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# Governing Solar Geoengineering at Planetary Scale: Pipe Dream or Possibility?

Frank Biermann,[1,2] Aarti Gupta,[2,3] Rakhyun E. Kim,[1] and Florian Rabitz[4]

[1]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands; email: f.biermann@uu.nl

[2]Climate Change Leadership Group, Uppsala University, Uppsala, Sweden

[3]Environmental Policy Group, Department of Social Sciences, Wageningen University and Research, Wageningen, the Netherlands

[4]Institute of International Relations and Political Science, Vilnius University, Vilnius, Lithuania

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## Keywords

solar geoengineering, solar radiation modification, climate interventions, stratospheric aerosol injection, governance

## Abstract

Solar geoengineering is being suggested by some scientists as a partial solution to the climate crisis. However, these hypothetical technologies to reflect parts of incoming sunlight back out into space pose significant governance challenges, due to their ecological risks, planetary scale, and long-term consequences. This review examines the literature on solar geoengineering governance since 2020, identifying three strands of debate. The first explores emerging research governance and institutional arrangements for potential future deployment. The second, critical, strand focuses instead on institutional pathways to prohibit such technologies. A third strand analyzes the debate itself, including through the lens of science and technology studies. While proposals for solar geoengineering are developed by small groups of researchers in industrialized countries, opposition is growing in the Global South, with governments from Africa and the Pacific calling for an international nonuse agreement. This growing resistance from vulnerable nations raises pressing moral and political questions about continuing research amid mounting global dissent.

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## 1. INTRODUCTION

In response to the escalating climate crisis, some scholars are advocating for research into solar geoengineering, also known as solar radiation modification or climate intervention technologies. These speculative technologies, which are not yet available in deployable form, aim to reflect a portion of incoming sunlight back into space to temporarily cool the Earth's surface. A wide array of techniques has been proposed, ranging from space-based mirrors to the brightening of ocean clouds and the coverage of polar ice with reflective plastic sheets (see **Figure 1**) (1, 2). While




**Figure 1**

Technological options for solar radiation modification: ❶ space mirrors located between the Earth and the Sun, ❷ stratospheric aerosol injection for dispersion of reflective particles, ❸ cloud brightening by spraying water droplets in the marine environment, ❹ cirrus cloud thinning for facilitating the escape of trapped heat into space, and ❺ surface brightening for enhanced reflectivity. Figure adapted from Scientific Advice Mechanism to the European Commission, Reference 4 (CC BY 4.0).

many of these ideas remain speculative, some have been explored through computer modeling and a few are being tested in field experiments. Among the most prominently discussed proposals is the large-scale injection of aerosols into the stratosphere from specialized aircraft. This method could generate a temporary layer of reflective particles that would reflect parts of incoming solar radiation (3).

The spectrum of approaches to solar geoengineering has been discussed in detail in several scientific assessments, which describe the planetary-scale ecological and climate-related risks and related uncertainties associated with each (4, 5). Major risks noted in these assessments include severe, unpredictable, and regionally uneven impacts on temperature and precipitation patterns, increased droughts and floods and other extreme weather events, and cascading effects on food production and food security. Large-scale impacts (e.g., changes to the monsoon system) cannot be ruled out. Because solar geoengineering would only mask the effects of persistently high—and possibly rising—atmospheric greenhouse gas concentrations, ending deployment would trigger a severe termination shock, with rapid temperature rebound and catastrophic global impacts (3).

Furthermore, any future use of solar geoengineering presents the unprecedented challenge of how to govern such planetary-scale interventions effectively, equitably, and democratically over very long periods of time (6). This is particularly the case because such planet-altering technologies would require globally inclusive decision-making and effective global political control. Yet, even before any deployment, complex governance challenges arise, including the regulation of international and national research, the management of transnational technology transfer and control, and questions of intellectual property rights and the possible role of the private sector. These concerns have generated growing interest across the social sciences, legal scholarship, and the humanities as well as among some natural scientists specializing in solar geoengineering research.

As a result, a diverse and expanding body of literature on the governance of solar geoengineering, covering analytical, critical, and policy-oriented perspectives, has emerged. This review assesses this evolving scholarship in the social sciences as well as some emerging policy approaches. Our analysis mainly draws on scientific articles published over the last 5 years that examine governance and policy issues related to the development and potential use of solar geoengineering technologies. Articles were selected through searches in the Scopus database, with inclusion limited to English-language publications from 2020 onward.

Broadly speaking, the literature of the last 5 years can be categorized into three strands. First, several studies explore possible governance mechanisms to support solar geoengineering research, development, and potential future deployment. These studies typically emphasize the need for further investigation to evaluate and guide development and future deployment of these technologies. A second strand adopts a critical perspective, calling for international bans or strict limitations on the development and deployment of solar geoengineering technologies, including proposals for international nonuse agreements. A third group of scholars approaches the debate as an object of inquiry, drawing on insights from science and technology studies, critical theory, and related fields to interrogate the political, epistemic, and socio-technical dimensions of solar geoengineering governance. A subcategory of this research focuses on expert and public perceptions of the desirability and risks of solar geoengineering.

We structure our review in four sections, each of which reflects a distinct strand of the literature. Section 2 surveys social science research on how solar geoengineering is framed as an issue domain, including rationales advanced for its development and potential deployment, and public and expert perceptions of these technologies. Section 3 focuses on research and development of solar geoengineering, while Section 4 turns to governance approaches related to hypothetical future deployment. Section 5 examines literature proposing mechanisms to restrict or prohibit research, development, or deployment of solar geoengineering. Section 6 concludes.



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## 2. STRUCTURING SOLAR GEOENGINEERING: INTERLINKAGES, RATIONALES, AND PERCEPTIONS

The scientific exploration and development of solar geoengineering technologies are proposed as potential responses to the climate crisis and the imminent overshoot of the 1.5°C global warming target. Yet, deploying such techniques on a planetary scale would represent an unprecedented level of deliberate human intervention in the Earth system (4, 5). Given this novelty, a growing literature addresses the conceptual understanding of solar geoengineering as a policy domain. This work includes studies on the possible links of solar geoengineering to established policy areas, prescriptive studies that frame solar geoengineering in certain ways, and analytical studies that critically unpack emerging discourses on solar geoengineering, often informed by science and technology studies, ecofeminism, decolonial studies, and related critical theories in the social sciences. Some scholars also study the perceptions of citizens or experts to gain a better understanding of the prospects for further solar geoengineering development.

