulation, in most cases complex technologies must be actually used before their effects become clear, and thus risk becomes inherent in the technology itself, and risks accumulate as it is deployed. Beck (1992) went even further to argue that since modern society is so intimately connected to high-risk sociotechnical or industrial systems, risk has become a defining feature of contemporary culture. Whereas previous historical societies were distinguished by lineage (aristocracy) or wealth and goods (capitalism), Beck (1992) argued that our new society is based on the production and distribution of risk, a rapid rise and diffusion of myriad risk types and exposures, culminating in a "risk society."

TABLE 1 Varying types and lock-in mechanisms for path dependence and climate geoengineering

Type	Primary lock-in mechanisms	Application to climate geoengineering
Institutional and governance	Collective action	Business models
	Complexity and opacity of politics	Experiments and scaling
	Differentiation of power and institutions	Market saturation
	High density of institutions	Emergency deployment
	Institutional learning effects	
	Vested interests	
Technological and environmental	Economies of scale	Economies of energy production
	Economies of scope	Land resources
	Learning effects	Storage capabilities
	Network externalities	Water resources
	Technological interrelatedness	Technological capability and capacity
Behavioral and temporal	Habituation	Social acceptance and opposition
	Cognitive switching costs	Rebounds in consumption
	Increasing informational returns	Dependence
		Colonialism

Source: Modified from Kotilainen et al. (2020).

Risks also have intrinsically social and political dynamics. Douglas and Wildavsky (1984) classically argued that since the risks facing societies are diffuse (including the risk of foreign attack, war, loss of influence and power, crime, internal collapse, failure of law and order, pollution, abuse of technology, economic failure, loss of prosperity, financial security, etc.), choosing which of these risks is the most important is an inseparably social, rather than technical process. Such a process depends on values, beliefs, and identity, which can all shape what are "acceptable risks" for particular communities in a way that differs greatly in comparison (Douglas & Wildavsky, 1984). Within a given culture, certain dangers are selected for attention; "each culture, each set of shared values and supporting social institutions, is biased toward highlighting certain risks and downplaying others" (Douglas & Wildavsky, 1984). Richard P. Hiskes (1998, p. 141) framed these as "societal risks," and he wrote that competing notions of risk are not simply those of divergent interests, but rather that confronting risk brings into question basic attitudes toward self, other, community, and national identity. The collective understanding of these risks produces a cultural understanding, but one that is dynamic and adaptable across communities of technology. But it also creates selection pressures in some cultures to accept some risks and downplay others. In many modern cultures, for instance, societies accept risks such as heart disease from food, alcohol, and drunk driving, and emphysema from smoking, but strenuously stigmatize those that are counter to democratic values (e.g., terrorism) or that threaten a community (e.g., xenophobia over immigration). Risk identification, risk avoidance, risk management, risk naturalization all become social and cultural phenomena.

When these themes are considered in the context of climate geoengineering, it becomes apparent that many research teams are not necessarily aware of recent advances in decision analysis or risk assessment and how those approaches can inform energy and climate policy. Some technoeconomic assessments may rely too narrowly on economic indicators that are unable to assess complex energy systems or their interactions; as Choptiany and Pelot (2014) write, "single-discipline decision analysis methods cannot properly assess complex energy projects because the projects often have multifaceted impacts." No single discipline, or single risk framework, is capable of capturing all composite risks (and their associated variables) across different spatial scales or temporalities. This is especially true with social convictions about the dangerousness of climate change, and the appropriate responses society should pursue to address it (Lorenzoni et al., 2005). Finally, risks with new technology are not static; they are dynamic or mutable, ever changing and fluid, given that technological risk can entail network effects that can destabilize organizations as well as power relations (Wong, 2015). This demands any climate geoengineering risk framework move away from traditional modes of risk analysis that may focus on probabilities and magnitudes, to a more expanded conception of risk that touches on what humans perceive as threats to their well-being, how they evaluate the magnitudes of unwanted consequences, the strength of knowledge which can be brought to bear, and how all of these elements are socially shaped and reconstructed (Renn et al., 1992).

In this paper, we examine multiple dimensions of risk through the prospective embedding or path dependence of carbon removal and solar geoengineering techniques at multiple levels of society. As a result, the analysis is guided by an active appreciation of the interconnected nature of risks, their spatial and temporal dynamism, and their mutability across societies.

3 | RESEARCH DESIGN: DATA COLLECTION, ANALYSIS, AND LIMITATIONS

Our research design is grounded in the use of original data collected through a large number of semi-structured expert interviews.

3.1 | Data collection and sampling

To determine and examine the risks and tradeoffs that may arise within and resulting from climate geoengineering pathways, our knowledge base relied on a large pool of semi-structured interviews with prominent experts with expertise about 20 climate geoengineering options:

- Carbon capture and utilization and storage;
- Afforestation and reforestation;
- Bioenergy with carbon capture and storage;
- Biochar;
- Soil carbon sequestration or enrichment;
- Ocean iron fertilization;
- Enhanced weathering and ocean liming or alkalinization;
- Direct air capture;
- Blue carbon and seagrass;
- Ecosystem restoration;
- Space mirrors;
- High altitude sunshades;
- Stratospheric aerosol injection;
- Cirrus cloud thinning;
- Marine sky or cloud brightening;
- Albedo modification via human settlements;
- Albedo modification via grasslands and crops;
- Albedo modification via deserts;
- Albedo modification via clouds;
- Ice protection.

We recognized that this explorative mapping is based on propositional knowledge under conditions of deep uncertainty, and that the "justified belief" of our experts can be called into question (Aven, 2016; Hansson & Aven, 2014). Accordingly, our recruitment and sampling of experts focused on a mix of advocates and critics of these different climate geoengineering options, to ensure a diverse and often antagonistic spread of perspectives. To ensure the credibility of our knowledge base, 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 10 years (from 2011–2020). Many are foundational thought-entrepreneurs in carbon removal and solar geoengineering assessment, policy, and technological development, and we took care to include individuals with expertise in both in view of the historic debates on what constitutes "climate geoengineering."

TABLE 2 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 geoengineering industry or research community	881
Average years spent in the geoengineering 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

Our engagement technique of semi-structured interviews asked participants a set of standard inquiries while also allowing 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 their potential consequences) as well as how they intersect with one's perceptions, beliefs, and values. Such an interview process also 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 conducted 125 individual interviews over the course of May to August 2021. We explicitly asked, among other questions, "What risks does the deployment of these options entail" as well as "What types of tradeoffs may emerge with their deployment?" We left it to our respondents to self-define "risk," not least in order that they might better draw on their own "strength of knowledge" as experts in the topic. Whenever asked for clarification, we defined risk in a manner that was consistent with the responding expert's perceptions of undesired and unintended consequences, in line with Society of Risk Analysis convention (SRA, 2015).

Table 2 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 interviews with members of civil society and nongovernmental organizations, governments, and commercial entities in the private sector, the sample is still strongly concentrated toward 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 given the sensitivity of the topic, the data from these interviews are presented here as anonymous with a generic respondent number (e.g., R010 for respondent 10, or R110 for respondent 110). First, anonymity was mutually agreed upon at the beginning of each interview to adhere to institutional review board guidelines at the 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 | Data analysis

In a rolling fashion, blocks of interviews were sent to a professional transcription service as they were completed. All returned transcripts were then checked and cleaned by the authors before being entered in the qualitative data-analysis program NVIVO. Making use of a three-part coding approach, every transcript was coded according to (i) the question to which a statement belonged; (ii) the theme or node that was mentioned; and (iii) lastly, the technology which was referenced. Regarding the second aspect of themes, there is a possible challenge of different coders linking a particular statement to a different theme or node, or using different language to describe a particular theme. For this reason, collaborative discussions among the authors preceded the start of coding, to set a shared set of expectations and strive toward a common terminology, with such discussions also repeated over the course of coding for 4 months as novel themes emerged iteratively as coding progressed. Through such discussions, for instance, the decision was taken to consider additional overarching themes when coding, such as "governance" and "social acceptance." Moreover, it became clear that respondent perceptions of "risk" began to converge in different clusters. More specifically, the recurring discussions were employed to purge the dataset of any inconsistencies in how a particular statement was coded by the authors and the existence of duplicate nodes for the same theme—notably, this involved a step-by-step discussion and examination of every node, how it was understood by the various authors, and the determination of if it should be merged with another (previously separate) node, with the new joint node serving as the object for subsequent coding. This process also took approximately a month.

