Futures 133 (2021) 102806

Contents lists available at ScienceDirect

Futures

journal homepage: www.elsevier.com/locate/futures

Solar geoengineering: Scenarios of future governance challenges

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ARTICLE INFO

Keywords:
Scenarios
Climate change
Global warming
Geoengineering
Solar geoengineering
Carbon dioxide removal

ABSTRACT

In the face of increasingly clear climate-change impacts and continued inadequacy of efforts to reduce greenhouse-gas emissions and adapt to ongoing climate changes, increasing attention has been directed to geoengineering: deliberate large-scale interventions in the Earth's climate system to moderate global warming. Such interventions could reduce risks in novel ways, but are controversial because they present an uncertain, high-stakes mix of potential benefits and risks. Solar geoengineering poses especially acute international governance needs, particularly in the case of potential future demands to use it. Many aspects of geoengineering present deep, ill-structured uncertainties that carry high stakes for near-term decisions, and are thus suitable for exploration through scenarios. This collection of papers reports on a major scenario exercise examining governance challenges and potential responses for solar geoengineering, held at the International Summer School on Geoengineering Governance in Banff, Canada in 2019. This opening paper introduces geoengineering and the concerns it raises, particularly as they pertain to governance; reviews the design and use of scenario exercises to inform decisions under uncertainty, including their prior uses related to climate change and geoengineering; and outlines the aims, design, and process of this scenario exercise.

1. Introduction

This special collection examines the use of scenarios to explore the novel governance challenges posed by geoengineering—a set of potential technological responses to human-driven climate change that are experiencing a rapid increase in attention and controversy.

Anthropogenic climate change presents serious and growing risks to human welfare and the environment. The first line of response is to slow and stop the changes by cutting the emissions of carbon dioxide (CO_2) and other greenhouse gases that are driving climate change. Unfortunately, emissions cuts increasingly appear insufficient to achieve politically agreed targets or limit risks to manageable levels, even with sharply increased efforts (United Nations Environment, 2020). Adapting societies to a changed climate is a second high-priority response. As the limits to near-term risk reduction that can be achieved through mitigation and adaptation alone have become clearer, increasing attention has been directed to geoengineering, "the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming" (Shepherd et al., 2009, p. ix). Geoengineering is a contested term, in part

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https://doi.org/10.1016/j.futures.2021.102806
Received 10 February 2021; Received in revised form 6 July 2021; Accepted 13 July 2021

because it covers two distinct types of intervention, which are dissimilar in their mechanisms and their research and governance needs. Carbon dioxide removal (CDR) would capture this most important greenhouse gas from the atmosphere and sequester it in stable reservoirs underground, undersea, in biomass, or in materials (National Academies of Sciences, Engineering, & Medicine, 2019; National Research Council, 2015). Solar geoengineering (sometimes called solar radiation modification) would alter the Earth's radiation balance, typically by reflecting or scattering a small amount (up to around 1 percent) of incoming sunlight, to directly cool the Earth and thus counteract some of the heating and other climatic changes caused by elevated greenhouse gases (National Academies of Sciences, Engineering, & Medicine, 2021; National Research Councils, 2015).

Both types of intervention hold substantial potential to reduce climate-change risks in ways that emissions cuts and adaptation alone cannot, but both also present serious environmental, socio-economic, and governance challenges. CDR can offer significant contributions, either by offsetting some continuing emissions from recalcitrant sources or—if used at vast scale—by making net human emissions negative, drawing down atmospheric CO_2 concentrations toward previous levels. All identified CDR methods have significant diffuculties related to scale limits, environmental or socio-economic impacts, and/or cost. Yet the scenarios that achieve agreed targets limiting global-average heating to 1.5 or 2 °C above pre-industrial temperatures rely on extreme amounts of future CDR, several gigatons (Gt) removals per year after mid-century (Warszawski et al., 2021).

Solar geoengineering can also reduce climate-change risks in ways not possible using only emissions cuts, adaptation, and CDR, but does so imperfectly and temporarily and presents its own distinct limitations and risks. Some solar geoengineering approaches, by virtue of their apparent low direct costs and technical feasibility, high leverage, global impact, and persistent uncertainties, present novel and severe challenges to international governance, which appear to exceed the authority and capability of any existing international treaty or institution. In view of their high stakes and deep uncertainties that thwart conventional methods of planning and assessment, the governance challenges of geoengineering, particularly solar geoengineering, are well suited for exploration using scenario methods.

This special collection reports on a major scenario exercise examining governance challenges and potential responses for geoengineering, particularly solar geoengineering. The exercise took place over three days at the International Summer School on Geoengineering Governance, held in Banff, Alberta, Canada in August 2019. The exercise used four scenarios, prepared in advance to represent distinct challenges related to future deployment of solar geoengineering. For each scenario, two parallel groups of participants developed governance proposals to address the specified challenge, "stress tested" these proposals, responded to the stress tests, and reflected on implications for near-term governance-related decisions.

This article opens the collection and provides background on geoengineering and the associated debates; on the uses, potential contributions, and limits of scenarios; and on the context and design of the exercise. The four papers that follow, each authored by members of the participant groups that worked with one scenario, discuss the scenarios, groups' governance proposals, and the identified limitations and potential pitfalls of those proposals (Belaia, Borth, & Weng, 2021; Dove, Horton, & Ricke, 2021; Pasek, Morrow, Lee, & Felgenhauer, 2021; Schenuit, Gilligan, & Viswamohanan, 2021). In the closing paper, we synthesize the experiences from the exercise and draw cross-cutting observations, both substantive ones on geoengineering's governance challenges and potential responses, as well as methodological observations on scenario-based methods' potential contributions to managing such high-stakes, long-range governance challenges (Parson & Reynolds, 2021).