### 2.1. Interlinkages

To begin with, solar geoengineering encompasses a novel and largely hypothetical suite of technologies whose governance would intersect with a range of existing institutions, regulatory frameworks, and policy domains. Disagreements over the extent to which solar geoengineering resembles, departs from, and intersects with other governed activities have generated extensive debate in the literature.

First, the development or deployment of solar geoengineering technologies would interact with conventional climate policy in many ways. Many scholars warn of the dangers of mitigation deterrence vis-à-vis existing climate policy, arguing that the prospect of the future availability of solar geoengineering technologies would weaken present commitments to rapid decarbonization (e.g., 7, 8). Low (9), for example, suggests that "solar geoengineering feeds into a logic of mitigation deterrence, or moral hazard, where techno-fixes delay rather than buy time for decarbonization" (p. 280). Others, however, remain skeptical of such deterrence and argue that the hypothetical threat of solar geoengineering would rather strengthen mitigation and ease hurdles to international climate cooperation (10, 11).

A second line of debate addresses the similarities and differences between solar geoengineering and atmospheric carbon dioxide removal, both of which have at times been classified under the rubric of "geoengineering." Some argue that the problem structure of each raises different challenges of governance and institutional design (12). Others emphasize the similarities between them and argue that both approaches have a chilling effect on current global mitigation efforts and may reduce political pressure to ramp up decarbonization (7). Separating solar geoengineering and carbon dioxide removal might also lead to a systematic underassessment of the risks associated with carbon removal relative to the risks of solar geoengineering (13).

A few studies link solar geoengineering with other policy areas. Some relate the possible use of solar geoengineering to the 17 Sustainable Development Goals of the United Nations, mapping possible negative and, as they argue, positive effects and interactions of solar geoengineering with these global goals and their 169 targets (14, 15). Others place solar geoengineering with similar high-risk interventionist technologies, often within a broader ecomodernist framework. Reynolds (16), for example, conceptualizes a range of "Earth system interventions" from solar geoengineering to large-scale carbon dioxide removal and de-extinction, arguing that while such technologies may appear "unappealing," their shared social, political and ethical challenges could be mitigated through effective governance and thus "deserve greater attention" (p. 142; see also 17). One study compares solar geoengineering with gene drives, another risky and contested technology, and



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draws lessons for governance based on issue-specific commonalities and differences (18). Rabitz et al. (19) argue that solar geoengineering, along with gene drive systems and bioinformatics, is part of a broader class of novel technologies that are ambiguous because they introduce new risks while potentially addressing existing risks. This ambiguity, they contend, creates particular difficulties for designing anticipatory governance, given the contested and uncertain nature of their potential costs and benefits.

Moreover, the risks of solar geoengineering go beyond environmental governance. For instance, scholars of security studies and geopolitics emphasize the security implications of developing or resisting development of solar geoengineering. They underscore how a "preemptive security logic and practices may shape the development and use of [stratospheric aerosol injection]" (20, p. 279) and how logics of militarization rather than a logic of multilateralism could shape development and future use of a planet-altering technology like solar geoengineering (21). Such severe security concerns stand in contrast, however, to one more positive study that emphasizes the potential of peacebuilding through stratospheric aerosol injection programs (22).

Overall, these debates show that solar geoengineering is not merely a technical problem but a deeply destabilizing planet-altering intervention that poses unprecedented global governance challenges. Because of its novelty, ambiguity, and planetary-scale risks, analogies with other policy domains are almost impossible. This raises important questions about the ability of any of today's institutions to effectively manage the development or deployment of solar geoengineering. In particular, the persistent risk of mitigation deterrence suggests that solar geoengineering would increase rather than resolve climate problems. Coupled with the heightened security and geopolitical stakes emphasized in the literature, governance scholarship thus cautions that solar geoengineering may be fundamentally incompatible with the political realities and capacities of current global institutions.

## 2.2. Rationales

Several studies also interrogate the rationales that are put forward to justify calls for the development of solar geoengineering technologies. One often-discussed rationale is the risk-risk argument, which seeks to compare the risks of future climate change with those of geoengineering (23–26). While solar geoengineering undoubtedly entails significant risks for Earth system dynamics and unevenly distributed impacts (e.g., 3), some studies suggest that the risks of not exploring solar geoengineering could be even greater, a view often linked to research on potential Earth system tipping cascades (27). Critical scholars (e.g., 25, 28) counter here that technocratic risk-risk approaches could lead to imaginations of calculable and manageable trade-offs that marginalize ethical issues and political realities. Also, securitized approaches that rely on worst-case threat logics could shift decisions from democratic debate toward exceptional measures. In the critical literature, risk assessments are seen as an inherently political activity, and uncertainties should be managed through inclusive political engagement rather than technocratic, expert-led processes.

Moreover, it has been suggested that scholars who adopt a risk-risk framing often do so without engaging with the broader limitations of risk assessment (4). This disconnect may explain the inadequate attention to the methodological challenges of quantifying, aggregating, and comparing risks across space and time, particularly given that risks lie in the future and may be unknowable. Aligned with this, some have argued that risk-risk balancing tends to assume that uncertainties can be resolved through producing more empirical data and observable facts. However, such an approach might obscure moral uncertainties that are neither comparable nor reducible through the accumulation of more data (29). One study concludes therefore that, given the potentially catastrophic yet unknowable impacts of solar geoengineering, it is "largely unanswerable" whether its

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harms would exceed those of climate change and that it is not feasible to assess unequivocally which risk would be worse (30, p. 13). On this basis, the study argues that heavy reliance on stratospheric aerosol injection would constitute "an imprudent policy response" (30, p. 1).

A key concern in debating risk-risk balancing is the relevance and interpretation of the precautionary principle. Some have suggested that precaution demands exploration of solar geoengineering to guard against future climate risks (e.g., 31). Others, however, argue that precaution calls instead for robust restrictions on solar geoengineering in the face of uncertain, unknowable, and potentially catastrophic future risks (e.g., 4). For example, the comprehensive scientific assessment of solar geoengineering by the Scientific Advisory Mechanism of the European Union has interpreted the precautionary principle as requiring restrictions (e.g., on outdoor experimentation and other forms of solar geoengineering research) in the face of uncertainties and unknowable risks associated with its development and potential future use (4, 5).