In this fashion, the transcripts of all 125 interviews were coded into NVIVO, with new nodes (and sub-nodes) iteratively created as needed—that is, where further distinction in a concept emerged from the interviews. Ultimately, the final dataset thereby offers a structured coding of the interview data, along with numerical information like how many participants touched on a particular theme or technology or how often such a theme or technology was discussed in total. Responses to the question on "Risk," for instance, generated a total of 33 nodes such as "Changing weather, environmental, climate under uncertainty," "Geopolitics, security, and weaponization," and "Mitigation deterrence," with several having their own sub-nodes—or even sub-sub-nodes in the case of "Mitigation deterrence." Identifying the data relevant for examining a question such as "Risk-risk governance" is thereby facilitated and structured by, broadly, looking at responses coded to the overarching question of risk and, specifically, by looking at the collected responses coded under a particular node, notably, those specified to be relevant by the overarching theoretical framework.

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 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. Furthermore, many studies using qualitative data such as ours are not fully replicable, given that even repeating our research design precisely (but at a later time period) would face complications over the availability of experts (some might decline the invitation), the timeliness of answers (some might change their answers), and the adaptability of answers (some may have changed their views or thoughts since the time of the interview). There are also few incentives, and many disincentives, toward conducting replication studies in the energy and climate field or the behavioral sciences at large, some of them psychological (Lurquin & Miyake, 2017), leading some to acknowledge a widespread "replication crisis" (Everett & Earp, 2015; Huebner et al., 2017).

Another limitation is that respondents tended to be more openly critical about risks and tradeoffs in this context. This is *not* because the authors were selective about comments but, perhaps, because anonymity itself incentivized participants to be more forthcoming about problems and issues instead of strengths. Joubin and Siegrist (2020) found this to be common in studies of climate engineering given that the more risks people perceive, the less benefits they associate and thus come to collectively view such sociotechnical systems as having scarce benefits but ample risks.

Finally, we took an ethnographic approach that did not correct or problematize responses, so we present the views of participants, even if they may have had misperceptions on specific points. We map their social perceptions of risk or risk construction, rather than any objectively situated notion of risk. This still has intrinsic value given that "how people perceive the risks and benefits of a technology is relevant for its acceptance" (Joubin & Siegrist, 2020).

4 | RESULTS: RISK–RISK TRADEOFFS ACROSS THREE DIMENSIONS

Our results illustrate a complex and interlocking number of risks involved with climate geoengineering. As R087 put it:

> *Energy system transition is like a game of poker. We won't know which technology will work, we don't have good predictive skill for technologies like solar that are already a decade ahead. Think back: for technologies in the 1950s, how much predictive skill did we really have for 2050? Imagine how actors then would have distributed their bets. It's a monumental challenge.*

R009 agreed and admitted that:

> *There are huge investment risks with deploying climate engineering: where to put the money, where to put the finance, where to create markets. There are risks everywhere. It comes down to how you talk about technology transitions, deal with futures, anticipate problems and integrate them into policy development.*

R045 also spoke about how climate-engineering deployment was prone to "*a spectrum of risks*" that are "*big and complex and difficult to grapple with*."

It is with this appreciation for a broader consideration of risks that we discuss institutional and governance tradeoffs, technology and infrastructural tradeoffs, and behavioral and temporal tradeoffs in this section. As Figure 2 depicts, these options both interconnect within various dimensions of path dependence (some institutional or technical tradeoffs spill over into other institutional or technical tradeoffs) but also across the dimensions (institutional tradeoffs can affect technological and behavioral ones, and vice versa). We explore each of these specific tradeoffs in more detail in this section.

4.1 | Institutional and governance tradeoffs

Tradeoffs in this dimension involve institutions and governance (broadly conceived), and center on business potential, scaling, misuse, and safety.

4.1.1 | Affordability versus business potential

The more affordable climate geoengineering technologies become, the more they are likely to be used, but at the same time, the cheaper they are, the less value there is for firms to capture, or motivation for incumbent firms to enter the market.

On the one hand, options need to be affordable and cost-effective to be taken up by climate. As R005 put it:

> *Direct air capture or bioenergy with carbon capture and storage will be attractive to investors and planners only if they make new green fuel at an affordable cost. Otherwise, it would be more economic just to use the zero-carbon renewable power, or the hydrogen, directly.*

R118 added that some particular "*low-cost*" and "*no-regret*" options include better afforestation, land use management, or ecosystem restoration to sink carbon dioxide. As they noted:

> *Our estimates of costs are that it is tremendously affordable to do these kinds of interventions. You are talking about $1 per person per year.… Even a farmer in Bangladesh is not going to blink if you say to him, "You can protect your land from flooding at that kind of a price range."*

However, the more affordable such options become, the less money there could be for incumbents to enter the market or for businesses to make viable profits compared to other areas of the economy they could invest in. Moreover, the more costly climate geoengineering options are, the more learning that can be justified and R&D claimed as needed. Hence other respondents spoke about how expensive and unaffordable many options currently are, with R003 noting that "*it costs $430 million alone to save the Great Barrier Reef in Australia with a small amount of marine cloud brightening; the amounts of funding needed for such options can be staggering*." R047 agreed and believed that "*high-quality negative-emissions technologies will need massive investments, probably as high as $1000 per ton given that they are fighting the second law of thermodynamics*." R075 estimated that even the cheapest solar geoengineering options would cost at least "*$10 billion per year for every 0.1 change in degrees C*;" the most affordable carbon dioxide removal and direct air capture methods would likely cost "*trillions of dollars for ever*." These statements all challenge the belief that options are affordable and could operate competitively without strong subsidies and monumental financial support from governments.

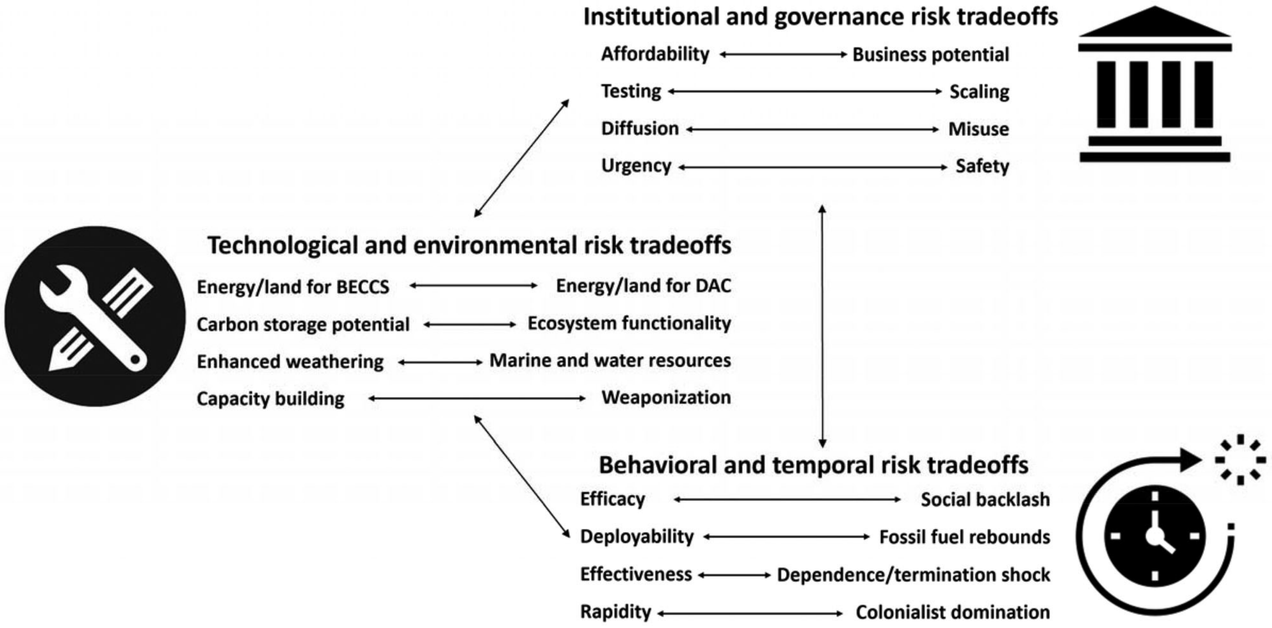

FIGURE 2 Institutional, technological, and behavioral tradeoffs in climate engineering deployment. *Source*: Authors. Note: The figure illustrates exemplary examples of risk–risk tradeoffs, and is not exhaustive. BECCS = bioenegy with carbon capture and storage; DAC = direct air capture

