INSIGHTS

POLICY FORUM

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CLIMATE POLICY

Toward constructive disagreement about geoengineering

A shared taxonomy of concerns may help

By **David W. Keith**[1,2]

The divergence of expert opinion about solar geoengineering (SG) may be sharper than in any other area of climate policy. As with other contested technologies, disagreement sometimes conflates divergent scientific and political judgments with divergent normative stances. It is impossible to cleanly disentangle the technical, political, and ethical aspects of the debate. But it is possible to disagree in ways that better serve the public's interests. Disaggregation of judgments about SG may allow experts to disagree more constructively and better serve policy-makers and diverse publics. An organized list of concerns about SG could serve as a tool to encourage disaggregation of complex disagreements while discouraging their conflation into an unhelpful "good versus bad" dichotomy.

SG is defined here as methods that could be used to ameliorate the climate hazards due to long-lived greenhouse gases (GHGs) by modifying the radiative forcing of climate—primarily by reducing the absorbed solar flux. SG is perhaps best defined in relation to other ways of managing climate risk; it is one of four toolboxes: emissions reduction, carbon removal, SG, and adaptation. Tools inside the SG toolbox include space-based shields, stratospheric aerosols, cirrus cloud thinning, marine cloud brightening, and increasing surface reflectivity (*1*).

There is evidence that some SG technologies could substantially reduce important climate hazards, including changes in water availability or extreme temperatures, over most of the world, with physical harms or risks that are small compared with the aggregated benefits of reduced climate hazards (*1*, *2*). Uncertainty is far too large to justify either a decision to deploy or to renounce deployment, but evidence of SG's potential to reduce human and ecological impacts is arguably sufficient to justify a substantial research effort and sustained policy attention. Of course, many scientists, climate policy experts, and climate advocates would likely disagree with this assessment.

A TAXONOMY OF CONCERNS

A systematic taxonomy of concerns could serve as a step toward more constructive disagreements. I propose an initial catalog, organized into a rough taxonomy with four top-level categories (see the box) ordered by conceptually distinct root causes.

PHYSICAL HARMS OF BENEVOLENT DEPLOYMENT

These concerns arise from side effects of altering radiative forcing, from climate response to that forcing, from accidents, or from incompetence. A benevolent deployment aims at some measure of distributive justice such as a Rawlsian difference principle (greatest benefit to the poorest) or a utilitarian maximization of benefits. Benevolence is a claim about intentions, not outcomes.

Side effects are never generic to SG; they are specific to the methods used to alter radiative fluxes (see the box). No geoengineered radiative forcing can exactly counter the spatial and spectral characteristics of GHG forcing. We may define an intervention as "moderating" a climatic variable when it reduces the local deviation of that variable from its preindustrial value and "exacerbating" when it increases the deviation. Exacerbation is the physical climate risk of SG.

Risk depends on the amount of SG. Reduction in precipitation is, for example, often cited as a risk of SG. Yet increased precipitation is an important climate hazard. Reduced precipitation is only a concern under this definition when SG is large enough to drive precipitation below a reference value so that any additional SG exacerbates the change from that reference. The reference is the climate to which the system is adapted, which may differ from the preindustrial.

The area that sees exacerbation of some climate hazards increases with the amount of SG (*2*), so SG is less able to provide widespread moderation of climate hazards as the amount of SG increases. This is the reason why SG cannot be a substitute for reducing carbon concentrations. The area that sees exacerbation will also be larger—for the same change in global average temperature—for SG methods that are localized as when arctic-only SG shifts tropical rainfall (*3*). This increased disparity of climate changes is a reason why localized deployment of SG may paradoxically increase global governance challenges.

"A serious research program must apply modern risk-assessment tools to the technology and to the institutions proposed for deployment."

Some technologies are particularly prone to errors. We should expect "normal accidents" (*4*) from such technologies even when they are managed with good intent. SG methods will differ in their sensitivity to error. A space-based shield that is only stable with dynamic control might be destroyed with a software error, whereas aerosol injection might be less sensitive to such errors because the 2-year stratospheric lifetime provides opportunity to respond to failures. There has been woefully little effort to assess SG's accident risk. A serious research program must apply modern risk-assessment tools to the technology and to the institutions proposed for deployment.

INJUSTICE

The research, development, and deployment of SG each entail concerns about procedural justice. Any deployment of SG would also entail concerns about distributive justice.