The rest of this introductory paper proceeds as follows. Section 2 introduces geoengineering and its concerns, particularly as they pertain to governance. Section 3 reviews the origins, uses, and principles of scenarios and related exercises. Section 4 outlines the prior uses of scenarios in studies related to geoengineering. Section 5 describes the aims, design, and process of this scenario exercise and the four specific scenarios, whose implications are explored in more detail in the papers that follow.

2. Geoengineering

There is a large and growing gap between agreed climate targets and present commitments and actions to cut emissions. While holding global-average temperature well below 2 °C above the pre-industrial level, as in the Paris Agreement, would require emissions to decline linearly to zero by about 2070 (Intergovernmental Panel on Climate Change, 2018), current national pledges—if met—allow emissions to decrease only slightly through 2030 (Climate Action Tracker, 2021). Moreover, a survey of energy experts found that they expect world emissions to remain above today's levels through 2100 (Ho, Budescu, Bosetti, van Vuuren, & Keller, 2019). Such an emissions trajectory would likely lead to global-average heating of around 3.0–3.5 °C by 2100, which would bring increasingly severe impacts and disruptions.

As the severity of probable climate impacts has become more evident and widely known, and the shortfalls of mitigation and adaptation efforts grown larger, potential geoengineering interventions have become more prominent and controversial. These could reduce climate-change risks in novel ways, while also presenting an uncertain, high-stakes mix of potential benefits and risks. The contested term "geoengineering" is used to cover two quite dissimilar types of intervention in Earth systems, CDR and solar geoengineering. While these both represent intentional interventions in large-scale environmental processes, they differ widely in their mechanisms of operation, potential contributions, limits, risks, governance challenges, state of knowledge, and research and development needs.

Even within each broad type there is substantial variation among particular methods of intervention. Currently identified CDR methods vary widely in knowledge and technological maturity, with most appearing to carry significant limits or risks related to saturation of sequestration reservoirs, environmental and socio-economic impacts, scalability, or cost (National Academies of Sciences, Engineering, & Medicine, 2019; National Research Council, 2015). Despite these limitations, most present climate-change scenarios rely on rapid expansion of CDR. Almost all scenarios that would likely meet the Paris 2 °C goal presume multi-gigaton removals after mid-century, as do virtually all scenarios that achieve the more ambitious 1.5 °C goal. Cumulative removals under both targets range from hundreds to more than a thousand Gt by 2100 (Intergovernmental Panel on Climate Change, 2018). Proliferating "net-zero emissions" targets by governments and corporations all rely, explicitly or implicitly, on large-scale CDR (Darby, 2019; Rogelj, Geden, Cowie, & Reisinger, 2021). This extreme reliance on uncertain future technologies carries risks that are not yet adequately recognized (Anderson & Peters, 2016). A substantial contribution from CDR appears both necessary and likely, but this will probably come from coordinated use of multiple methods and will require support from public policies and expenditures. Large-scale CDR will pose international governance challenges related to reliably monitoring removal and storage, allocating credit for removals without double-counting, managing site-specific and larger-scale risks, equitably sharing benefits and burdens, avoiding imprudent over-reliance that might undercut needed emissions cuts, and controlling systemic interactions, particularly in complex integrated systems that use removed carbon in building materials or enhanced oil recovery.

Solar geoengineering covers a less heterogeneous group of intervention methods. Those now being prominently discussed include spraying a fine mist of reflective aerosols (very small solid or liquid particles) in the stratosphere to mimic the natural cooling effects of some volcanic eruptions, and spraying seawater into the marine boundary layer to make low-elevation clouds denser and whiter (National Academies of Sciences, Engineering, & Medicine, 2021; National Research Councils, 2015). Solar geoengineering appears capable of limiting climate-change risks in ways that other responses—mitigation, adaptation, and CDR—cannot. This is mainly due to its potential for rapid reduction of global-average temperature, on time-scales of about one year, allowing it to serve as a powerful complement to other climate responses (Kravitz, MacMartin, Leedal, Rasch, & Jarvis, 2014). For example, one widely discussed ideal for integrating all potential climate responses—as shown in Fig. 1—includes incremental, temporary deployment of solar geoengineering, to limit near-term climate change while large programs of mitigation and CDR are scaled up, followed by a gradual phasedown as these other responses return the climate to some agreed safe state..

Solar geoengineering also, however, carries important limitations and risks. It can only imperfectly offset some of the environmental harms caused by elevated greenhouse gas concentrations. It may also carry significant environmental impacts, possibly including delaying recovery of the stratospheric ozone layer (Robrecht, Vogel, Tilmes, & Müller, 2020). Although climate-model studies suggest that well designed, moderate solar geoengineering interventions may reduce climate change quite uniformly across major world regions with modest new environmental impacts (Irvine & Keith, 2020; Kravitz et al., 2020), these results are not yet conclusive. In view of its many potential limitations and risks, solar geoengineering can at most complement emissions cuts and other responses, not replace them.

The strongest concerns raised by solar geoengineering are not geophysical or technical in character, but social and political. These pertain to how it might be used, under what conditions, under whose control, with what goals, and with what broad social and political consequences. The apparently low direct cost (Smith, 2020) and ease of implementing stratospheric aerosol injection put it, in principle, within the capabilities of multiple actors, raising concerns about unauthorized or unilateral use (Barrett, 2014). Whether by one or more world powers or by coalitions of smaller states, such use would raise risks of inequitable implementation, international destabilization, and conflict (Halstead, 2018). Any use, whether based on a global consensus or as action by smaller groups, could be blamed for subsequent damaging extreme weather or climate-related events, regardless of their actual cause. The most widespread and influential concern is that developing or using solar geoengineering may tempt policy-makers to overlook its limitations and rely on it excessively. Such over-reliance, as may already be occurring in the case of CDR, could further weaken the already inadequate political support for essential efforts on mitigation and adaptation (Lin, 2013). Moreover, if high-intensity use of solar geoengineering were suddenly stopped and not promptly resumed, the previously masked global heating would appear rapidly and with severe impacts (Trisos et al., 2018). Counter-arguments and potential correctives to each of these concerns have been proposed (Horton & Keith, 2019; Parker & Irvine, 2018; Rabitz, 2016; Reynolds, 2015), but none of these issues is clearly and confidently resolved.