4.1.2 | Testing versus scaling

Current geoengineering experiments are usually piloted and implemented at very small scales to minimize risk—making them safer for the environment—but this also makes it more difficult to scale up such experiments or to predict impacts at larger scales. Small-scale experiments would have no measurable effect on the climate or atmosphere, but large experiments extending up to many kilometers in altitude or over vast areas of land would of course pose greater risks but also increase scientific understanding considerably (Long et al., 2015).

For instance, many advocates of geoengineering argue that experiments must be done first at a smaller scale to minimize risks. R056 explained that such small-scale experiments are also a clever way to hedge risk:

> *For climate geoengineering to work, the research community needs small-scale testing, coordination, innovations in multiple technologies at once. For stratospheric aerosol injection in particular, a large number of small modifications are required to overcome problems with desired size distribution, testing, scaling, optimizing, and nozzle-sizing. We need these experiments to avoid future uncertainties but also to help ensure we can make parallel advances in multiple technologies. It is a hedging strategy as well given that there may be no single salient, conspicuously effective innovation.*

R009 agreed and noted the necessity of how such experiments can contribute toward "deployment innovation":

> *We need innovations in experimentation, governance and accountability, innovations in deployment, rather than technical improvements themselves. It's an emergent area, many technologies are early-stage. We need small-scale, more open and inclusive experiments, as we need to learn not just about the technology, but deployment, social perceptions, social feedbacks. That's a missed part of much of this work, we don't even know the social barriers yet, don't know how people are going to respond, it is too lazy just to assume everyone will accept it because its climate related, or supposed to be good for the country.*

However, such small-scale experiments give rise to other risks such as limiting the predictive power of an experiment or even hiding particular impacts. R027 explained that:

> *Small trials obscure the knock-on consequences with actual deployment, and you're not sequestering any real carbon or reflecting sunlight at any scale that matters, making them almost useless.*

R011 commented that:

> *The scale of experimentation is completely mismatched with the scale of deployment, which*

> *will be immense. To put aerosol injection into context, humanity would need four or five Pinatubo eruptions a year every year to control the RCP 8.5 pathway, so five a year, 50 every ten years and the equivalent of 500 eruptions a century to produce the necessary tropospheric aerosols. It could also cause massive acid rain problems and black soot distribution. And then you still need to invent airplanes that can get into the stratosphere and have enough of them.*

R062 concurred and stated that "*planetary-level solutions require planetary-level effort, need to innovate at bringing technological capabilities, financial resources, and political legitimacy together, and you can't do that with small experiments*."

4.1.3 | Diffusion versus misuse

Accelerating innovation and deployment in geoengineering would undoubtedly improve performance and make such options cheaper, but the cheaper they become, the more problems of control arise because geoengineering options become more accessible to nonstate actors including rogue nations or even terrorist groups.

For example, R081 expressed concern that if options get affordable enough, "a *capitalistic dictator like Bill Gates or Elon Musk could decide to deploy at a moment's notice, dictating for all of humanity a pathway for climate protection*." R040 also identified blackmail as a real possibility with negative-emissions options, as malign actors could "*threaten to release all of the carbon from their reservoirs*" unless their "*demands were met*." R047 agreed and stated that: "*It's a nightmare, and it's a totally understandable nightmare … where this kind of research leads you either to semi-rogue action from hostile states or private-sector rich dudes with money that launch a program from their couch in Vanuatu*." R109 surmised that "*the special sauce of the private sector is to be ruthless and quick and that's not a good prescription for things that have, potentially, such large consequences*."

A corollary of this argument is that centralized control and political systems could result from quick deployment, but this would make diffusion less democratic and more difficult to reverse. R075 noted an explicit tradeoff between less democratic actors deploying easier and more quickly, but also then being prone to misuse and social resistance. As they said:

> *Coordinating geoengineering globally has all of the same problems as climate-change mitigation. Coordination is slow. It's expensive. It has real problems relative to – and this is the "scientist's savior complex" here – the notion that all you need is a dozen people in a room figuring out how to save the world, as opposed to, basically, saying, "Hey, let's get all seven billion of us together, or 197 heads of state and the parliaments and so on, to get the right things in place, to move toward the right direction." But deployment could literally be one scientist and one government just solving climate change for the rest of us, imperfectly, of course, and doing it quickly – versus doing the broad-based, bottom-up, if we get lots of people together to do the right thing sort of action.*

4.1.4 | Urgency versus safety

As a final institutional tradeoff, the urgency and immediacy of addressing climate change could generate a powerful incentive to deploy geoengineering options as soon as possible—but this also means there will be fewer tests, possibly less stringent safety protocols, and greater uncertainty about their impacts. In this way, urgency lies in direct tension to safety.

On the one hand, there is a strong sense of urgency and emergency behind fast deployment, especially to offset potential tipping points in the climatic system or to shave emissions in the near term. As R017 put it:

> *Immediate deployment is often spoken about as a way to achieve peak shaving: it's more temporarily shaving global warming above some threshold. In the prospect of the larger scale, CDR can bring down this overshoot warming, but that comes only later. It's possible, also it's very beneficial, but at the same time, it comes with the risk that, if you bet on the SRM just working as a temporary solution, for buying time, you also need to be open to losing opportunities and using SRM for quite a significant time, maybe indefinitely.*

The "peak-shaving" potential of both carbon dioxide removal solar geoengineering has been documented in the literature as well, with studies noting that earlier and less intensive use could "*shave the peak off projected near-term heading*," helping buy time for mitigation to be ramped up and reducing the cost of a global transition to low-carbon energy (Parson, 2014). R071 added that "*this is why solar geoengineering and carbon capture and storage are so nicely used together, because one offers fast temperature reduction and the other fast storage and removal of carbon, these are the best shots we have in terms of emergency break-glass and deploy soon options*."

On the other hand, deploying quickly and urgently could worsen risks related to unforeseen impacts, cost overruns, and more severe impacts to the environment. As R081 articulated:

> *The international community simply lacks the proper governance regimes or protections to do climate engineering quickly but safely. Scale is more a curse than a blessing in this context, because what you gain in economies of scale,*