Perhaps the central concern about SG is that deployment, or even the credible possibility of deployment, will slow emissions cuts. This concern—moral hazard, or mitigation inhibition—arises from political links between decisions about SG and emissions cuts in the face of climate risks, not from any physical or technological link between SG and emissions.

SG is fast, cheap, and risky, whereas emissions cuts and carbon removal are—comparatively—expensive and slow because of inertia in the energy system and carbon cycle. Doing a bit less emissions cutting and a bit more SG will tend to provide short-term benefits while imposing long-term costs.

Mitigation inhibition may occur as a collective behavior if the current generation deploys SG while foregoing emissions cuts, reducing their climate risk while increasing risks for the next generation. Even if the current generation's choice conformed to some standard of procedural justice, such a decision could violate intergenerational distributive justice. This is mitigation inhibition as economic free-riding on our grandchildren. Such mitigation inhibition would be bolstered when irrational technological optimism about the effectiveness of SG or of future carbon removal serves as a collective excuse for shortsightedness.

Mitigation inhibition may arise as a violation of procedural justice if a self-interested minority, such as fossil fuel–rich countries or industries, is able to overcome the majority by exaggerating the efficacy of SG.

If the pace of emissions cuts is determined by balancing the cost of faster cuts against future climate risks, then a benevolent policy-maker who expects SG to reduce some risks will delay emissions cuts relative to the rate of mitigation without SG. Mitigation inhibition arises only if emissions cuts are irrationally or unjustly delayed.

Mitigation inhibition couples procedural questions—who makes decisions—and distributive questions about the net distribution of the costs and benefits of emissions cuts and SG.

Independent of the political linkage with emissions cuts, any research and development of SG requires decisions about the conduct and objectives of research, decisions that in turn raise questions of procedural justice. How to resolve disputes between groups such as the Saami council, who oppose SG research, and environmental groups who support research?

Whatever is done about emissions, deployment of SG will require choices, such as the choice to focus the cooling on the tropics or the poles, choices that entail concerns about distributional justice.

CONFLICT

Concerns that SG may induce conflict are rooted in the Cold War salience of weather and climate modification (*5*). Use of weather modification by the United States in the Vietnam war led to a treaty prohibiting hostile use of environmental modification technologies. Conflict could be caused directly by

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A taxonomy of concerns about solar geoengineering (SG)

Bullet points indicate examples of potential concerns.

PHYSICAL RISKS OF BENEVOLENT DEPLOYMENT

Side effects of perturbing radiative forcing. Physical consequences other than those arising from an idealized reduction in insolation

- Stratospheric sulfates cause ozone loss
- Iodine from sea salt spray increased methane lifetime
- Scattered light alters ecosystems
- Health hazard when aerosols add to particulate matter at surface

Exacerbation of climate changes. SG increases the deviation of a climatic variable in some region from the preindustrial.

- Change in drought frequency
- Increased nitrate contribution to particulate matter ($PM_{2.5}$) due to reduced warming

Accidents

- Termination due to catastrophic failure of deployment system

Incompetence

- Errors in quantities deployed

INJUSTICE

Moral hazard. Unjust reduction in emissions cuts, better termed "mitigation inhibition"

Political exploitation. SG exploited by a group to advance their private interest against the collective interest in emissions cuts

- A petrostate covertly funds civil society groups to exaggerate benefits of SG and lobby for deployment and for slowing emissions cuts
- The industries that will implement SG promote SG

Collective addiction

- Irrational technological optimism serves as a collective excuse for delay

Procedural injustice

- Unilateral deployment

Distributive injustice

- SG is deployed for polar cooling, disproportionally benefitting relatively wealthy mid-latitude countries while doing little to reduce peak temperatures in the tropics.

CONFLICT

Malevolent use

- Weaponization of weather control
- Termination due to destruction of deployment system

Exacerbation of existing conflicts

- Conflict exacerbated by realized or perceived unequal impacts or benefits
- Conflict arises from attribution of weather-related disasters to an SG program
- Conflict arises from perceived illegitimacy of SG deployment

HUMANITY AND NATURE

Earth becomes more of an artifact. Deliberately altering climate—whatever the harms or benefits—makes Earth appear more of an artifact of human political choices.

Slippery slope to enhancement. If SG becomes widely accepted, there will be temptations to use the technology to tailor climate for humanity's benefit rather than to reduce climate changes.

- A combination of increased CO_2 concentrations and SG is used to decrease pole-to-equator gradients and increase biological productivity, nudging the climate toward "equitable" climates.

malevolent deployment or indirectly by deployment that exacerbates existing conflicts.