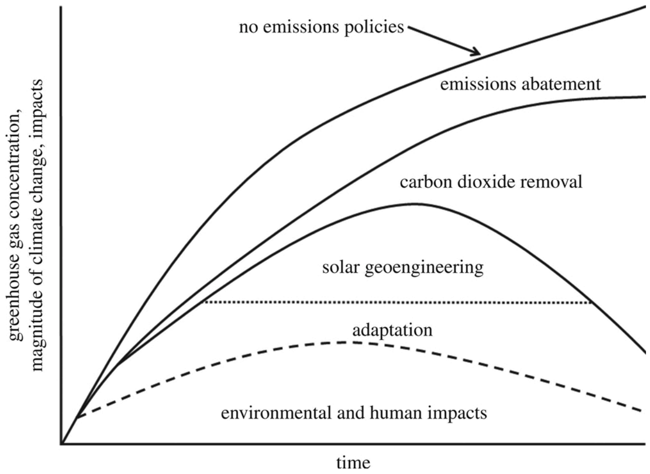

Fig. 1. A schematic of complementary responses to climate change, often called "the napkin diagram." (originally in Long & Shepherd, 2014; reproduced from Reynolds, 2019b).

A clear implication of these concerns is that solar geoengineering presents novel and acute needs for international governance (Currie, 2018; Parson & Ernst, 2013; Reynolds, 2019a). In terms of functions, governance needs will include the ability to make competent, prudent, and legitimate decisions regarding whether, when, and how interventions may be conducted; to competently execute any interventions so authorized; to effectively integrate advancing scientific and technical knowledge into these decisions; to monitor interventions and consequences, and adjust or stop them as needed; to address claims that interventions have caused harm and provide appropriate compensation; to avoid and manage associated conflicts; and to handle interactions with other forms of climate policy so as to promote, not hinder, an effective overall climate response. No existing international body or treaty has the formal legal authority and the technical and administrative capacity to meet these governance requirements. Despite widespread calls for early consultations to consider governance needs and potential responses (Parson, 2017; Shepherd et al., 2009), governments have been reluctant to engage the issue (Jinnah & Nicholson, 2019), or even to expand research. It has been suggested that research and governance should co-evolve adaptively, and that early development and consultation on steering research could provide early steps to longer-term governance robust enough to handle deployment proposals (Long & Parson, 2019).

The present lack of governance-building initiatives, and national governments' limited attention and willingness to take leadership, contribute to a potentially severe concern about solar geoengineering: that it may come suddenly onto international decision agendas, as a geopolitical crisis triggered by some proposal or demand to use it (Buck, Geden, Sugiyama, & Corry, 2020; Corbett, 2021). Such a crisis could be especially dangerous if it occurs without either the prior research needed to understand potential intervention methods, contributions, and risks, or the prior consultation and planning needed to develop governance approaches, shared knowledge, and norms.

Various potential types of geopolitical crisis from solar geoengineering have been proposed. These have certain commonalities, particularly in the background conditions that set the stage for the hypothesized crisis. The narratives typically assume that climate change and impacts have continued to grow more severe. This trend is most often attributed to weak mitigation efforts, but it could also arise from unfavorable resolution of climate uncertainties even under low emissions trajectories. Against this background, hypothesized crises typically propose that mounting climate impacts generate demands for corrective action in places most severely affected, but that prior delays in mobilizing effective action have made it impossible to stop the harms quickly enough through mitigation, adaptation, and CDR, even with rapidly intensified efforts (Michaelowa, 2021).

Beyond these broad commonalities, there are many possible ways such a crisis could arise. Differences among these may be important in determining the severity and character of the resultant threats as well as the promise and risks of alternative responses. For example, a solar geoengineering challenge could take the form of a demand for a deployment program, an announcement that one is planned or has already begun, or a charge that someone else has started one—perhaps coupled with a claim that the alleged intervention is responsible for some observed destructive weather or climate event. A challenge might be triggered by a wide range of actors, including national governments of widely varying global stature and power, development status, and climate vulnerability, acting alone or in concert; or through coordinated action by coalitions of state and non-state actors. It could occur under wide-ranging levels of knowledge, global governance capacity, and other background conditions.

While these uncertain prospects all pertain to future events—maybe ten years from now, maybe thirty—they may have important implications for near-term decisions. Large uncertainties in how much disruption and conflict a future solar geoengineering challenge may cause would increase the value of an early start to both research and governance consultations, particularly if different methods or deployment patterns seem able to make large differences in the distribution of risks and benefits among world regions. Even if early consultations do not yield formal agreements or widely recognized authorities, they could still increase understanding of the nature and dynamics of potential challenges, as well as shared knowledge, norms, and trust.