A second rationale to call for research on solar geoengineering is the notion of a planetary emergency, which suggests that the climate crisis has become so urgent and unmanageable that conventional norms of democratic decision-making, public deliberation, and climate justice might need to be temporarily set aside in order to respond effectively—by simply dimming the sun. In the words of solar geoengineering start-up entrepreneur Luke Iseman, "This is about acting in an emergency [and] we shouldn't have to ask permission to try to fix it" (32). Some scholars have suggested that, if solar geoengineering were ever considered, it should be treated as an emergency measure and a last-resort option grounded in necessity—and governed as such. One study contends that an emergency framing would better reflect the political and ethical stakes of solar geoengineering and proposes a governance model designed specifically for crisis contexts, with time-limited authorizations, clearly separated and monitored functions, strong oversight mechanisms, and multilateral decision-making procedures (33).

Such emergency framings, however, have been challenged by many other scholars (see 34). Gupta et al. (35), for example, argue that emergency framings could "be misused to justify the setting aside of democratic decision-making to accommodate alleged exceptional situations" (p. 10). Also, studies drawing on ecofeminist and antiracist perspectives (36, 37) counter emergency rationales as a way to justify solar geoengineering. Stephens (38) criticizes an argument often linked to an emergency rationale—that solar geoengineering might be needed to alleviate suffering of the most vulnerable—by arguing that "while solar geoengineering used to be a fringe idea, it has been strategically promoted by a small, but powerful, group of white male scientists from the United States" (p. 69). She concludes that "attempts to present solar geoengineering to help those most vulnerable . . . misrepresents the fact that solar geoengineering creates yet another mechanism to concentrate power among the already powerful. Advancing this technology provides a way for rich and powerful individuals and countries to influence the world and the lives of everyone" (p. 69).

In short, much of the critical literature highlights that some of the main rationales for solar geoengineering—risk-risk trade-offs and emergency framings—rest on assumptions that reduce profound ethical and political questions to technical calculations and justify bypassing democratic deliberation and planetary justice. The result is a problematic framing that makes geoengineering seem inevitable or necessary, while obscuring the underlying power dynamics and value decisions that would shape its development and use.

## 2.3. Perceptions

Solar geoengineering technologies are still speculative and play only a limited role in public discourse, and they have never been subjected to a public vote. Consequently, a growing body of



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research seeks to advance understanding of public attitudes toward solar geoengineering. These studies explore a range of perspectives, including how citizens, experts, and others perceive research and development efforts as well as how they might respond to the prospect of future deployment.

Low et al. (39), for instance, examine how experts view current approaches to anticipating the risks of carbon removal and solar geoengineering. Based on 125 interviews, they find that systems modeling, which is dominant in climate assessments such as those by the Intergovernmental Panel on Climate Change, cannot capture the complex socio-technical dimensions of hypothetical geoengineering interventions. Experts interviewed in this study voice concerns about the narrow epistemic base, the limited inclusion of stakeholders, and the insufficient integration of qualitative and deliberative methods. Another similar study finds considerable skepticism among Southeast Asian experts regarding the research and potential deployment of solar geoengineering (40). In contrast, Dai et al. (41) report that researchers from the United States and China share broadly aligned views on the risks, potential benefits, and governance requirements of solar geoengineering. While experts from both countries often support more research, this is less the case for actual deployment. Another study looks into perceptions among government negotiators and observers at conferences of the parties to the United Nations Framework Convention on Climate Change and finds a widely shared view across the Global North and Global South that including stratospheric aerosol injection in the climate convention would "increase conflict between nations" and "further frustrate global climate actions on mitigation" (42, p. 7).

In addition to these expert surveys, a few studies explore perceptions of the general public (e.g., 43). Often this research aligns with traditional acceptance research, seeking to identify the conditions under which solar geoengineering could become acceptable to broader audiences, should governments decide on such measures. A study on public acceptability of stratospheric aerosol injection in the United Kingdom, for example, finds that psychological factors such as perceived benefits influence acceptability, while pessimism regarding a possible global agreement on solar geoengineering remains a key barrier (44). A study of United States citizens reports that public skepticism is higher when research is funded by military or corporate actors (45). A survey experiment in China offers mixed outcomes, partially due to the short information prompts of only 100 words about solar geoengineering provided to participants (46). Another study suggests high levels of trust in scientific experts and institutions, which creates a corresponding responsibility for experts to communicate uncertainties and risks transparently (47).

A few studies compare public perceptions between the Global North and the Global South. A study of 44 focus groups in 22 countries suggests that people in the Global South might be more hopeful but also more concerned about solar geoengineering, given the inequities in climate action as well as potential geopolitical conflicts (48). A set of surveys in 30 countries across the Global North and Global South on perceptions of carbon removal technologies and hypothetical solar geoengineering methods suggests that citizens in high-income countries tend to be more skeptical of all technologies, which could be explained, among other factors, by lower techno-optimism, lower trust in industry, stronger "don't meddle with nature" norms, and lower perceived personal climate risk (49). An online survey of college students in 6 Asia-Pacific countries concludes that public support for solar geoengineering deployment varies among these countries, with greater support in China, India, and the Philippines than in Australia, Japan, and South Korea (50). A follow-up study highlights the need for public perception elicitation to be linked to concrete scenarios of solar geoengineering use, rather than being conducted in a policy vacuum (51). On this basis, support for solar geoengineering seems to be higher in India and the Philippines compared to Japan and Australia. Strikingly, the scenarios upon which these perceptions are based "did not present any information on distributional impacts of [solar geoengineering] across



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different countries," which may, the study acknowledges, have reduced their salience for respondents (51, p. 435).