Despite long-standing concerns about weaponization, there are few or no specific analyses of the military use of SG technologies. Militaries increasingly seek precision weapons, so the long time scale and spatially diffuse climate changes produced by geoengineering appear to lack a credible military use. Perhaps the most plausible military application is weather control. This might be achieved by modulating the radiative forcing with feedback from a weather forecasting system. It would only be possible with methods that can be modulated on synoptic scales (on the order of 1000 km or more), such as marine cloud brightening and cirrus cloud thinning. But this is unproven and, even if possible, might be too diffuse, or easily countered, to have meaningful military application. Beyond weaponization of the system itself, military force might be used against deployment systems to cause or threaten termination shock.

Conflict may be induced if SG deployment sharply exacerbates inequalities, or conflict might arise from instabilities introduced by counter geoengineering (*6*). The likelihood of conflict may also increase if disagreement over deployment of SG distracts political attention from unrelated conflicts.

HUMANITY AND NATURE

If SG was used only to supplement emissions reductions by limiting climatic change, then it can reasonably be seen as a means to limit the human footprint on nature. This use of SG would be anthropogenic but not anthropocentric (*7*). Yet even if SG protects ecosystems by limiting the "climate velocity" (the rate at which species must migrate to find climate conditions suitable to their survival in a warming world), climate being partially controlled by a centralized, high-leverage technocratic process would mark a change in humans' relationship with nature.

Deployment might begin with the goal of limiting environmental change, yet once developed, the temptation may grow to use SG for climate "enhancement." A high-CO_2 climate in which SG reduces pole-to-equator temperature gradients might, for example, provide utilitarian benefits in the form of increased primary productivity and reduced climate extremes. The slippery slope to enhancement is for me a sharper concern than the teleological concerns about the end of nature.

TOWARD MORE CONSTRUCTIVE DISAGREEMENT

An expert can better serve their audience—other experts, policy-makers, or diverse publics—by disaggregating their judgments. They might say that some specific geoengineering proposal "could reduce deaths in heat waves by 30%" while also saying that "research on SG should not proceed because it will be exploited by fossil-rich nations to block emissions cuts" rather than conflating their judgments by saying "geoengineering is risky."

Audiences look to experts because of their knowledge. But expertise in one discipline is not strongly correlated with accurate judgments in other domains (*8*). An expert at predicting heat waves may be no better—and perhaps worse—than an average citizen in predicting political outcomes of deploying SG. Disaggregation allows the audience to weigh expert claims using their own judgment about the expert's accuracy across various domains.

Disaggregation may also help find places where experts agree. Experts who disagree strongly about proceeding with a SG field experiment might nevertheless agree on specific technical judgments, such as the mortality caused by SG aerosols that add to particulate matter pollution or the reduction in mortality from heat waves when SG reduces peak temperatures.

When experts provide an aggregate policy recommendation, they combine their judgment about the likelihood of specific technical and or political outcomes with their personal valuation of those outcomes. This is unhelpful when the audience does not share the expert's valuation. Disaggregation can help avoid conflation of facts and values (*9*).

Support for SG research seems to be stronger in poorer countries (*10*, *11*). It is plausible that this arises from divergent weights given to the outcomes of SG. Residents of poorer and hotter countries may weigh the benefits of short-term cooling more strongly, whereas residents of richer, cooler countries who feel less threat from the immediate impacts of heat may accord more weight to the long-term concerns about SG. There is no value-free resolution to trade-offs between the benefits and harms of SG. What is certain is that experts' valuation of outcomes will likely differ from their audience, and that climate experts are generally more educated, wealthier, and less racially diverse than their audiences. So experts do their audience a disservice by implicitly folding their values into policy recommendations.

How to encourage disaggregation? Experts should strive to delineate areas in which they have expertise from areas in which they do not and should give audiences the opportunity to use their own values. Policy intermediaries such as journalists and opinion-leaders can encourage the distinction between factual judgments and valuation.

A community-based taxonomy of SG concerns could help. Such a taxonomy might be seen as reasonably unbiased if it were maintained by a community using rules adapted from Wikipedia in which substantive statements require pointers to peer-reviewed literature.

Organizations such as the National Association of Science Writers can help by explicitly promoting best practices for reporting on politicly contentious topics. Journalists might better encourage experts to provide narrower answers that are better supported by data in the expert's arena of expertise.

This is not an injunction that experts "stay in their lane." Transdisciplinary research requires collaboration across disciplinary boundaries. Moreover, experts are also citizens and, as citizens, have a right to participate in public policy. But in participating, they have a duty to distinguish statements made on the basis of their expertise from statements they make as citizens.