Gaining more insights into uncertainties related to the likelihood, risks, and benefits of potential future interventions can also inform near-term decisions on other climate responses, which clearly interact with solar geoengineering events and decisions. Interactions of solar geoengineering with mitigation have been widely noted, while those with adaptation are more recently identified (Buck, Furhman, Morrow, Sanchez, & Wang, 2020). On the former, the present research literature and policy debate make two major points, which have generated some confusion: in particular, these have been taken to contradict each other, when in fact they do not. First, in models that assume an optimal response to climate change, adding solar geoengineering to the set of potential response options, and assuming safe and effective methods are available, reduces the optimal level of other responses, including emissions cuts (see Harding & Moreno-Cruz, 2016). These assumptions, however, are both strongly violated in the present climate debate. Solar geoengineering research does not yet give confidence that safe and effective interventions will be available, and efforts on the other, first-rank climate responses are starkly inadequate. This state of affairs underlies the second point. Under these conditions, using solar geoengineering, perhaps even researching it, may tempt decision-makers to rely on it excessively and uncritically and thus weaken support for mitigation even further. This potential displacement of needed mitigation is the strongest and most prominent concern raised about solar engineering: indeed, analogous weakening of mitigation effort may already be occurring from present enthusiastic promotion of CDR (for a speculative estimate, see McLaren, 2020). Although this is a plausible concern about solar geoengineering that would have serious implications if it operated strongly, it is not clear that the dynamic would actually proceed this way. There are also plausible claims, and some indirect evidence, that the effect of solar geoengineering could act in the opposite direction, catalyzing additional mitigation (Reynolds, 2019a, pp. 37–40). Serious critical study of solar geoengineering might identify additional limitations, risks, and governance challenges, and thus help to restrain naïve optimism and over-reliance (e.g. Dai, Weisenstein, Keutsch, & Keith, 2020). Such investigation could also credibly signal the gravity of climate-change risks and thus galvanize support for all responses, including strengthening presently inadequate efforts on near-term mitigation, adaptation, and CDR. At the moment, the specific nature of potential solar geoengineering methods, their effects, the ways they might be used, social and political reactions, and interactions with other climate responses—and thus the implications for near-term actions—are all deeply uncertain.

3. Scenarios: methods, uses, contributions, and limits

Scenarios are descriptions of potential future conditions, created to inform planning and decision-making on issues marked by deep uncertainty (Amer, Daim, & Jetter, 2013; Parson et al., 2007; van der Heijden, 2005). They can include both qualitative/narrative and quantitative elements and can vary widely in their subject-matter, time-horizon, form, scale, complexity, intended audience, and use (Godet, 2000; Schnaars, 1987; Selin, 2006; van den Berg, Scholten, Schachter, & Blok, 2021; Vervoort, Bendor, Kelliher, Strik, & Helfgott, 2015). Although similar devices were employed earlier, the formal use of scenarios to inform decisions emerged in nineteenth and early twentieth century military planning (Brewer & Shubik, 1979). Since the mid-twentieth century, applications of scenarios have broadened to encompass geopolitical analysis, corporate strategic planning, and diverse policy areas with long-term consequences—including, since the early 1990s, climate and other forms of global environmental change (O'Neill, Pulver, VanDeveer, & Garb, 2008; Parson et al., 2007; Sala et al., 2000; Schwartz, 1991; Swart, Raskin, & Robinson, 2004; Wilkinson & Eidinow, 2008; Wodak & Neale, 2015).

Scenarios are used to represent uncertainties that are judged important for decisions, but for which reliable knowledge or more bounded analytic depictions—such as causal models, point projections, or quantitative probability distributions (even as subjective judgments)—are not available. Scenarios thus combine elements of knowledge, expert judgment, and speculation. Rather than creating new knowledge, scenarios are tools for the organized and explicit structuring of available knowledge, integrating it with judgment and speculation, when more precise or better validated representations are not available.

Scenarios do not predict the future and thus cannot provide confident or specific guidance for action. Yet they do offer several important benefits to decision and planning processes. Scenarios can shake up over-confident reliance on presumptions that current conditions or trends will continue, thereby expanding the scope of recognized uncertainty. They can broaden the set of potential actions considered, with associated risks and opportunities. They can provide insights into causal structures, by facilitating explicit reasoning into sequences of events under the assumed conditions.

Many of the benefits of scenarios arise from the playful, "let's imagine" character of well-designed scenario exercises. Successful exercises construct an environment for collective investigation that captures the open, creative, and exploratory early phase of a new inquiry or project. While maintaining this character, scenarios can also incorporate and integrate relevant knowledge from diverse sources; structure explorations to give them boundaries and discipline; organize communication among participants who bring diverse knowledge, expertise, and perspectives to the issue; and create a sense of occasion and pressure of deadlines, helping move participants to produce more concrete outputs than typically emerge from less structured and decision-focused discussions.

At the same time, scenarios are subject to certain predictable misunderstandings, disagreements, and risks, most of them related to their hypothetical, stipulated character. The most significant of these pertain to scenarios' future orientation, their predictive power, and their generalizability. Because scenarios usually represent uncertain future conditions, they are sometimes viewed as providing advice for future decisions, but this is not their main use. Future decision-makers will act from their own knowledge, objectives, and contextual conditions. Scenarios constructed today are as unlikely to be directly useful for future deliberations as those created in the 1970s are for decisions today. Rather, scenarios represent uncertain future conditions to inform current and near-term decisions. This does not mean that they have no value for future decisions, however. Many near-term actions can strongly influence future capabilities and choices. To the extent that a scenario exercise identifies research, capacity-building, or other near-term actions that could strengthen ability to navigate future crises, this may help shift the distribution of future possibilities in a favorable direction. But how, and whether, future decision-makers use the results of this work will be for them to decide.

Regarding predictive power, to say that scenarios are not predictions is virtually a cliché, but is not entirely correct. Scenarios are not—and cannot be—precise, confident, or unconditional predictions. This merits emphasis, because the vivid, engaging character of well-crafted scenarios can mislead people into judging them more confident predictions than they can be. Yet to be useful, scenarios must also meet some minimal threshold of subjective likelihood. Creators and users must judge the scenario, or a similar pattern of events, as sufficiently likely to merit their attention and consideration in planning. While this condition falls far short of precise confident prediction, it is more than nothing. It is this relatively weak, diffuse epistemic status that most strongly distinguishes scenarios from other types of statement about future conditions, variously called forecasts, predictions, or projections.

Scenarios are usually most valuable when they address a specific issue, for which the associated decision-makers, their responsibilities, and concerns are identified. Such a focused context helps guide needed choices in scenario design, such as which uncertainties are most important and their plausible range of outcomes. No authoritative resolution of such matters is possible, so scenario design decisions generally rest on the collective judgments of those most involved, who have the relevant responsibilities, decision authority, and knowledge. But reliance on these judgments also tends to limit the generalizability of insights drawn from a scenario exercise, because these remain to some degree anchored to the perspectives and concerns of the initial designers and users. The same condition limits the ability of scenario exercises to explore future situations that differ radically from current configurations of authority, expertise, and values. These limitations arise in part because relevant knowledge and expertise decline as a scenario's assumptions diverge from the status quo, making the needed judgements about importance, relevance, and plausibility more deeply contestable.