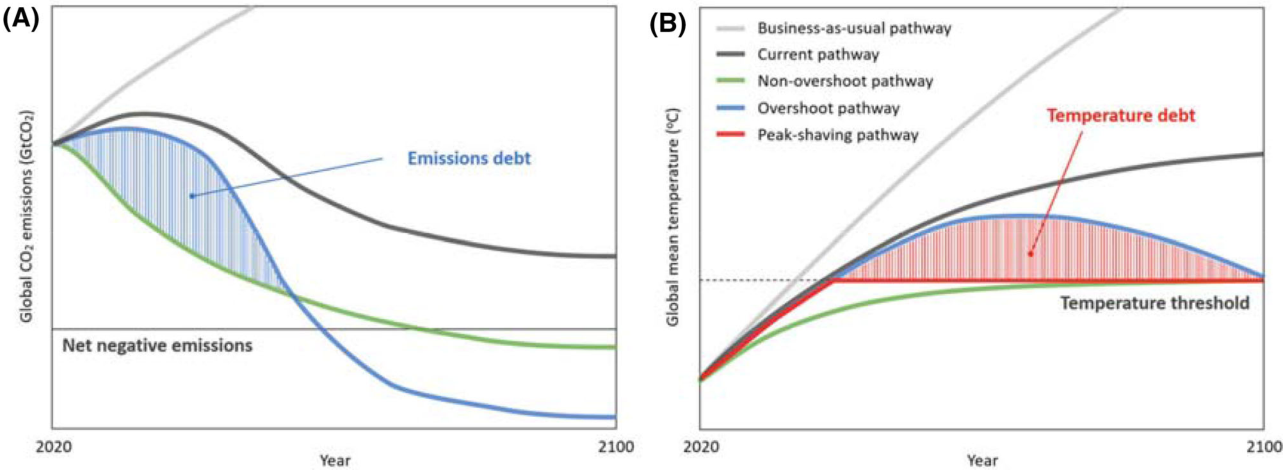

FIGURE 3 Potential emissions and temperature debts accumulated by a peak-shaving climate strategy. *Source*: Asayama and Hulme (2019). Panel A depicts a potential emissions debt accrued by negative-emissions technologies that must be paid off at a later date; Panel B, a temperature debt accrued from the temporary masking of warming from excessive emissions, or an overshoot pathway

> *the traditional advantage after the World War II period, has now reversed exactly into the opposite. Deploying urgently at scale means lumpiness, high complexity, persistent cost overruns. It means very structured ways of building technologies and operating technologies, at odds to value systems of pluralistic, cooperative society with feedbacks, pluralistic and diverse decision-making process, granular technologies that you can more easily control.*

According to this logic, deployment done quickly could result in humanity having to coexist with large monolithic technologies, with no endogenous capabilities, that future generations will have to cope with. Moreover, the peak-shaving strategy is not risk free, as prolonged peak-shaving could place the world in a "double debt" of emissions as well as temperature (see Figure 3, Asayama & Hulme, 2019).

4.2 | Technological and environmental tradeoffs

Tradeoffs in this dimension involve technologies and infrastructures and their risks to energy and land requirements, storage potential, water use, and the weaponization of options.

4.2.1 | Energy and land requirements for bioenergy versus direct air capture

Both bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) hold great promise for climate protection, but the insufficient availability of land and constraints on energy use may force hard choices between them. R005 spoke about these tensions explicitly:

> *BECCS and DAC both need vast carbon stores which we don't have yet. BECCS will need vast areas of biomass plantation. BECCs will need energy to run. There may be innovative solutions to these problems, though I can't personally see what can be done. The more you use BECCS, you reduce the energy and land available for DAC; and the more you use DAC, you do the same for BECCS.*

R103 confirmed that:

> *Bioenergy provides energy, but BECCS doesn't. Either BECCS is an energy penalty on bioenergy, as CCS is an energy penalty on fossil energy, or we are talking about the annexation of new land resources to extend the energy system so as to accommodate a less productive and less energy-efficient means of producing energy from bioenergy. So, the sort of system configurations in which you can imagine the addition of BECCS leads to more availability of energy, but that has a definite side-effect on the land use … and then BECCS could compete with the land available for DAC. We could need three times the land area of India to feed a BECCS system. The numbers for DAC add up to something like nine times the primary energy use of India. Where are we going to get all of the land or energy for either, yet alone both?*

R058 noted that "*BECCS processes would need large sources of energy … DAC processes are huge energy consumers too, making it difficult to scale up both.*" R093 also elaborated that: "*If you move to BECCS and DAC, it's clear they will both need a huge amount of energy or land, making them both controversial because of land use and* *biosphere integrity*." Respondents also spoke about how BECCS and DAC could compete for carbon storage capacity as well; R066 suggested that oil and gas reserves can store 1000 GT of carbon dioxide in total, and this limit could create real carbon dioxide storage constraints for CCS, BECCS, and DAC.

A final dimension to this tradeoff is that both BECCS and DAC can exacerbate air pollution close to where they are used—achieving climate protection but at the cost of degraded health. R018 said that:

> *The current evidence is that BECCS has quite high air-pollution impacts. That's something that people don't often talk about, but combusting biomass is generally quite a dirty fuel with generally quite high PM2.5 and PM10 emissions. Historically, it's vulnerable communities, lower socio-economic classes, often black, Asian, and minority ethnic communities, who are placed near big fossil-fuel plants. If you look at the correlation between deprivation and air pollution, often there's a very strong overlap.*

R029 noted that similar concerns arise for DAC:

> *With DAC, if you are putting in these massive installations to capture carbon, having big building construction going on, there is lots of potential for diesel fumes from trucks and stuff like that going in to build it. DAC facilities are not capturing everything. So I would worry about a community thinking, "This is going to clean up my air," when it is actually not. It is not doing the pieces of it. It is not getting the particular matter or whatever, that is affecting their kids' asthma.*

R032 added that BECCS and DAC could both generate unwanted and unintended effects on air pollution and local biodiversity.

4.2.2 | Carbon-storage potential versus ecosystem stability

This tradeoff concerns the ability for forests or ecosystems to storage carbon effectively (and over very long periods of time), contrasted with those ecosystems functioning healthily or normally. As R009 explained:

> *There are trade-offs in your forestation. Are you going for the most carbon efficient? Is your monoculture rapid and able to be scaled up via plantation planting? Or is it a lower density, slower-growing option which potentially consumes more land but is the most valuable for biodiversity? And then any nature-based solutions are vulnerable to the future impacts of climate change.*

R002 also spoke about how afforestation and ecosystem options "*need far more land and irrigation if you do it naturally without fertilizers, making it better for local ecosystems, but if you want to double or triple yields, you have to introduce nitrogen fertilizers, which are bad for the environment*." R010 added that another concern is whether you rely on fast-growing, genetically modified, perennial grasses that can be designed to consume less water or match a particular ecosystem—replacing natural crops with human designed ones—or instead use slower growing, naturally selected crops that do not need gene editing.

A final concern relates to the ability for land-based and ocean-based carbon dioxide removal options to rob nutrients from local ecosystems. R060 spoke about how:

> *Although there are some environmental co-benefits to carbon dioxide removal like stimulating fisheries and so on, in the surface waters there are other issues such as "nutrient robbing": removing nutrients that would otherwise be utilized at some other point in the ocean when those water masses move somewhere else. So, you could actually damage fisheries.*

Similarly, R060 commented about how:

> *Things like macro-agriculture, if you have very large-scale cultures of trees or crops, you're going to be taking nutrients out that were there … Any biomass-type technique that would need a massive amount of nutrients has potential, at least, to cause an issue with nutrient robbing.*

4.2.3 | Enhanced weathering versus water availability and quality

This technological tradeoff relates to the deployment of enhanced weathering and the resulting stress it would have on water availability and quality. According to R002:

> *Enhanced weathering is going to shift large amounts of mass from mines and the land to water. It will likely rival mining operations and land moving around the world, could become connected to mine tailings, with similar impacts to mining and agriculture on water systems.*

R041 noted that:

> *Rock weathering and marine alkalinization would, at the scale which the IPCC has discussed, result in 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 or processing of mining goods. What is the water demand? What is the land demand? What is the energy demand for all that? If you want to do that, not on land because land is limited, then you have 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. Which means a large-scale changing of the acidity of ocean water, which would kill the locally existing ecosystems. This is completely out of control because the substances would be transported by marine transport, which can change any time with a big storm or anything like that, so there is a lot of unpredictability in the impacts. And you have high energy consumption, probably a bad carbon balance in that with the current energy sources, you have unpredictable income from the marine sector, and you have significant biodiversity and water impacts in terrestrial ecosystems … When you have ever been to an area where they have a mining industry for granite or anything like that, you have experienced the enormous amounts of water that they need to keep the dust down, and still the enormous amounts of dust which are SPM10 [suspended particulate matter] particles, which affect air quality and human health. So water is a big problem for weathering.*

R022 concurred and noted that: "*This is why I say it really depends on the management practices…. You can just pump something into the ocean water and destroy something locally*." Enhanced weathering therefore could store substantial amounts of carbon but only by overstressing water resources.