Nor is this a claim that facts and values can be sharply separated; they cannot. But more careful reporting of expert judgments could help to reduce the role of "cultural cognition" in determining policy preferences (*12*).

Behavioral social science may help untangle interplay between expert judgments, values, and public understanding. Analysis of SG is oversupplied with generic normative claims about governance and undersupplied with detailed empirical research to understand the mental models of relevant groups. Empirical social science could adapt research projects to identify and characterize subjective aspects of expert judgments and anticipate and clarify conflicts that arise from inequitable effects of climate change and geoengineering (*13*).

A coordinated SG research program could support development of community-based taxonomies of SG's benefits and concerns. The program could then use such structures to aid program managers in supporting research that addresses concerns that are both salient and researchable. The program could also encourage development of community-based codes of conduct that include best-practice guidelines for reporting results.

There is no recipe to resolve hard problems at the science-policy interface, but that should not discourage incremental improvements that may allow experts to better serve the public. ■

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CLIMATE POLICY

Social science research to inform solar geoengineering

What are the benefits and drawbacks, and for whom?

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As the prospect of average global warming exceeding 1.5°C becomes increasingly likely, interest in supplementing mitigation and adaptation with solar geoengineering (SG) responses will almost certainly rise. For example stratospheric aerosol injection to cool the planet could offset some of the warming for a given accumulation of atmospheric greenhouse gases (*1*). However, the physical and social science literature on SG remains modest compared with mitigation and adaptation. We outline three research themes for advancing policy-relevant social science related to SG: (i) SG costs, benefits, risks, and uncertainty; (ii) the political economy of SG deployment; and (iii) SG's role in a climate strategy portfolio.

Some concerns have received increased attention in debates over SG and thus illustrate the need for greater social science evidence and understanding. For example, some stakeholders have suggested that undertaking SG research could create a form of moral hazard by deterring emission mitigation efforts, whereas other scholars have challenged this claim. Still other scholars have questioned the ethics of seeking to hide from future generations policy choices that they may wish to consider. And given the evidence of strong free-riding incentives for emission mitigation, it is not clear that there would be much of an additional emission mitigation disincentive from SG. But these questions deserve further study in more realistic models of multiple, heterogeneous actors (*1, 2*).

Further, if a major economy with the technical capacity to implement SG makes a decision about its use, this would have important equity and justice implications, especially for the people living in least developed countries and small island states. These implications take the form of procedural justice—do these peoples have a voice in the decision-making process—as well as the distributive justice of the outcomes associated with a SG intervention decision. Such justice considerations arise regardless of whether the decision is to take or opt against an SG intervention. A critical assessment of the justice implications of SG implementation would enrich the political economy evaluation of government decision-making.

SG is one of several emerging climate engineering technologies. For example, carbon dioxide (CO_2) removal would reverse the flow of greenhouse gases into the atmosphere through large-scale biological and chemical sequestration and industrial direct air capture technologies. In contrast to CO_2 removal, SG faces fewer technological and financial hurdles and would likely influence temperatures more quickly. Indeed, the largest developed and developing nations have the resources and technical means to implement SG interventions in no more than a few years.

Despite the potential for SG to reduce climate change risks, the international community has not addressed SG under the UN Framework Convention on Climate Change. This is mirrored by a dearth of national programs and governance. The limited policy landscape provides an opportunity for new social science research to inform the design of institutions, policy, and governance of SG.

COSTS, BENEFITS, RISK, AND UNCERTAINTY

Policy-makers would gain from assessments of SG's costs and benefits, recognizing uncertainties in quantification, potential indirect costs, and risk-risk trade-offs. The direct costs of implementing SG interventions could be about $5 billion per year (*3*), two to three orders of magnitude less than estimated climate change damages and the costs of ambitious emission mitigation (*4*). These estimates, however, represent direct engineering costs of deploying SG interventions, and more extensive SG assessments can better inform decision-making. This work should be informed by advances in physical science and engineering research on SG deployment, including alternative technologies and design choices, potential small-scale experiments, and the resulting impacts of climate change and SG interventions. For example, building on high spatial resolution, climate change modeling can enable greater precision in estimating benefits and costs and help identify social science data needs where official economic statistics may be limited.