These general observations about scenario uses apply, with some adjustment, to the specific difficulties of using scenarios for climate change assessment and decision planning. There are two major differences between the use of scenarios for climate change and other, more bounded decision domains (Wodak & Neale, 2015). First, climate-change scenarios aim to inform a vast global audience with wide-ranging responsibilities and concerns, not an identified decision-maker or small group. This broad scope presents several difficulties to scenarios' design and use. It blurs the distinction between decisions and uncertainties, which is central to scenario design in more bounded domains, because climate-relevant decisions by some actors—for example, those in other jurisdictions or in the future—represent uncontrollable uncertainties for other actors. The broad scope and audience for climate scenarios also makes their relationship with decisions indirect: climate scenarios usually serve to organize other assessments or analyses, which inform debate but only broadly and indirectly influence particular decisions. A second difference is that some climate-change scenarios become high-stakes objects of public contestation. This is particularly the case for the widely reported scenarios of future emissions and resultant climate trends that are used to organize official assessments, such as those of the IPCC, and feature prominently in communication of their outputs. Used in this way, climate scenarios come to be widely viewed—despite their creators' clear denials of strong predictive claims—as informal predictions of the likely range of climate futures and feasible responses. As a result, they are sometimes attacked by those who oppose the implied responses. These difficulties will also apply to use of scenarios for solar geoengineering, although these have thus far been less numerous and prominent than general climate change scenarios.

4. Scenarios for geoengineering decision-making

Many aspects of geoengineering present deep, ill-structured uncertainties that carry high stakes for near-term decisions and are thus suitable for exploration through scenarios. Scenarios have been used to support studies of geoengineering, in distinct ways for CDR and solar geoengineering. CDR was introduced in the early 2010's into general, emissions-centered climate scenarios, to maintain the feasibility of the 2 °C goal despite persistently high emissions. Within the cost-minimization structure of integrated-assessment models, this addition yielded the result noted above: extreme reliance on large-scale future removals to offset near-term emissions. Subsequent work has begun to treat CDR using a more standard scenario approach, specifying plausible deployment trajectories exogenously rather than letting them be determined by models' cost-minimization algorithms (Keller et al., 2018).

For solar geoengineering, scenarios have been used in two dissimilar ways. Model studies of the climate effects of solar geoengineering use quantitative scenarios to specify deployment trajectories over time, superimposed on background conditions drawn from pre-existing general climate scenarios. A major vehicle to coordinate these studies has been the Geoengineering Model Intercomparison Project (Kravitz et al., 2011), which specifies solar geoengineering deployment scenarios to standardize climate-model runs and support comparison of their results. To serve the scientific aims of generating informative model responses with strong signal-to-noise and clear separation between scenarios, these have specified strong, simple perturbations. These scenarios are of limited relevance for informing policy or other decisions, however, since potential implementation appears likely to be more limited, incremental, and temporary.

Other scenario exercises have focused specifically on these uncertainties related to how solar geoengineering capabilities are developed and used, their socio-political consequences, and their governance (Böttcher, Gabriel, & Harnisch, 2015; Banerjee, Collins, Low, & Blackstock, 2013; Bellamy & Healey, 2015; Boettcher, Gabriel, & Low, 2016; Buck, Martin et al., 2020; Haraguchi et al., 2015; Sugiyama, Arino, Kosugi, Kurosawa, & Watanabe, 2018; Sweeney, 2014; Talberg, Thomas, & Wiseman, 2018). In these deliberative exercises, participants have been tasked either to develop scenarios of geoengineering use under specified background conditions, or to respond to previously prepared scenarios by identifying associated governance challenges or potential responses. These scenarios are predominantly qualitative and narrative in form, typically centered around a discrete challenge or event occurring a few decades hence. They focus on solar geoengineering implementation, usually in the context of extreme climate-change impacts. Some exercises have also included critical assessment of the scenario's plausibility. Participants have mostly been academics, other experts, or students, all with some prior familiarity with the issue.

Despite the substantial investment of effort in these exercises and their engaging and plausible character, conclusions and insights reported from this work thus far have been rather thin. These include, for example, that solar geoengineering is likely to be a prominent and contentious global issue in which powerful states are expected to be important actors; that framing and perceptions of both climate change and solar geoengineering may vary widely, with high stakes for outcomes; that avoiding or preventing reckless, provocative, or unilateral deployment will be a central difficulty; that general levels of international cooperation and trust will strongly influence governance responses and outcomes, but that these are shaped by interactions across a wide range of issues and thus largely external to solar geoengineering; and that uncertainty is high and unexpected events are likely to be important drivers of outcomes. The geoengineering scenario exercise reported here sought to further extend and sharpen these well-established insights.

5. The 2019 scenario exercise

The six papers in this collection discuss the results of a major scenario exercise, which was conducted in August 2019 at the International Summer School on Geoengineering Governance in Banff, Alberta, Canada. The sixth in a series of such summer schools, this differed from previous ones in its predominant focus on governance—both immediate governance issues raised by proposals for expanded research and longer-term challenges related to potential use of solar geoengineering. The Summer School brought together sixty participants, including leading researchers as well as post-graduate students, early-career researchers, and professionalss. The first two days were devoted to intensive briefings by faculty. The remaining three days consisted of two parallel tracks of collaborative work. One track, not discussed here, consisted of self-organized group projects, proposed and chosen by participants in a bottom-up, decentralized process (see e.g. Buck, Furhman et al., 2020). The second track was the scenario exercise discussed here, which was organized and planned in advance.