Overall, public perception research has some value for assessing the prospects for solar geoengineering. Surveying the literature, however, we note important limitations and potential biases. First, in most social and geographic contexts, public knowledge about solar geoengineering is limited. Since most study designs thus need to prompt participants with prepared summaries and brief information sheets for querying their responses, study results depend on how scientists present information on solar geoengineering and its risks. Also, public perception research relies on small samples and cannot serve as a proxy for democratic decision-making. Indeed, Dove et al. (52) identify several shortcomings across the 132 studies they reviewed, including persistent inequities in the geographic and social representation of participants and researchers, the continued dominance of studies investigating support for solar geoengineering, and an explicit intent in some studies to use findings to increase public approval. Care must thus be taken not to overestimate the explanatory power of public perception research for future real-world politics.

Consequently, other proxies for the views of citizens must be considered—and some of these express rather cautious views on solar geoengineering. For example, if civil society advocacy is taken as a reflection of public concerns and perspectives, it is notable that many civil society organizations have long articulated highly critical positions on solar geoengineering. Broad-based civil society organizations, such as the Climate Action Network (53) or the Hands Off Mother Earth (HOME) Alliance (54), representing large constituencies worldwide, continue to warn that solar geoengineering is a false solution and a dangerous distraction to transformative and ambitious climate actions. Thousands of civil society organizations have endorsed the academic call for an International Nonuse Agreement on Solar Geoengineering (55); in addition to the Climate Action Network and the HOME Alliance, these organizations include Fridays for Future International and the Pacific Islands Students Fighting Climate Change, which won the 2025 Right Livelihood Award.

## 3. GLOBAL GOVERNANCE OF RESEARCH AND DEVELOPMENT

Although solar geoengineering technologies remain hypothetical, several scholars and research institutions advocate for expanding research, developing related technologies, and conducting comprehensive assessments of these technologies (overview in 56, 57). Three strands of argumentation relating to solar geoengineering research and development can be distinguished in the literature since 2020. First, several studies focus on the need to develop novel governance systems, or to adjust existing ones, and to incentivize and regulate national and transnational research programs on solar geoengineering, including technology development. A second body of literature draws on science and technology studies to critically examine the underlying assumptions, processes, and power dynamics shaping solar geoengineering research and development. A third line of research, drawing on these critical studies, seeks to explore limitations and prohibitions of geoengineering research and technology development. This latter body of literature is discussed in Section 5 on the prohibitions of solar geoengineering.

Scholars who advocate for more research into solar geoengineering technologies argue that this would improve the knowledge base for future decision-making. This strand of scholarship proposes procedural rules and norms to incentivize and steer research and generate transparency and accountability. Yet as Huynh & McNeill (58) observe, "there is still little to no governance . . . frameworks in place [that] would entail guidelines and regulations regarding the scope and responsibility of [solar geoengineering] research, including regional and global deployment and maintenance" (p. 132).



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One widely cited approach for governance of research on solar geoengineering is that of the Tollgate Principles (59), which emphasize the need for decisions to be taken by bodies representing global or intergenerational publics, along with principles of trust, accountability, consultation, and respect for general ethical and ecological norms. Studies argue that because solar geoengineering research could soon turn to outdoor experimentation—such as in the Stratospheric Controlled Perturbation Experiment, which was discontinued after protests by Indigenous leaders (see 43, 60, 61)—effective governance of research is urgently needed (62). One study suggests the 1996 London Protocol to the 1972 London Dumping Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter as a template for governing solar geoengineering research (63). The London Protocol was amended in 2013 to address certain forms of marine geoengineering. Research governance modeled hereupon would establish assessment criteria for delineating deployment from legitimate scientific research and put in place procedural requirements regarding notification, consultation, transparency, and accountability.

Beyond principles to guide it, geoengineering research governance would also need to account for the problem of mitigation deterrence (discussed above) to avoid posing a "systemic risk for the energy transition" (64). It would also need to acknowledge normative uncertainties that cannot be reduced through more empirical data, given that these uncertainties are linked to contested and evolving norms, values, and ethical considerations (65). A critical strand of the literature on solar geoengineering research governance notes that even climate modeling—often presented by research advocates as being free of risks—could require some oversight, because of the presence of "non-epistemic political and ethical values in the design, tuning and interpretation of climate models" (66, p. 103). This suggests also that interdisciplinary collaboration would be critical to unveiling underlying normative assumptions. A study from Germany suggests, for instance, that interdisciplinary dialogues could correct for overly optimistic assessments, highlight complexities, and support more legitimate knowledge production, along with preventing disciplinary dominance and fostering epistemic humility (67).

A key element of research and development is the right of patenting innovation (68), another topic covered in the literature. Some patents have been granted for solar geoengineering technologies, yet given the novelty of solar geoengineering, Ramos & Santos (69) argue for a more systematic approach to classifying such technologies from a patenting perspective. They suggest that "the filing of patent applications in geoengineering raises urgent questions regarding the regulation and governance of these technologies, including not only research and experimentation but also their potential deployment" and that it is "essential to establish international frameworks to oversee these activities to avoid undesirable consequences at the geopolitical level" (69, p. 30). Others have called for outright bans on the patenting of solar geoengineering techniques (6).

Several studies examine the role of public participation in decisions regarding the design of solar geoengineering research (e.g., 70). One such study analyzes how nonstate actors shape the governance of solar geoengineering research through knowledge dissemination, scientific capacity-building, and lobbying. The study argues for a broader perspective on transnational research governance that encompasses not only formal steering mechanisms but also indirect forms of influence, such as informing, persuading, and exerting pressure (71). A case study of Arctic communities in Finnish Lapland relies on focus groups to coproduce scientific knowledge on albedo-modification geoengineering scenarios. This study found that ethical and justice concerns emerged once scientific granularity increased and concluded that, in the absence of formal governance structures, community-driven coproduction could act as a provisional governance mechanism, shaping the scientific interpretation and the normative framing of solar geoengineering research (72).



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In contrast, numerous studies offer a critical perspective on solar geoengineering research. For instance, Stephens et al. (73, 74) analyze a major report by the United States National Academies of Sciences, Engineering and Medicine (3) and highlight the risks of pursuing a national research program on solar geoengineering, as proposed there, without adequate international governance or public participation (see also 75). Such a national research program would risk normalizing unilateral action, preempt public deliberation, and deter climate mitigation, thus constituting a de facto form of solar geoengineering governance in the absence of the very forms of governance that it recommends. In another study, Stephens & Surprise (76) suggest that "solar geoengineering research is being advocated for by a small group of primarily white men at elite institutions in the Global North, funded largely by billionaires or their philanthropic arms, who are increasingly adopting militarized approaches and logics." Research itself would advance "an extreme, expert–elite technocratic intervention into the global climate system that would serve to further concentrate contemporary forms of political and economic power," concluding that it would be "unethical and unjust to advance solar geoengineering research" (76, p. 2).