4.2.4 | Capacity building versus weaponization

A final technological tradeoff relates to capacity. For some options such as sunshades or aerosols or even carbon-dioxide options, the more you distribute capacity and infrastructure, the more it might lead to weaponization risks or security threats. R070 stated that:

> *Options that depend upon the expansion of an aerospace or space industry are a security risk, as you are bringing high-tech space industries into countries that don't normally have them. Players gain new capabilities that they didn't have before, and these could spill-over into an arms race or new technology in the hands of new actors could become military or hostile, that could be a possibility. If a rogue nation develops launch systems, that opens a door to their launching new satellites or defense systems or even missiles, creating tensions.*

R010 also spoke about how, while solar-geoengineering techniques might not be realistic weapons in their own right, they could become "*coupled to weapons, by enhancing military capability, especially how much it would improve high-technology skills, skills that would be very useful for crossover impacts on military design*."

Meanwhile, carbon-removal infrastructures could come under direct attack. R081 notes that the coupling of digitalization with carbon dioxide-storage facilities could be prone to "*hacking*," and that "*I think the attack will not be physical…. I think the attack will be mostly on software so the systems might be hacked, and you might blackmail whatever, a company or government and say if you are not paying me, whatever, ten billion Bitcoins, I'm going to release ten gigatons of carbon in an instantaneous impulse from your reservoir*." Carbon-removal infrastructure could also be the subject of unintended or collateral damage in conflict. R055 argues that "*power plants and pipelines get attacked or destroyed all the time; I don't see why geoengineering infrastructure would be any different*." R100 concurs that "*carbon-storage reservoirs would also invariably exist in some conflict zones; all of this would create a security risk*."

4.3 | Behavioral and temporal tradeoffs

Tradeoffs in this dimension involve social behavior or issues of temporality and include social backlash, rebounds in fossil-fuel consumption, the risk of termination shock and even perceptions of colonialist domination.

4.3.1 | Efficacy versus social backlash

More effective climate geoengineering options would indeed be more efficacious at storing carbon or reducing global temperatures, but the more they are used, at least at the outset, the more people could take note and become frightened of them and begin to resist them. R011 even cleverly referred to this as the "sticky slope" problem of deployment:

> *Some options like stratospheric aerosol injection are downright scary and would require some frightening technologies to become a reality, things like the U.S. Navy using 16-inch guns to fire particles into the stratosphere or using drones to spray sulfur into clouds. The SCOPEX people couldn't even fly a single balloon in Sweden, this shows you how difficult it may be, it may be socially impossible to do this. Many opponents worry about a slippery slope to deployment. I think it will be the opposite: a sticky slope. The more we do some of these*

> *options, the harder it is socially and politically, preliminary deployment oddly reduces the probability of actually doing it.*

R003 also spoke about how for some options such as ocean iron fertilization, the more effective they are, the more socially controversial they become. Iron flakes that disappear in 2 weeks are mildly controversial but have a small effect on the climate. Buoyant flakes designed to stay in the ocean for up to a year have the potential to provide magnitudes of order longer climate protection, but would likely be even more strongly opposed. R020 spoke about another type of backlash that could occur due to the uneven and asymmetrical nature of climate protection offered:

> *The higher temperature reduction you go for, the more unlikely you are to have uneven impacts, especially among the poles or in particular regions. So the more you solve the climate problem with engineering, the more uneven and unjust the technology pathways become, and the more opposed or unacceptable they likely will be.*

R075 even quipped that, to some social actors, the further invention or refinement of climate geoengineering options have the same popularity as "*designing smallpox*"; they are perceived, rightly or wrongly, as so high risk that they could "*backfire and kill everything and everyone on earth*."

4.3.2 | Deployability versus fossil-fuel rebounds

While Section 4.3.1 is about the agency of actors and their potential to backlash socially against some deployment options, another risk concern is more structural, and it relates to the near-term embedding of fossil fuels within the broader economy or macrosocial systems. For instance, the more both carbon-dioxide removal or solar-geoengineering options are successfully deployed, the more they can be perceived as reducing the impacts of climate change, and thus the more some social actors may respond by increasing the use of fossil fuels or arguing that there are legitimate needs for further growth in fossil-fuel consumption. R016 spoke about how:

> *To me the real risks with geoengineering are not if it doesn't work, but if it does work, it starts to work really well. Then, there will be pressure to keep coal plants operating, to keep mines going, to keep fossil-fuel markets alive. It could also keep coal or gas or mines running, and thus can keep the jobs going, the skills, and avoid the need for all of these "Just Transition" compensation packages, as those communities all stay employed and supported.*

R085 agreed and noted that "*the deployment of climate geoengineering enables the continuation of profitable oil and gas enterprises longer than it might be otherwise possible*." R031 also framed such options only as "*temporary countermeasures*," sort of like "*an Air Bag in a car*." It can stop a single accident but will not reduce climate emissions or result in more sustainable behavior. As they went onto say:

> *The biggest risk is that by putting effort into climate geoengineering, there is the possibility that politicians think we can continue with our emissions. So it could lock-in unsustainable behaviour, and not reduce climate emissions.*

R009 also spoke about their worry that deployment would merely be "*a delaying tactic that doesn't solve anything, nor does it address the root causes of climate change or ocean acidification, which is possibly our greatest risk*."

In the extreme, deployment could even result in more dangerous (high-emitting) carbon behavior. R071 surmised 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, and even greater levels of emissions.*

R099 expressed concern that deployment "*could lead to a seriously dangerous delay of decarbonation*." R081 remarked that:

> *The most serious risk is that climate geoengineering delays or jeopardizes the transition to low-carbon energy. It kills all of the promising options we have in our hands, particularly social dimensions … these are now crowded out, with government attention, financial resources, and human resources taken away with the illusion that there is an easy fix, and we can continue for the next 100 years without having to change anything else.*

To experts of this perspective, climate geoengineering is "*the epitome of stupidity, repeating the same mistake again and again and expecting a different outcome*" (R81).

4.3.3 | Effectiveness versus dependence and termination shock

This tradeoff underscores the temporal tensions of deployment, and it involves that any effective deployment would create a risk of dependence in perpetuity, and an ensuring termination shock if humanity was ever unable to maintain the operation of that particular technological system (through accident, malice, or even social pressure to turn it off). R003 explained that:

> *Climate geoengineering has some huge downsides. Once started, 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.*

R004 added that "*maybe some climate engineering is an answer, but if you shock a system by stopping it suddenly, the risk of ecosystem wipeout is huge*." R020 spoke about not only the technical challenge of operating such a system, but the social and political challenge:

> *Whatever option you decide to deploy, you need to put a response system in place that will last for a few decades, maybe one or two generations, minimum, and that's a long time. And in that period, it has to continue. It cannot stop. It doesn't matter what the world economic, political, cultural outlook looks like. You still have to maintain this package and that itself is challenging.*

R022 added that "*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*." R084 framed this in temporal terms, noting that:

> *There's also the termination problem which, essentially, puts a load on future generations and increases their risk. So it's a transfer of risk from current generations to future generations.*

R101 lastly stated that both carbon-dioxide removal and solar-engineering options have the same risk of termination shock, given that:

> *If you think about SRM you are immediately buying carbon-dioxide-removal problems in as well, in a very fundamental way. Because if you speak about SRM, if you ever wanted to stop it, you would need to remove all the carbon you have emitted to actually be able to phase it out. So the question of SRM being able to resolve some short-term climate problems, or something, is insufficient if you do not have an exit strategy, because we do know the biggest risk is, basically, catastrophic climate change as a result of stopping it … This means that all future generations are stuck between a rock and a hard place. If you discuss feasibility of large-scale CDR, you would start deploying SRM before we know if large-scale CDR comes about.*

4.3.4 | Rapidity versus colonialist domination

Urgent deployment not only creates tradeoffs with safety (see Section 4.1); it can also create issues with fears of colonialism and technological domination between countries. R004 framed this in terms of climate geoengineering only propagating a new form of climate colonialism:

> *I think the challenge is, how do you predicate investment in transition and infrastructure and change without doing more harm? We saw that with REDD+. Despite the fact it was a great idea, it screwed up majorly. Climate engineering could do the same thing, fast deployment could become just colonialism writ large in some places.*

R084 added that:

> *There is potential for some of these techniques – and I'm thinking particularly here, of CDR techniques – to operate in parts of the world which are generally less economically developed. So there is potential for use of large land areas, sparsely populated, which often correlates with a low development index. So there could be benefits there that pass, economically. But there's also risk of the resource curse, where money flows to the elites in those societies, or corruption where benefits aren't actually what they're thought to be, because of poor governance. Then there's also a kind of almost colonialism, where more developed economies basically say, "Well, we don't want to do the hard work ourselves, so we'll shift it onto other people," who are less economically advanced.*

R064 also worried that:

> *The most basic risk is what you might think of as a climate colonialist approach to solar geoengineering, where a small set of powerful actors decide that we're going to do this, maybe for our own benefit. Maybe they even say, "It's for the benefit of developing countries," but it's still their decision, right? So, the physical impact is separate from this question of legitimacy and domination, where a small set of actors just shouldn't be making these sorts of global decisions on their own.*

This latter form of colonialism would even be perceived by those doing it as benevolent, on behalf of countries in the Global South who do not have the capacity or resources to do so—a tradeoff that could also accelerate the weaponization risks discussed in Section 4.2.

R103 emphasized that some patterns of colonialism and dependence need not be intentional. As they noted:

> *Generically, it would be those who were already most vulnerable who would still be the most vulnerable to some uneven impact of climate engineering, whether that be the change in rainfall patterns, or a change in rainfall seasonality, or whatever. If you're a subsistence economy, and they're subsistence populations, those things matter. There would still be a distribution of effects, and an unknowable one. It may be that we deliver climate protection which is not optimum for them but optimum across the planet as a whole.*

R119 added that:

> *It's pretty unlikely that the real, fundamental reason that climate engineering occurs or is being paid for is to benefit those who are already suffering and are going to suffer more under climate change. It's more to preserve the way of life of those who live in wealthy regions and to make sure that we don't suffer as much from climate change as would be the case.*

Essentially, this comment suggests that the outcome of sacrificing parts of the Global South might be inevitable, if indeed more powerful actors could be able to prove that it resulted in greater climate protection.

5 | CONCLUSIONS

We offer four conclusions for policy, deployment, and future research concerning risk management as well as climate geoengineering. First, and as underscored by Figure 4, climate geoengineering options most certainly require adaptive risk management, as risks and tradeoffs intersect within and across our three dimensions of institutions and governance, technology and the environment, and behavior and temporality. The path dependence these new technologies can exert is thus uncertain and an active and contested process. Moreover, the way that risks cut across categories is deserving of particular attention, for how this helps to identify areas of "high" risk connection. For example, the more affordable options become (Section 4.1), the more often that other risks relating to testing and scaling, diffusion and misuse, land use, weaponization, fossil-fuel rebounds, or colonialist deployment occur (Sections 4.2 and 4.3), because it is easier for institutions to afford them and easier for firms or countries to adopt them. The more some technologies are potentially misused, the more other risks relating to weaponization (Section 4.2) or the potential for social backlash and stigmatization (Section 4.3) could occur. The more actors focus on urgency and rapid deployment, the more risks related to experimentation, scaling, and weaponization could also occur (as technologies could diffuse widely outside of established norms or governance protocols). The technological and environmental risks for BECCS, DAC, enhanced weathering, and even afforestation and ecosystem restoration mentioned in Section 4.2 could thus exacerbate not only interlinkages in terms of environmental degradation (energy use and air pollution, land use, water pollution, nutrient robbing) but also negatively inflame perceptions of social backlash or colonialist domination (Section 4.3), which could in turn have environmental triggers. Conversely, social stigma and perceptions of backlash or colonialist domination could make deployment more expensive and slower or more difficult to proceed with experiments (affecting aspects in Section 4.1) or more prone to capacity-building that could elevate risks of weaponization (affecting Section 4.2). Finally, both fossil-fuel rebounds and termination shocks (Section 4.3) could worsen many of the drivers behind environmental destruction and technological disruption (Section 4.2). Thus, Figure 4 negatively suggests that addressing some bundles of risk will only spillover and generate risks in other areas; all options interconnect with at least some other risks, creating a nested hierarchy of tradeoffs, a veritable basket of risk versus risk potential.

Positively, however, there is the potential for mitigating risks in some dimensions to help alleviate risks in others, that is, if more progressive and adaptive risk management is undertaken. For example, mitigating some of the environmental risks connected to land, energy, ecosystem stability, or water availability and quality (Section 4.2) would also help mitigate perceptions of social backlash (Section 4.3) or address issues of scaling and safety (Section 4.1). Similarly, undertaking slow, sound, inclusive, bottom-up governance approaches (Section 4.1) would have positive spillovers into improved technological and environmental design (Section 4.2) along with minimizing any potential behavioral and temporal tradeoffs (Section 4.3). In other words, the interconnectivity of risks can be both a strength or a weakness, depending on how one approaches such issues and the level of thought and preparation one commits to doing so.

Second, given the scale and scope of risk–risk tradeoffs, one cannot just "add up" the mitigation or carbon storage potential for the various options examined here, as they invariably compete for land, energy, water, capacity, policy attention, experimental governance, and other resources—and, what is more, introduce risks that can ultimately undermine institutional stability, technological performance, and social behavior. This is confirmed in some of the literature which is critical of negative-emissions pathways, which highlights in particular that the deployment potential of individual options cannot be additively combined and that scenarios deploying portfolios of multiple options tend to show decreasing rates of diffusion the more options are added together (Fuss et al., 2018). In simpler terms, options have more diminishing returns when utilized as part of a portfolio.

Third, although our contribution to the risk literature is primarily and critically empirical, our evidence does support the complex adaptive conceptualization of risk described

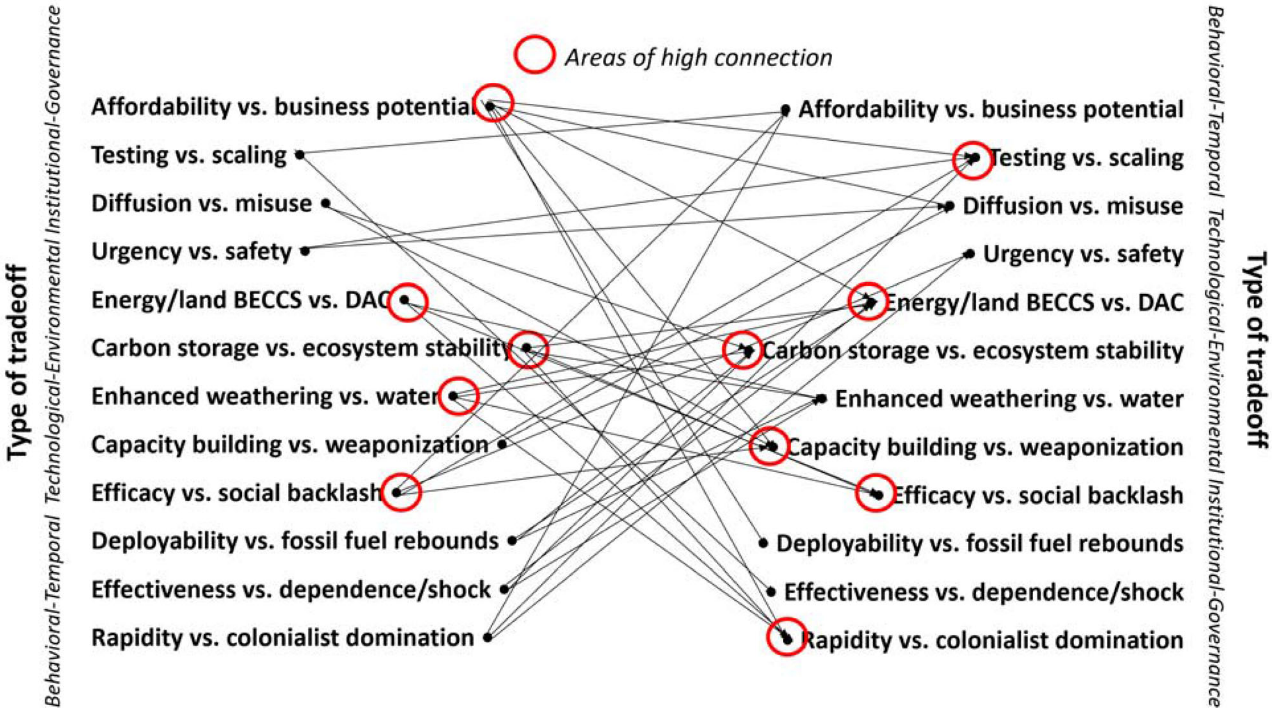

FIGURE 4 Visualizing risk–risk tradeoffs and high areas of connection in climate geoengineering pathways. *Source*: Authors. Note: Lines are meant to illustrate a substantive connection between two different dimensions of risk discussed in Section 4, drawn from our expert interviews ($N = 125$) along with the authors' collective judgment. "Risk" refers to any unintended or unanticipated consequence or outcome (see Section 2.2 for more details)