Higher-resolution representation of physical and socioeconomic impacts can also illustrate the distribution of costs and benefits from SG interventions (*5*). Like climate change, SG interventions would impose heterogeneous impacts across the world and over time (*6*), which would have important social welfare, equity and justice, social, and political implications. SG research can build upon and integrate with the growing empirical evidence of climate change impacts on conflicts, migration, health, labor and agricultural productivity.

The outputs of such analyses could be inputs in models with modified social welfare functions that vary in how they weight inequality and justice of outcomes. They can also serve as inputs in models of political economy and international relations. Taking a multi-objective assessment framework to evaluating SG can also guide survey work and laboratory experiments to elicit preferences and trade-offs over SG impacts, risk, inequality, and other considerations. Drawing study participants from developing countries can help address concerns about how integrated assessments reflect the attitudes and preferences of those populations most likely to be affected by climate change.

Integrating science, engineering, and economic analyses can help address uncertainties in the benefits and costs of SG design and deployment decisions, which could vary across geography, altitude, seasonal timing, technique, magnitude of intervention, and other factors. Integrated frameworks that incorporate risk analysis and decision theory can improve the characterization of, and reduce uncertainty about, SG benefits and risks (*1*).

Integrated assessments of SG interventions should also account for the costs of monitoring, attribution, redundancy, evaluation, updating, and any necessary risk management mechanisms. Such analyses can also consider the benefits of learning through a value of information framework. Theoretical and integrated assessment models (IAMs) can illustrate the dimensions of SG deployment with the greatest potential for learning, which in turn could focus future experimentation and measurement.

An SG intervention is not simply reversing climate change. Some climate change impacts, such as ocean acidification, are only to a small extent directly influenced by SG, and SG would occur against the backdrop of recent decades of rapid warming. Moreover, SG may result in unintended, ancillary risks (*7*). A rich array of research tools—models calibrated to real-world observations as well as statistical evaluations—can provide insights on ancillary impacts of SG interventions. For example, studying potential adverse respiratory health outcomes from SG interventions could inform future technical design of SG interventions—e.g., substituting new materials for sulfur particles—and direct evaluations of alternative policy remedies—e.g., improved health care access and treatment. Evaluations of ancillary or unintended impacts could serve as inputs in survey-based research on SG risk communication and political acceptance. SG interventions could also necessitate updating of damage functions used in IAMs, because such damage functions are typically calibrated to temperature as a proxy for climate change (*8*).

POLITICAL ECONOMY OF DEPLOYMENT

Solar geoengineering deployment scholarship has typically focused on either (i) a single, global actor or (ii) a stylized depiction of strategic interactions among possible SG actors. To understand the roles of incentives, institutions, norms, and international relations in SG deployment, the next generation of analyses could build on these to develop more realistic scenarios of SG intervention and political economy dynamics (*1*).

For example, absent strong international governance, a globally coordinated SG regime is unlikely, and decision-making

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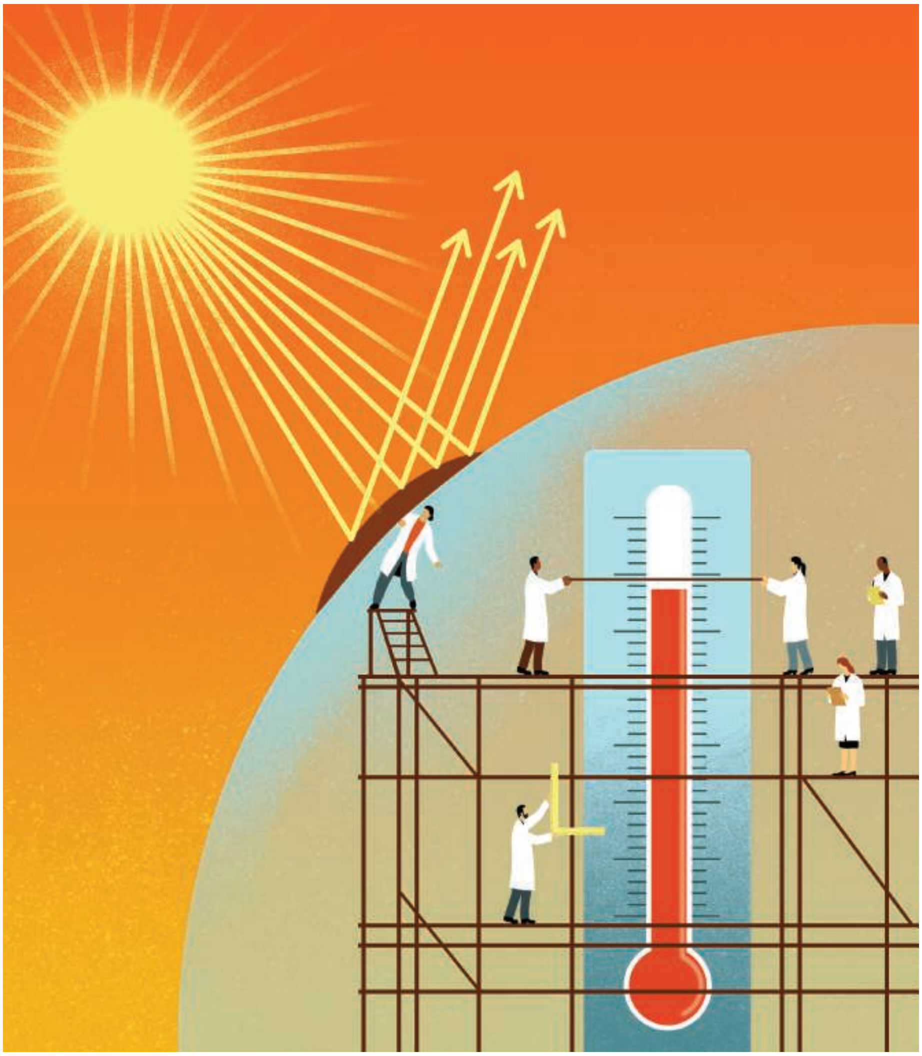