Regarding expert assessments on solar geoengineering, Low (77, p. 279) argues that "expert assessments of solar geoengineering are not neutral, but entwined with normative beliefs about the state and direction of climate governance." Low continues by stating that in such assessments, "Complex ethical and societal questions are bracketed—that is, mentioned up front, then set aside (and for all intents and purposes, ignored) as orthogonal to technical study. The argument is that solar geoengineering, sensibly following optimized modeling, can buy time for mitigation while protecting the most vulnerable. Yet, there are no governments, international bodies, or (perverse) geopolitical considerations present—one must assume that in an increasingly multipolar world, all governments agree to cooperate on solar geoengineering for many decades" (77). These arguments mirror those by McLaren & Corry (78, p. 1), who have reviewed a range of proposed research governance frameworks, observing "a reproduction of Northern norms, instrumental approaches to public engagement, a weak embrace of precaution, and a persistent—but questionable—separation of research from deployment" across most of these.

On this latter question of separating research from deployment, the literature also discusses the so-called slippery slope of solar geoengineering research (79), which can lead from initial research to technology development and planetary-scale deployment. For instance, research could lead to the further normalization and legitimization of solar geoengineering, spark technology hypes that create ever more investment and support for these hypothetical technologies without much basis in evidence, facilitate alignment with powerful actors such as fossil fuel sectors, create deployment incentives by early patenting of solar geoengineering technologies, and support sunk costs bias by creating expansive laboratory infrastructures and dependent research communities that all stand to lose if solar geoengineering were not further pursued.

Such critical studies thus emphasize that research could lead to deployment by normalizing, legitimizing, and locking in a set of dangerous technologies while disincentivizing, delaying, or discursively obstructing decarbonization of our societies. As Tang (79) argues, "Those presenting [stratospheric aerosol injection] as a legitimate option may currently be a minority, but this does not preclude [its] broader legitimisation . . . over time" (p. 6). With continued research on solar geoengineering, "initially small changes can spark nonlinear feedback loops that can quickly transform an underdog into a frontrunner" (79, p. 8).

Given these risks of current research programs, public announcements that solar geoengineering has no role in climate policy are important. For that reason, more than 600 academics and more than 2,000 civil society organizations support an International Nonuse Agreement on Solar Geoengineering (55), explicitly calling upon governments to "prohibit their national funding agencies from supporting the development of technologies for solar geoengineering," "ban outdoor



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experiments of solar geoengineering technologies," and "not grant patent rights for technologies for solar geoengineering."

Overall, the literature suggests that solar geoengineering research is not a neutral scientific pursuit but a political process that can normalize and lock in risky technologies before governance and ethical questions are resolved. With limited international oversight, elite-driven funding, and the possibility of a slippery slope from research toward deployment, expanding research could inadvertently strengthen technocratic power and undermine decarbonization. In this light, strong precautionary limits—or even prohibitions—are increasingly called for in the literature, which we discuss in Section 5.

## 4. GLOBAL GOVERNANCE OF HYPOTHETICAL DEPLOYMENT

Although no solar geoengineering technology currently exists in operational and deployable form, several studies have debated how the deployment of technologies could be governed effectively, equitably, and democratically and what institutional arrangements would be required at the planetary scale and over time frames of centuries.

A critical strand in the governance literature maintains that effective and fair planetary-scale governance of solar geoengineering would be simply implausible (6) or an impossible requirement (80). This argument draws, among others, on critiques of the generalized and idealistic assumptions about world order and global governance that underpin many proposals supportive of solar geoengineering (81). As one critical study argues, one needs to analyze the prospects of solar geoengineering governance from worst-case assumptions about international cooperation—not from best-case assumptions (82). Young (83), for instance, scrutinizes the assumptions of international order behind many proposals for solar geoengineering and contends that the crisis of the liberal international order and of multilateralism undermines the prospects for any future global governance of solar geoengineering deployment. Other studies criticize the often stylized modeling assumptions in solar geoengineering research about deployment governance that are unlikely to hold in real-world geopolitics, where deployment schemes might turn out to be "unilateral, uncoordinated, or competing" (8, p. 261). One study shows how solar geoengineering is socially constructed through visual representations—such as satellite images—that may not reflect scientific knowledge in a neutral manner but actively constitute solar geoengineering as a manageable political and governance issue. Such images could create or reinforce framings of a controllable planet, enabling risky policy trajectories while foreclosing others (84).

Other scholars, however, argue that the global governance challenges of deployment are surmountable and that international institutions are more stable than often assumed (e.g., 85, 86). Some studies, for example, explore whether solar geoengineering could be governed under the existing global climate governance framework and how it might be incorporated into this regime (87). Critics contend, however, that this would be problematic, given a mismatch between solar geoengineering and the structure of current global governance (88), suggesting that the introduction of solar geoengineering as a novel policy tool would further intensify the existing cooperation problems in international climate policy (89).

Theoretically, global institutions beyond those dealing with climate change could support the governance of solar geoengineering. For instance, McGee et al. (90) discuss whether the 1977 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques could be a forum for governing solar geoengineering, especially in the short-term, as the convention prohibits military or other hostile environmental modification with "widespread, long lasting or severe effects" (91, Article I.1). However, given that the convention permits peaceful uses of environmental modification techniques but lacks strong institutional



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support, such as a dedicated secretariat, the authors conclude that substantial institutional development would be required to effectively govern any future peaceful uses of solar geoengineering under this regime.