A basic design choice in any scenario exercise is how, and by whom, the scenarios are created. In one approach, they are created by participants during the exercise, typically based on a limited prompt that defines the scope and focus. Alternatively, scenarios can be created in advance by organizers, with participants asked to further elaborate, critique, or respond to them. This exercise took this latter path, generating scenarios in advance then refining them through two rounds of consultation among summer school faculty.[1] This approach allowed more time for scenario development and control over which elements were consistent and variable among scenarios. It also enabled intentional choices regarding scenarios' degree of plausibility and helped to situate the exercise relative to prior literature, thus identifying significant differences or advances in understanding that emerged. Specifically, we strove for scenarios that seemed feasible while also exploring new territory, particularly regarding which actors implemented geoengineering.

Relative to prior geoengineering scenario exercises, this one was of larger scale in its duration and number of participants, and included participants with more prior engagement with geoengineering issues and concerns. These differences allowed for deeper, more sustained development, analysis, and critique of responses. In addition, this exercise included multiple scenarios that aimed to present a range of distinct plausible governance challenges and to facilitate stimulating interaction among participants by use of the paired-group structure described below.

Participants were assigned to eight groups of six to eight people each, aiming for diversity within each group in field of expertise, seniority, nationality, gender, and extent of prior experience with geoengineering. Sixteen countries were represented, with most participants from industrialized ones. Academics from various social (e.g. political science, law and governance, economics, ethics) and natural sciences (e.g. climate science, earth sciences, engineering) were dominant, with minorities from nongovernmental organizations and governments. About one-third of participants were female, and roughly half held a Ph.D. or other advanced degree. Because the relatively senior summer school instructors also took part in the scenarios exercise, career stages were well represented from graduate students to full professors, with somewhat more of those at early stages. Other than having a specified schedule of meeting times (four sessions totaling six hours over three days) with deadlines and required outputs, each group was responsible for managing its own process, without outside facilitation or substantive steering. Each group was named for an animal found around Banff. All received the same instructions regarding the exercise's procedure and schedule, and a set of common background conditions that applied to all four scenarios. Each group was assigned to work on one of the four scenarios, with each scenario having two groups working in parallel as well as some cross-group interaction. Groups worked for a total of six hours in four scheduled sessions over four days, plus variable amounts of additional work outside scheduled sessions. The documents that describe process instructions, common background conditions, and four specific scenarios are available as online supplementary material to this article.

5.1. Common background conditions

Much of the context for decision-making was common to all four scenarios, described in a separate document distributed to all groups along with their individual scenarios. (See the supplementary files, Appendix A, for this and other documents.) All were set in the year 2040. This date was chosen to be near enough that scenarios are not dominated by vast technological or socio-political transformations and their relevance for near-term decisions is clear, while also being distant enough that greatly strengthened social and political forces promoting solar geoengineering would be plausible.

In that year, the general state of world development and geopolitics is described as broadly similar to that of today. Present trends of broad world development and relative decline of dominant powers have continued, but there have been no world wars, regime changes in major powers, or fundamental re-alignments of the international system. Cooperation on climate change has achieved limited progress, mostly within the existing regime of the UN Framework Convention on Climate Change and the Paris Agreements of 2015 and 2023. World greenhouse gas emissions increased from about 40 Gt CO_2 in 2020 to about 50 Gt CO_2 in the mid-2030s. That level now appears to have been a peak in global emissions, which subsequently declined to 47 Gt CO_2 in 2040—with nearly half of that reduction coming from China. Unpacking this global emissions trend, it reflects widely variable mitigation performance among the high-income countries, ranging from roughly constant emissions to decreases of about 40 percent below current levels; substantial emission increases in middle- and lower-income countries, driven mainly by economic growth; and large decreases worldwide in emissions intensity (emissions per unit of economic output). The resultant trends fall far short of the reductions needed to meet the 2015 Paris Agreement's goals of limiting global heating to 1.5–2 °C.

While recent emissions trends through 2040 provide modest good news, recent climate trends do not. Global heating reached 1.5 °C in the mid-2020s, then slowed for a decade before surging in the mid-2030s to more than 2.2 °C in 2040. The Arctic is largely ice-free most summers. Mean sea level has risen 30 cm and is projected to exceed 1.5 m by 2100. Severe and unequally distributed impacts are causing serious disruptions and political stresses in many countries and regions, not just low-income ones.

CDR has grown rapidly to reach annual removals of about 50 million tons (Mt) CO_2. This represents huge growth relative to 2020, but still lies far below the roughly 10 Gt/year that many analyses suggest is needed to limit end-of-century heating to 2 °C. There remain serious concerns about the feasibility of such a large further scale-up and the acceptability of the associated environmental and

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[1] The scenario development process was led by the five-member organizing committee for the Summer School. It involved: 1) Inviting all summer school instructors to identify widely varying plausible future deployment challenges that could provide the core of useful scenarios; 2) From these suggestions, outlining a few scenarios judged sufficiently plausible, mutually dissimilar, and distinct from thoroughly-examined extant geoengineering scenarios; 3) Soliciting feedback on these outlines from instructors and other colleagues with interest or experience in scenarios; 4) Extending scenario descriptions and documentation based on this feedback, send for further comment from summer school instructors; 5) Revising scenario materials based on this feedback.

socio-economic impacts. There are also persistent concerns that claimed removals may be exaggerated or vulnerable to re-release.

Based on a decade of modestly funded solar geoengineering research (about $100 million/year worldwide), it is widely—but not totally—agreed that this approach could achieve 1–2 °C of global-average cooling within a few years with modest environmental side effects. Moreover, it appears feasible to manage implementation to dial back climate change fairly uniformly across world regions, and thus avoid large spatial divergence of impacts that would create regional "winners and losers." No disqualifying limitations or risks have been identified. Since no such intervention has ever been carried out, however, the actual effects remain uncertain. Moreover, the long-recognized structural limitations of solar geoengineering still apply: its correction to anthropogenic climate change is imperfect, and its effects operate on much shorter time-scales than those of long-lived greenhouse gases such as CO_2. As a result, solar geoengineering remains at best a limited, imperfect, and temporary corrective for climate change—not an acceptable replacement for emissions reductions, CDR, or adaptation. Finally, in 2040 there has still been no significant progress at developing relevant international governance capacity.