in Section 2.2. Notably, climate geoengineering approaches threaten to compound four differentiated types of risk. It can result in the frequent occurrence of unfortunate consequences such as an accident during testing, improper assessments of safety due to the sense of urgency imparted by climate change, intentional misuse (e.g., terrorism), or acute termination shocks. These types of risks can be classified as fairly uncertain (of lower probability), but with a greater magnitude of impacts if they did occur (i.e., catastrophic rather than systemic). Conversely, climate geoengineering can also result in unwanted negative consequences that are fairly certain (of higher probability) but more chronic or systemic in their impacts. These include very likely negative impacts on land or water, or rebounds in fossil fuel consumption. Other types of risk are more cumulative—they operate more like the flipping of a switch or the crossing of a threshold, rather than a catastrophic event or chronic risks that recur but stay roughly at the same magnitude. Examples here would be the accumulated risks of a social backlash, of entrenching colonialism, or building capacity up to a point where weaponization becomes widespread. Finally, almost all of the risk–risk tradeoffs identified across all of our tradeoffs (institutional, technical, behavioral) involve differing conceptions of (or the contestation between) things that humans value: affordability versus safety, protecting land versus protecting water, protecting the climate versus protecting marginalized communities. Risks abound within and across climate geoengineering pathways and fundamentally relate to the probability and magnitude of possible consequences, the strength of knowledge which can be brought to bear as well as the potential to accumulate and conceptions of values which are hold.

Fourth and lastly, our study seriously challenges those arguments in favor of a "portfolio approach" (Reiner, 2016) or "cocktail approach" (Cao et al., 2017) whereby as many potential negative-emissions and solar-geoengineering options as possible are bundled together at once. In the context of climate-engineering technologies, a portfolio approach, if done poorly, risks endorsing a bundle of technologies randomly jumbled together rather than any coherent vision. If each specific option involves different dimensions of risk and incompatibilities, supporting some or addressing one set of risk threatens to erode another or unleash a new set of risk. Risks are never wholly eliminated, managed, or reduced, only shifted across time or redistributed across different actors. As a consequence, energy and climate research needs to urgently consider how to effectively manage or reduce risk–risk tradeoffs. Although our study offers insight into a broader collection of risks, complexities, and tradeoffs, it is only the first step toward more rigorously identifying technologies that could effectively complement, rather than contradict, each other in a low-carbon future. There are no inherently safe or risk-free climate geoengineering pathways; there are only gradations of exposure to different types of danger and risk.

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ANNEX I: LIST OF 125 SEMI-STRUCTURED EXPERT INTERVIEW RESPONDENTS

Name	Actor Type	Gender	Country	Institution
[Anonymous Aerospace Engineer]	Private Sector + Industrial Associations	Male	Germany	[Aerospace and space systems company focusing on integrated spacecraft]
Aganaba, Timiebi	Universities + Research Institutes	Female	USA	Arizona State University
Asayama, Shinichiro	Government + Intergovernmental Organizations	Male	Japan	National Institute for Environmental Studies
Bauer, Christopher Dean 'Casey'	Private Sector + Industrial Associations	Male	USA	Raytheon Space and Defense
Bazilian, Morgan	Universities + Research Institutes	Male	USA	Colorado School of Mines
Bellamy, Rob	Universities + Research Institutes	Male	United Kingdom	University of Manchester
Beuttler, Christoph	Private Sector + Industrial Associations	Male	Switzerland	Climeworks
Biermann, Frank	Universities + Research Institutes	Male	Netherlands	Utrecht University
Boettcher, Miranda	Universities + Research Institutes	Female	Germany	Institute for Advanced Sustainability Studies (IASS)
Brauer, Uwe	Private Sector + Industrial Associations	Male	Germany	Planetary Sunshade Foundation
Brickett, Lynn	Government + Intergovernmental Organizations	Female	United States	Department of Energy
Briggs, Chad	Universities + Research Institutes	Male	USA	University of Alaska, Anchorage
Brown, Marilyn	Universities + Research Institutes	Female	USA	Georgia Institute of Technology
Bruce, John	Private Sector + Industrial Associations	Male	Canada	Carbon Engineering
Buck, Holly Jean	Universities + Research Institutes	Female	USA	University at Buffalo
Burns, Wil	Universities + Research Institutes	Male	USA	American University
Caldeira, Ken	Universities + Research Institutes	Male	USA	Breakthrough Energy, Carnegie Institution for Sciences, and Stanford University, and Stanford University
Camilloni, Ines	Universities + Research Institutes	Female	Argentina	University of Buenos Aires (and Harvard University)
Carton, Wim	Universities + Research Institutes	Male	Sweden	Lund University
Centers, Ross	Private Sector + Industrial Associations	Male	Germany	Planetary Sunshades
Chalecki, Beth	Universities + Research Institutes	Female	USA	University of Nebraska Omaha
Chavez, Anthony E.	Universities + Research Institutes	Male	USA	Northern Kentucky University
Clarke, Leon	Universities + Research Institutes	Male	USA	University of Maryland
Clarke, William S. (Sev)	Private Sector + Industrial Associations	Male	Australia	Winwick Business Solutions
Cobo Gutiérrez, Selene	Universities + Research Institutes	Female	Switzerland	ETH Zurich
Cox, Emily	Universities + Research Institutes	Female	United Kingdom	Cardiff University
Creutzig, Felix	Universities + Research Institutes	Male	Germany	Mercator Research Institute on Global Commons and Climate Change (MCC)
Delina, Laurence	Universities + Research Institutes	Male	Hong Kong	Hong Kong University of Science and Technology
Di Marco, Leon	Private Sector + Industrial Associations	Male	United Kingdom	FSK Technology Research - Consultant
Dooley, Kate	Universities + Research Institutes	Female	Australia	University of Melbourne