The ozone regime established under the 1985 Vienna Convention and the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer is also sometimes cited as a potential global institutional framework for governing solar geoengineering technologies that could harm the ozone layer. The ozone regime would constrain use of solar geoengineering technologies with adverse impacts on the ozone layer while mandating intergovernmental scientific cooperation to assess such effects (92). Another relevant institution is the Convention on Biological Diversity. This treaty's decision X/33 from 2010, reaffirmed in 2024 (93, 94), is generally seen as a quasi-moratorium on various forms of geoengineering, as it asks states to put in place onerous assessment requirements prior to conducting geoengineering research or experimentation. Solar geoengineering has also been addressed in other international fora, such as the 1972 London Dumping Convention and its protocol, which is often seen as more permissive toward research than, for example, the Convention on Biological Diversity. Finally, solar geoengineering has been debated in the United Nations Environment Assembly, with no decisions taken thus far (95, 96). These variations in governance outcomes have been attributed to differences in the discursive and institutional structures across these global regimes (97), which could further influence and shape future efforts at global governance (98).

Overall, existing international institutions appear ill-equipped to govern the full-scale, planetary deployment of solar geoengineering technologies. At the same time, a range of existing—albeit fragmented—international legal obligations already address many issues directly relevant to potential future deployment. These obligations cannot simply be set aside or superseded by a hypothetical future deployment of solar geoengineering. Rather, any such deployment would have to comply with the many restrictions and prohibitions already in place (92).

If existing institutions are unable to govern solar geoengineering effectively, there would be a need to create entirely new institutions—ideally supported by all states and with enough authority to regulate all forms of deployment globally over long periods of time. Yet proposals for such novel governance arrangements are rarely articulated in concrete terms. One possible model could be a powerful global authority with planet-wide jurisdiction. In the current geopolitical climate, however, the establishment of such an overarching and universally accepted institution is highly unlikely.

Therefore, some studies investigate whether less demanding and more flexible new governance arrangements could regulate the hypothetical deployment of solar geoengineering—without participation of all countries or focused only on specific regions. For instance, some suggest that plurilateral clubs of countries could govern deployment (99), prioritizing here effectiveness and efficiency over equity and universal democracy. Parson & Reynolds (100) contend that states should proactively "advance exploration of broadly acceptable governance arrangements" individually or in small groups as a form of "contingency planning" (p. 10). The possible formation of such clubs of countries and related interstate bargaining have attracted multiple studies that draw on game theory and economic modeling. Some present a game-theoretical analysis of the credibility of threats in different smaller country coalitions to avoid solar geoengineering deployment (101). Others analyze the prospects for coalitions of countries that combine solar geoengineering with mitigation efforts (102). Taking these ideas of smaller clubs of countries one step further, one study argues for the moral responsibility of the United States to develop and possibly unilaterally deploy solar geoengineering even without the consent of other actors, suggesting that "deployment is in certain circumstances not 'merely' morally permissible, but . . . quite possibly morally required of sufficiently capable actors" (103, p. 13).



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Addressing the challenges of governing deployment has led some scholars to suggest that certain solar geoengineering technologies might lend themselves to regional deployment (e.g., the whitening of clouds). They propose that lessons can be drawn from weather modification law for such regional solar radiation modification (104). One study suggests targeted geoengineering, in the form of regional-scale interventions to produce global climate benefits without the need for full planetary deployment (105). Regional solar geoengineering programs are also discussed based on Australian experiences (106) or targeted subpolar aerosol injections to protect the polar caps and reduce sea-level rise (107). One study proposes to use strategic environmental assessments as a governance tool to support social inclusiveness of regional applications of techniques such as marine cloud brightening and surface albedo modification (108).

Such proposals for plurilateral or regional governance arrangements for solar geoengineering have been criticized as well. For instance, a group of polar scientists (109, p. 1) voiced strong opposition to attempts at "dangerous geoengineering" in the polar regions. Dove et al. (110) argue that, in a hypothetical scenario where a group of middle powers decides to initiate solar geoengineering, the possible use of an emergency framing could increase the risk of imprudent and less democratic decision-making and undermine political legitimacy. Governance fragmentation would create further coordination challenges. Along these lines, one study argued that without a robust global governance framework, differences in preferred temperature targets between countries could lead to excessive cooling, as countries with the lowest preferred temperature target would seek to cool the planet beyond the collective optimum (111).

Importantly, different deployment patterns could produce distinct types and magnitudes of regionally unequally distributed impacts. Solar geoengineering researchers Visioni et al. (112), for example, observe that "the location(s) of the injection of $SO_2$ in the stratosphere results in important differences in the effects produced on the surface climate" and that it is "therefore possible to devise injection strategies depending on different climate goals." They further conclude that "if multiple strategies can result (or are projected to result) in similar goals being achieved at a global scale, yet with different impacts in different regions, then various actors with particular interests might have divergent preferences over which strategy to use" (112, p. 8). The implications of regionally unequal outcomes for the design of global governance frameworks are profound. So too are the justice concerns raised by potential plurilateral or unilateral solar geoengineering initiatives in light of such unequal distributions, especially for vulnerable countries in the Global South, which generally cannot influence decisions taken by powerful states in the Global North that might seek to control a global thermostat according to their own interests.

Finally, several studies examine the potential role of the private sector in governing planetary-scale solar geoengineering, including major corporations and ultrawealthy technology entrepreneurs and philanthropists. For example, Reynolds & Parson (113) argue that nonstate global governance could be effective and legitimate enough to serve as a functional equivalent to state-centered governance. Reynolds & Wagner (114) debate the potential for highly-decentralized deployment by citizens operating small, high-altitude balloons and possibly coordinating through social media. Lockley (115) proposes that states could delegate deployment of solar geoengineering to private contractors. Lockley et al. (116, pp. 8–12) explore in more detail the legitimacy of solar geoengineering by private actors, debating whether a "billionaires' club" or a group of "technocrats" from the "world's leading research universities," maybe supported by crowdfunding or industry-based carbon offset programs, could operate a planetary-scale geoengineering deployment scheme, citing also traditional citizens' rights to lawfully extinguish fires or use emergency brakes in trains. While these proposals seem far-fetched, they indicate the strong reliance of some solar geoengineering advocates on elite-driven political fantasies. Possibly not coincidentally, Lockley is also known as an initiator of the first outdoor geoengineering



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experiment in the United Kingdom called SATAN (Stratospheric Aerosol Transport and Nucleation) (117).