5.2. Groups' tasks

In the context of these common background conditions, each scenario posed a different specific challenge—a set of disruptive events related to actual or proposed solar geoengineering use that clearly required a response. The scenarios aimed to probe the causal mechanisms of potential challenges and their associated risks, potential governance responses, and responses' likely feasibility, effectiveness, requirements, and limitations.

Each participant group represented a senior advisory or decision-making body, with a specified series of tasks and associated deadlines. How they carried out these tasks was up to the groups; organizers of the exercise did not intervene other than to enforce the schedule and requested outputs. As a first step, after their first two hours of work, each group was asked to produce an initial governance proposal in response to the challenge in their scenario, in the form of advice to senior decision-makers. The two groups working on each scenario then shared their initial proposals with each other, and each prepared a "stress test" for the other's proposal. This second step introduced an adversarial relationship between each pair of groups, similar to the "red team/blue team" exercises used in technology assessment and war-gaming. In their stress tests, groups were invited to include explicit criticism of their counterpart's proposal, or stipulations of subsequent actions or events that would expose the proposal's most serious weaknesses. Groups were invited to include a wide range of factors in these stress tests—for example, actions by other parties as well as relevant climatic, political, technological, or other events—but were urged to avoid implausibly extreme assumptions. Stress tests were produced and shared over a further two hours of scheduled time, via written memos as well as in-person meetings to explain and discuss details of the critique.

The third stage of the exercise was more open-ended. Following the exchange of stress tests, groups were invited either to separately revise their initial proposals to address weaknesses exposed by the stress test, or to join with their counterpart group to identify the most important vulnerabilities identified by both stress tests and jointly develop a revised, more robust governance proposal. In the final stage of the exercise, all eight groups reported out their initial proposals, stress tests, subsequent revisions, and resultant insights, for discussion in plenary.

5.3. The four scenarios

The four scenarios all involve programs of solar geoengineering deployment that have either just been implemented and announced or are about to be, in a way that presents a clear challenge to governance. The "initiators"—those making the challenge —are groups of national governments in the first two scenarios and international coalitions of non-state actors in the latter two. One aim of these scenarios was to broaden debate over potential deployment initiators and narratives that have been considered thus far, at the same time probing the boundaries of plausibility. This section summarizes the main elements of each scenario. Table 1 shows their major characteristics.

Table 1
Summary of Scenarios.

Scenario	1	2	3	4
Short name	Middle Powers	Vulnerable States	Grassroots Deployment	Private Sector
Initiators	~10 rich middle powers	~10 climate-vulnerable nations	Global citizens' movement	Fossil producers plus technology platform
Initiator type	State	State	Non-state: citizens	Non-state: corporate
Participant groups	Bear, Bighorn Sheep	Lynx, Cougar	Elk, Mountain Goat	Otter, Wolf
Group role	Inter-government advisory group of senior officials	Inter-government advisory group of senior officials	Ad hoc expert advisory group	Ad hoc expert advisory group
Group's principals	Heads of government, Initiator states	Heads of government, respondent states (great powers)	Coalition of global environmental, inter-government, philanthropic, and civil-society bodies	Ten national governments plus coalition of civil-society and philanthropic groups
Article	Dove et al., 2021	Schenuit et al., 2021	Pasek et al., 2021	Belaia et al., 2021

5.3.1. Scenario 1: the middle powers roar

In the first scenario, the initiators making the challenge are a group of rich, industrialized, middle-power states—including Canada, the Nordics, Switzerland, Japan, and a few others not specified—that typically seek international consensus and operate through multilateral channels. These states have been collaborating for nearly twenty years to promote expanded research and governance consultations on solar geoengineering but have achieved little success. Frustrated, their heads of government have now agreed that some sort of implementation is essential for an effective climate response and they are determined to force the issue, even if it means triggering a diplomatic crisis.

The two participant groups working on this scenario, Bear and Bighorn Sheep, each represent a task force of senior officials from the initiator states, convened by their heads of government to develop a strategy to implement their plan. This represents a major difference between this scenario and the other three: Participant groups here are part of the initiator group, whereas in the others they react to a challenge initiated by other actors. The groups' task in this scenario is to propose the broad outline of an incremental yet meaningful solar geoengineering program, to be announced and implemented in parallel with a proposed governance system and communications strategy. These programs need not be fully fleshed out, but their major elements should be specific enough that heads of government, if they approve, can pass them on to appropriate officials for implementation. Groups are instructed that their political leaders recognize that this is a bold, risky initiative, but they want the proposed plan to limit these risks by gathering additional support and persuasively making a contribution to an effective overall climate response. Above all, political leaders of the initiator coalition want to avoid triggering violent international conflict.

5.3.2. Scenario 2: vulnerable states demand, and act

In the second scenario, the initiators are the "Climate Emergency Coalition," a group of states that all share high vulnerability to climate change but are diverse in other respects. Among its members are India, South Africa, Egypt, Mexico, Saudi Arabia, Iran, Nigeria, Venezuela, and Australia. Although several prior scenario exercises have considered solar geoengineering deployments by one or more vulnerable states, this one differs in the wide variation among the initiator states in their development status, past mitigation efforts, and reasons for supporting solar geoengineering. The purpose of this heterogeneity is to make the initiator states not all sympathetic victims of climate change. Based on severe impacts already occurring and soon projected, the Coalition states have demanded an international solar geoengineering program. To back up their demand and force the issue, the Coalition has also announced that it has already begun a pilot-scale program over the prior three years, which is exerting a small global-average cooling of -0.1 W/m^2, offsetting a few per cent of the radiative forcing at that time from anthropogenic greenhouse gases. Together with this pilot-scale deployment, the Coalition has rolled out a provisional governance program, including a distinguished international advisory board, and has stated a commitment to full transparency of their program and its decision-making. As a good-faith gesture, the Coalition has also promised to hold its pilot program at its present low intensity for two years to await a global response. Its members have also stated, however, that they are prepared to gradually ramp up the program on their own if the response is unsatisfactory.