Name	Actor Type	Gender	Country	Institution
Draper, Kathleen	Civil Society	Female	USA	International Biochar Initiative
Elliott, David	Universities + Research Institutes	Male	UK	The Open University
Erbay, Yorukcan	Private Sector + Industrial Associations	Male	United Kingdom	Element Energy
Felgenhauer, Tyler	Universities + Research Institutes	Male	USA	Duke University
Florin, Marie-Valentine	Universities + Research Institutes	Female	Switzerland	EPFL International Risk Governance Center (IRGC)
Forster, Piers	Universities + Research Institutes	Male	United Kingdom	University of Leeds
Frumhoff, Peter	Civil Society	Male	USA	Union of Concerned Scientists
Fuhrman, Jay	Government + Intergovernmental Organizations	Male	United States	Pacific Northwest National Laboratory (PNNL)
Fuss, Sabine	Universities + Research Institutes	Female	Germany	Mercator Research Institute on Global Commons and Climate Change (MCC)
Gambhir, Ajay	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Geden, Oliver	Government + Intergovernmental Organizations	Male	Germany	German Institute for International and Security Affairs (SWP)
Ghosh, Arunabha	Civil Society	Male	India	Council on Energy, Environment and Water (CEEW)
Grant, Neil	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Gruebler, Arnulf	Universities + Research Institutes	Male	Austria	International Institute for Applied Systems Analysis (IIASA)
Guillen Gosalbez, Gonzalo	Universities + Research Institutes	Male	Switzerland	ETH Zurich
Haberl, Helmut	Universities + Research Institutes	Male	Germany	BOKU Vienna
Haigh, Joanna	Universities + Research Institutes	Female	United Kingdom	Imperial College London / Grantham Institute
Hamilton, Clive	Universities + Research Institutes	Male	Australia	Charles Stewart University
Hartmann, Jens	Universities + Research Institutes	Male	Germany	University of Hamburg
Hawkes, Adam D.	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Healey, Peter	Universities + Research Institutes	Male	United Kingdom	Oxford University
Heap, Richard	Civil Society	Male	United Kingdom	Carbon Removal Centre, Foresight Transitions
Hepburn, Cameron	Universities + Research Institutes	Male	United Kingdom	Oxford University
Herzog, Howard	Universities + Research Institutes	Male	United States	MIT
Heyen, Daniel	Universities + Research Institutes	Male	Germany	TU Kaiserslautern (formerly ETHZ)
Heyward, Clare	Universities + Research Institutes	Female	Norway	UiT - the Arctic University of Tromso
Honegger, Matthias	Universities + Research Institutes	Male	Germany	Institute for Advanced Sustainability Studies (IASS)
Horton, Joshua B.	Universities + Research Institutes	Male	USA	Harvard University
Irvine, Pete	Universities + Research Institutes	Male	United Kingdom	UCL
Jinnah, Sikina	Universities + Research Institutes	Female	USA	UC Santa Cruz
Johnson, Les	Government + Intergovernmental Organizations	Male	USA	NASA Marshall Space Flight Center
Kammen, Daniel	Universities + Research Institutes	Male	USA	UC Berkeley

Name	Actor Type	Gender	Country	Institution
Karami, Khalil	Universities + Research Institutes	Male	Slovenia/Germany	University of Ljubljana/University of Leipzig
Karlsberg Schaffer, Madeleine	Civil Society	Female	USA	SilverLining
Keller, David	Universities + Research Institutes	Male	Germany	GEOMAR - Helmholtz Centre for Ocean Research Kiel
Keller, Klaus	Universities + Research Institutes	Male	USA	Penn State University
Kravitz, Ben	Universities + Research Institutes	Male	USA	Indiana University
Kruger, Tim	Private Sector + Industrial Associations	Male	UK	Origen Power
Kuswanto, Heri	Universities + Research Institutes	Male	Indonesia	Institut Teknologi Sepuluh Nopember
Lawrence, Mark	Universities + Research Institutes	Male	Germany	Institute for Advanced Sustainability Studies (IASS)
Lehmann, Johannes	Universities + Research Institutes	Male	USA	Cornell University
Lenton, Andrew	Government + Intergovernmental Organizations	Male	Australia	CSIRO
Lin, Albert	Universities + Research Institutes	Male	USA	UC Davis
MacMartin, Doug	Universities + Research Institutes	Male	USA	Cornell University
Mahajan, Aseem	Universities + Research Institutes	Male	United States	Harvard University
Malik, Abdul	Universities + Research Institutes	Male	Saudi Arabia	King Abdullah University of Science and Technology (formerly Grantham Institute)
McLaren, Duncan	Universities + Research Institutes	Male	United Kingdom	Lancaster University
Mengis, Nadine	Universities + Research Institutes	Female	Germany	GEOMAR - Helmholtz Centre for Ocean Research Kiel
Merk, Christine	Universities + Research Institutes	Female	Germany	Kiel Institute for the World Economy
Michaelowa, Axel	Universities + Research Institutes / Private Sector + Industrial Associations	Male	Switzerland	University of Zurich / Perspectives Climate Group
Montserrat, Francesc	Universities + Research Institutes	Male	Netherlands	Project Vesta / Royal Boskalis Westminster N.V.
Moore, John	Universities + Research Institutes	Male	Finland	University of Lapland / Arctic Centre
Moreno-Cruz, Juan	Universities + Research Institutes	Male	Canada	University of Waterloo
Morrow, David	Universities + Research Institutes	Male	USA	American University
Muri, Helene	Universities + Research Institutes	Female	Norway	Norwegian University of Science and Technology (NTNU)
Obersteiner, Michael	Universities + Research Institutes	Male	United Kingdom	Oxford University
Odoulami, Romaric	Universities + Research Institutes	Male	South Africa	University of Cape Town
Parker, Andy	Civil Society	Male	UK	SRM Governance initiative
Parson, Edward 'Ted' A.	Universities + Research Institutes	Male	USA	UCLA
Pasztor, Janos	Civil Society	Male	Switzerland	Carnegie Climate Governance Initiative
Pidgeon, Nick	Universities + Research Institutes	Male	United Kingdom	Cardiff University
Pinto, Izidine	Universities + Research Institutes	Male	South Africa	University of Cape Town
Pongratz, Julia	Universities + Research Institutes	Female	Germany	University of Munich

Name	Actor Type	Gender	Country	Institution
Preston Aragonès, Mark	Civil Society	Male	Norway	Bellona Foundation
Rahman, Mohammed Mofizur	Universities + Research Institutes	Male	Germany	TH Cologne - University of Applied Sciences
Raimi, Kaitlin T.	Universities + Research Institutes	Female	United States	University Michigan
Reiner, David	Universities + Research Institutes	Male	United Kingdom	Cambridge University
Renforth, Phil	Universities + Research Institutes	Male	United Kingdom	Heriot-Watt University
Reynolds, Jesse	Universities + Research Institutes	Male	USA/Netherlands	UCLA/Independent Consultant
Rickels, Wilfried	Universities + Research Institutes	Male	Germany	Kiel Institute
Robock, Alan	Universities + Research Institutes	Male	USA	Rutgers University
Rothman, Dale	Universities + Research Institutes	Male	USA	University of Denver
Rouse, Paul	Universities + Research Institutes	Male	United Kingdom	University of Southampton
Schleussner, Carl	Civil Society	Male	USA	Climate Analytics
Schmidt, Joern	Universities + Research Institutes	Male	Germany	Kiel Institute
Schneider, Linda	Civil Society	Female	Germany	Heinrich Boell Foundation
Scott, Vivian	Universities + Research Institutes	Male	United Kingdom	Edinburgh University
Simonelli, Lucia	Civil Society	Female	United States	Carbon 180
Smith, Pete	Universities + Research Institutes	Male	United Kingdom	University of Aberdeen
Smith, Steve	Universities + Research Institutes	Male	United Kingdom	Oxford University
Smith, Wake	Universities + Research Institutes	Male	USA	Harvard University
Spangenberg, Joachim	Universities + Research Institutes	Male	Germany	Sustainable Europe Research Institute SERI Germany e.V
Stephens, Jennie	Universities + Research Institutes	Female	USA	Northeastern University
Stoefs, Wijnand	Civil Society	Male	Belgium	Carbon Market Watch
Sugiyama, Masahiro	Universities + Research Institutes	Male	Japan	University Tokyo
Sunny, Nixon	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Surprise, Kevin	Universities + Research Institutes	Male	USA	Mount Holyoke College
van Vuuren, Detlef	Government + Intergovernmental Organizations	Male	Netherlands	PBL Netherlands Environmental Assessment Agency
Vaughan, Nem	Universities + Research Institutes	Female	United Kingdom	University of East Anglia
Victor, David	Universities + Research Institutes	Male	USA	UC San Diego
Vivian, Chris	Government + Intergovernmental Organizations	Male	UK	GESAMP
Wagner, Gernot	Universities + Research Institutes	Male	USA	NYU
Wolske, Kimberly S.	Universities + Research Institutes	Female	United States	University Chicago
Wood, Robert	Universities + Research Institutes	Male	USA	University of Washington
Workman, Mark	Universities + Research Institutes	Male	UK	Energy Futures Lab, Imperial College London