Other studies raise concerns about this possible involvement of nonstate actors—particularly multinational corporations and ultrawealthy individuals—in governing solar geoengineering. Several critical scholars (76, 118–119) have examined the role of corporations in the discourses on the development or deployment of solar geoengineering. They argue that the emergence of for-profit solar geoengineering firms—such as the United States–based company Make Sunsets, which sells cooling credits as a way for individuals to offset their carbon emissions—shows the dangers of neoliberal, market-driven climate governance, in which profit incentives outpace public deliberation. Such studies criticize the framing of solar geoengineering as a monetizable service and see such ventures as products of climate policy directions that prioritize technological innovation and involvement of venture capital over equity and precaution. In this view, private companies, such as Make Sunsets, are not rogue actors but an outcome of governance logics that commodify climate risk. What is needed according to these critics are restrictions on commercial initiatives for solar geoengineering through bans or nonuse provisions in international regimes to prevent risky techno-optimistic pathways from displacing mitigation and reinforcing global injustices (118).

## 5. GLOBAL GOVERNANCE TO PROHIBIT DEVELOPMENT AND DEPLOYMENT

In recent years, a growing coalition of civil society organizations and networks of academics has pushed for governance frameworks that would prohibit the development and deployment of solar geoengineering (120). Governments across Africa, Latin America, and the Pacific are also increasingly supporting a nonuse agreement on solar geoengineering technologies. In 2023, the African Ministerial Conference on the Environment called for the establishment of a "global governance mechanism for nonuse of solar radiation management" (121, p. 32), and in 2025, African ministers stated their "full rejection of any attempt to promote stratospheric aerosol injection or other forms of solar geoengineering technology as a climate change mitigation solution" (122, para. 6; see also 123, p. 7), calling again for "the establishment of a solar-geoengineering nonuse agreement" and "for a United Nations General Assembly resolution on the same" (123, p. 7). These critical positions were echoed at the 2024 United Nations Environment Assembly, where African countries—supported by Colombia, Fiji, Mexico, Pakistan, Vanuatu, and other Global South nations—called for the nonuse of solar geoengineering and rejected solar geoengineering as a climate solution (95, 96). Similar opposition has emerged in other intergovernmental arenas. At the 2024 conference of the parties to the Convention on Biological Diversity, governments reaffirmed the 2010 Decision X/33 (124), widely interpreted as establishing a de facto moratorium on geoengineering activities that could harm biodiversity. Together, these developments point to the rise of a potential plurilateral alliance—led by countries in Africa, the Pacific, and Latin America—firmly opposing the further exploration of solar geoengineering technologies.

At the national level, Mexico announced in 2023 a ban on solar geoengineering experiments on its territory (125). In 2024, Germany's Federal Environment Agency (126) issued a position against the use and development of solar geoengineering, emphasizing that "an international nonuse agreement should be sought beyond existing governance structures" and that such technologies are not a future emergency measure nor a transitional solution. Echoing this stance, the German government declared in 2023 that it did not see solar geoengineering as a climate policy option (127). Similarly, the European Parliament (128) in 2023 urged the European Commission and member states to "initiate a non-use agreement at [the] international level." Vanuatu asserted in 2024 that already existing international legal obligations "constrain and prohibit" reliance on



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solar geoengineering, noting the requirement "that States refrain from developing and using these technologies and prohibit their development and use, including by private parties such as corporations" (129, pp. 286–87). Vanuatu, together with the Melanesian Spearhead Group (130), which includes Fiji, Papua New Guinea, and the Solomon Islands, further argued that responsible states should "proactively ban false and dangerous 'solutions' such as geoengineering" (p. 36).

In parallel with this political opposition to solar geoengineering, a growing body of literature is exploring legal and political strategies to support bans or moratoria on its development and use at national, regional, and global levels. This scholarship has highlighted, for example, that customary international law creates legal obligations on states that restrict the development and deployment of solar geoengineering even in the absence of more robust and specific governance frameworks (131) and that existing legal obligations could already offer a framework for restrictive and prohibitory governance regarding solar geoengineering (92).

Going beyond customary law and existing rules, Biermann et al. (6) formulated a succinct outline for an international nonuse agreement on solar geoengineering in 2022. These authors identify several reasons why solar geoengineering technologies should not be further developed, arguing that these technologies are inherently too risky, cannot be governed fairly or democratically at planetary scale, and would likely be controlled by a small number of powerful states. Moreover, the mere prospect of future solar geoengineering could weaken mitigation efforts and exacerbate global inequalities. Based on this analysis, they outline a political roadmap toward establishing a solar geoengineering nonuse agreement to prevent further development of these technologies. Gupta et al. (132) examine how such a nonuse regime for solar geoengineering could be concretely developed. Building on lessons from international prohibitory regimes governing other issue areas—such as nuclear testing, chemical weapons, and deep seabed mining—they argue that proactive legal and political constraints are feasible for solar geoengineering and offer multiple design options for such a global nonuse regime, including prohibitory mechanisms, decision-making procedures, and monitoring and compliance mechanisms. VanDeveer et al. (133) offer a complementary perspective from political science, outlining how civil society networks, regional coalitions, and expanding clubs of like-minded countries could, even without the support of powerful countries, build and institutionalize a global solar geoengineering nonuse norm over time.

Unsurprisingly, such calls for a global ban on solar geoengineering have prompted critical responses from some advocates of more research and technology development (e.g., 134). From another perspective, Táíwò & Tàlati (135) have argued—before African and Pacific governments called for a global ban—that framing solar geoengineering as colonial and unjust risks reproducing the very same power dynamics that critics are concerned about. They contend that banning solar geoengineering while Global South countries remain insufficiently informed about these technologies would be undemocratic and unjust. They propose instead a public research program to first build Global South capacity for solar geoengineering assessment and decision-making—an argument, however, that increasingly clashes with the critical stance of many Global South governments that fundamentally oppose these risky and hypothetical technologies.

## 6. CONCLUSION

Solar geoengineering continues to fuel a contentious debate between those emphasizing its potential role in global climate policy and those emphasizing the many biophysical and political risks it poses. Questions of how to govern solar geoengineering, in terms of facilitating or prohibiting research, development, and deployment, continue to be divisive. This review highlights that such questions are approached from different perspectives. One group of scholars is open to the



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development of solar geoengineering technologies and thus focuses on identifying enabling policies and governance systems, searching for ways to use existing institutions to regulate research and potential deployment or identifying alternative institutional designs (e.g., 1). A second set of perspectives focuses instead on probing the assumptions behind calls for research and technology development, providing critical perspectives on the associated dynamics of knowledge and power asymmetries, and typically concludes by calling for prohibitions on further development and use of solar geoengineering technologies (e.g., 6). These different strands in the literature are broadly at odds with each other. Where some authors focus on the practicalities of what they see as global governance challenges that are acute but surmountable, others consider solar geoengineering as being beyond the scope of what global institutions are effectively capable of addressing.