The two participant groups, Lynx and Cougar, represent a task force of senior officials and experts convened by an *ad hoc* group of great powers, including the five permanent members of the Security Council plus Japan and Germany, to recommend how to respond to the Coalition's challenge. The great powers are internally divided, however, regarding both how severe a provocation the Coalition's announcement represents and their general stance on solar geoengineering. The task force is asked to recommend the major elements of a coordinated response. This should include, at a minimum, the main points of a joint statement responding to the Coalition's announcement, and a recommendation whether or not to establish an international solar geoengineering program as the Coalition has demanded. If the task force does propose such a program, it is asked to also specify the program's broad design characteristics, such as the scale and duration of an intervention and the outlines of a governance system, including what bodies with what national participation, will be in charge.

5.3.3. Scenario 3: decentralized grassroots deployment

Whereas the first two scenarios presented challenges driven by groups of state actors, in the latter two the initiators are international coalitions of non-state actors. In this one, a global "geo-hackers guild" has encouraged concerned citizens to make their own contributions to climate protection by launching small amounts of reflective material using balloons and other low-cost methods (Reynolds & Wagner, 2020). The movement is informally supported by a few wealthy entrepreneurs and foundations. A vibrant small business sector has developed to distribute the needed materials and devices, and an online community has formed that encourages individual citizens to pledge to do their part by lifting one ton of material per year. Although environmental groups are divided on the efforts, a few of them are participating. The movement is not effectively coordinated and there are increasingly sharp disagreements among participants over how—and whether—it should be. With no clear leadership or even coordination, the movement's size and impact, and the identity of its participants, are difficult to track. One widely cited estimate says that 500,000 tons of sulfur-equivalent were lifted last year, and a few scientists have estimated that the activity is exerting a radiative forcing of -0.5 W/m^2, although other observers have objected that both these figures are large over-estimates.

In this scenario, the participant groups—Elk and Mountain Goat—represent an *ad hoc* advisory body established at the request of a diverse coalition of prominent inter-governmental and non-governmental organizations, including the UN Environment Program, the Gates and Aga Kahn Foundations, the World Economic Forum, the Norwegian Sovereign Wealth Fund, and the Vatican. The advisory body has been asked to prepare a report for broad circulation, assessing the situation and recommending a response. In its report, the advisory body is to address whether the program should be encouraged, ignored, taken over, regulated, or shut down—and if they do recommend some form of continuing solar geoengineering intervention, who should do it and how. The report is also to state what additional actions should be taken, by governments or other bodies, to address the strong citizen demand for action on solar geoengineering that the existence of this movement suggests. The advisory body and its sponsoring organizations have no legal authority to back up their proposals. Given the prominence of the issue and the stature of the sponsoring organizations, however, a compelling report and program of action would have substantial ability to mobilize attention and resources.

5.3.4. Scenario 4: the private sector to the rescue?

In this final scenario, the initiators are a group of private firms from the fossil-fuel production and technology sectors. In the 2020's, a few major fossil-fuel producers reversed their long-standing positions to acknowledge climate change as a serious, human-caused risk. But even with this reversal, the firms argued that the best response to climate change was a massive world-wide CDR program coupled to continued production of oil and gas. In principle such an integrated program could produce energy with net-zero or even net-negative emissions—if removals are sufficiently large and secure—but this program was so badly implemented that net emissions continued to rise. As the gravity of this failure became clear, participating firms faced an intense backlash, which now threatens their ability to operate in multiple jurisdictions. In response, they have announced a new initiative, in partnership with the world's largest technology platform—a near-monopoly in multiple areas of web services, social media, and artificial intelligence with global reach—which will conduct an "integrated, rational, optimized" program of global climate-change response. In addition to aggressive and better managed mitigation and CDR, the new program includes moderate and temporary deployment of solar geoengineering, which the firms plan to operate from private facilities located in a half-dozen fossil-producing nations. The participating firms claim that their objective is to help governments effectively respond to climate change, but governments are sharply divided over the initiative.

The participant groups for this scenario, Otter and Wolf, represent an *ad hoc* expert advisory body convened by ten national governments, with support from several global foundations, religious bodies, and civil-society organizations. The advisory body is to prepare recommendations—for the sponsoring governments and other organizations, and for wide public distribution—regarding what risks the initiative poses, how to respond to it, and whether and how to introduce governmental or other broader control over its direction. The advisory body is also asked for available options in the event that the firms running the initiative refuse to relinquish or share control.

6. This collection

This article has introduced the aims, context, and design of the 2019 geoengineering scenarios exercise. The next four papers each focus on one scenario and the experience of the two groups working on it (Belaia et al., 2021; Dove et al., 2021; Pasek et al., 2021; Schenuit et al., 2021). They provide greater detail and context for their scenario, then summarize and explain the two groups' initial responses, the stress tests each group provided for its counterpart, and how the two groups revised or integrated their responses. The articles identify the major points of agreement and divergence between the two groups, the underlying assumptions or weaknesses these reveal about the scenarios, and what these imply for geoengineering, its risks, and its governance. In the closing paper of the collection, we draw out preliminary insights from the exercise, for solar geoengineering governance and for the use of scenario-based exercises to advance related understanding (Parson & Reynolds, 2021). In addition, the complete texts of all materials used in the exercise—the common background conditions, process instructions, and the four scenarios—are posted in the supplementary online material.

Acknowledgements

The authors are grateful for the support of the Open Philanthropy Project.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.futures.2021.102806.

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