A further divide relates to whether solar geoengineering is simply one of many complex global governance challenges or whether it represents a unique and unprecedented challenge. Some scholars view solar geoengineering as one among several Earth system interventions, possibly on par with nitrogen cycle management, landscape burning, or large-scale human agriculture (136). Others stress instead the uniqueness of solar geoengineering, the many planetary-scale risks, unresolvable uncertainties, and the ungovernability of such technologies given the state of world politics. The extent to which solar geoengineering is seen as a normal governance problem has profound implications for the choice of governance instruments: the more anomalous one considers solar geoengineering, the stronger the rationale for precautionary regulation and international prohibitions.

Furthermore, the literature on solar geoengineering tends to reflect a structural bias toward advancing research and development in the field, and reviews tend to generate what Low (77) describes as an "artificial conversation" that "creat[es] a false equivalence between a small and static network of [solar geoengineering research] advocates, versus scholars, publics and stakeholders invested in mainstream climate governance" (p. 284). The relatively small group of scholars who publish on solar geoengineering are mostly supportive of continued research and further exploration. This correlation is hardly surprising: Mainstream academics who oppose such technologies are less inclined to participate in these debates and invest their limited time and resources in analyzing speculative and controversial interventions that they regard as fundamentally flawed or dangerous.

The field of solar geoengineering thus remains concentrated among a small group of academics in a few industrialized countries—sometimes referred to as the geoclique (82, 137, 138). Many receive funding from well-resourced United States–based lobbying organizations such as SilverLining and private foundations, with support from Facebook cofounder Dustin Moskovitz, billionaire Rachel Pritzker, and venture capital partner Bill Trenchard (32, 118, 119). The limited solar geoengineering research in the Global South, meanwhile, remains broadly tied to private-sector funding mechanisms like the United Kingdom–based Degrees Initiative, which seeks to incentivize Global South scholars through small grants and scholarships to shift their homegrown academic agendas toward solar geoengineering studies (139)—even though governments and civil society across Africa and the Pacific increasingly oppose these risky planetary interventions.

Moreover, much of the governance literature remains inherently speculative, given that solar geoengineering technologies are yet to be developed. With few exceptions, neither governments nor private entities have made significant commitments to outdoor experimentation or technological advancement in this area. As a result, the discourse on global governance is abstract and theoretical, centering on how a technology that does not exist and may never be realized could be regulated in an uncertain future.

At the same time, political resistance to solar geoengineering is intensifying, especially in the Global South. Recent declarations, such as the African Ministerial Conference on the



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Environment's support for a global nonuse agreement, backed by countries like Fiji and Vanuatu, might signal the emergence of a broader international coalition opposing solar geoengineering. In parallel, opposition is also growing in the United States, where 25 states have introduced bills to ban or restrict the deployment of solar geoengineering, which has even raised "concern [that] they could create legal consequences for researchers [in the United States] hoping to conduct legitimate research on [solar geoengineering]" (56, p. 664).

Vanuatu's (140) suggestion to include "dangerous geoengineering" under the proposed international crime of ecocide underscores the deep unease many vulnerable countries feel toward the prospect of managing climate change through planetary-scale geoengineering rather than through decarbonization, lifestyle changes in the Global North, and global climate justice. In the end, researchers in industrialized countries may find it increasingly difficult—both morally and politically—to continue or expand solar geoengineering programs amid vocal opposition from African and Pacific leaders and growing pressure from civil society groups.

Looking ahead, what has so far been a largely theoretical debate is now entering formal political arenas, with solar geoengineering becoming a topic of discussion in intergovernmental fora and national policy circles. As a result, the academic literature around its governance is likely to shift as well—moving from speculative exploration, hypothetical policy designs, and thinly veiled political advocacy to the concrete analysis of real-world political decision-making—in an increasingly fragmented and tense multipolar geopolitical context.

## SUMMARY POINTS

1. An expanding literature discusses the governance of the development and possible use of technologies for solar geoengineering—hypothetical methods to reflect some incoming sunlight back into space in order to limit the impacts of global warming.
2. A first research strand explores institutional mechanisms that could govern research, development, and potential future deployment of solar geoengineering.
3. A second research strand analyzes institutional mechanisms to instead restrict the development and use of solar geoengineering technologies, motivated by the belief that solar geoengineering would be too risky to deploy and that its development could derail current climate policies.
4. A third line of studies analyzes the discourse around solar geoengineering as such, often from critical perspectives of science and technology studies and related fields.
5. Politically, no government supports the development of solar geoengineering technologies. Several international institutions, notably the Convention on Biological Diversity, include restrictions on its development and use.
6. Some funding has been given for research on solar geoengineering from a few national agencies and private donors, largely in the United Kingdom and the United States, and a few private actors have taken first steps to develop research programs that would include outdoor testing.
7. Several countries from Africa and the Pacific have called for global bans on the development of solar geoengineering technologies, including through an international nonuse agreement on solar geoengineering. This call is supported by a growing global network of scientists and more than 2,000 civil society organizations.

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## FUTURE ISSUES

1. Recent calls by African and other countries for a global nonuse agreement on solar geoengineering require more political and legal research into the institutional options and strategies that these political actors could rely on.
2. The increasing involvement of investment firms, corporations, and private donors in the development of solar geoengineering technologies requires more research into the governance challenges posed by such private sector activities.
3. Scientific assessments need to carefully consider biases within the emerging literature on solar geoengineering development and deployment. Such biases include North–South biases through research dominance from the Global North, disciplinary biases through dominance of modeling and technical approaches, and confirmation bias through strong involvement of research groups and private funders that firmly advocate for solar geoengineering research.

## DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

## AUTHOR CONTRIBUTIONS

All authors contributed equally to the research. F.B. wrote the first draft, which was further revised by A.G., R.E.K., and F.R.

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