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would rest primarily among national governments. Weak global governance, coupled with modest SG engineering costs, has raised concern about "free drivers" unilaterally deploying SG interventions. Social science research can explore the options and incentives for a state (or nonstate) actor to deploy a global SG project or a local intervention (e.g., marine cloud brightening, regional cirrus thinning, or enhancing surface albedo). Such local intervention possibilities raise the prospect that multiple state actors could pursue independent SG strategies without explicit coordination. The atmosphere, however, has nonlocal "teleconnections," so a local intervention's impacts may spill over to other regions, raising governance challenges. Game theory and lab experiments could be used to explore the political, economic, and sociological drivers and inhibitions on a state actor to pursue or refrain from unilateral SG—including the types of events that could trigger unilateral SG deployment.

Inadequate efforts to reduce emissions have also prompted calls for retaliatory measures, such as border tax adjustments. This reaction points to the prospect for countermeasures targeting states that deploy SG by those opposed to such actions (*9*). Might states respond through counter-geoengineering or alternative means, such as military interventions or trade sanctions (*10*)? Such responses could influence incentives for deployment, international conflict, and the efficacy, costs, and benefits of SG interventions. This suggests new social science research convening national security experts to understand the theory, models, and evidence that can be drawn from related international problems.

A smaller group of countries could work together for a collectively managed SG intervention. Such a club approach to governance raises additional questions about legitimacy, political organization, and effectiveness. A club could test technologies and governance regimes to build mutual trust and support for SG as a credible climate change response strategy. The emergence, composition, and decision-making of such a club would likely play a key role in determining whether it would enhance confidence in SG as a strategy, or spur greater concern among states outside the club. This suggests a combination of decision- and game-theory tools to explore possible outcomes and equilibria. For example, a club of countries that are simultaneously pursuing ambitious mitigation efforts may be more credible and sustainable than a coalition of mitigation laggards. There may be opportunities to explore clubs in which SG is one element of a broader climate partnership. The prospect of a club could also benefit from study of the procedural justice implications of such institutional design.

Yet another possibility is a mutual restraint agreement. Countries might build the capacity to launch SG and then agree with other SG-capable peers to a mutual agreement to restrain unilateral deployment. This would be akin to an arms control treaty and suggests that legal expertise and experience with such treaties could be leveraged to answer these questions, alongside game theory and lab experiments. For example, the prospect of such a restraint game raises questions about incentives and institutions for such participation and verification to yield a stable outcome.

The incentives and political economy of SG will reflect actors' assessments of the benefits, costs, risks, fairness, equity, and justice. In turn, the institutional design of SG decision-making will also influence the efficacy and related SG outcomes. The need for redundancy and risk management requirements that may emerge through negotiations could likewise affect the returns on SG deployment. The value and risk tradeoffs of SG—evaluated through cost-benefit analysis—would also depend critically on how it may be paired with, or affect, emission mitigation and adaptation.

A PORTFOLIO APPROACH?

Policy-makers have long pursued a portfolio of policies and programs, in lieu of a single policy instrument, to combat climate change. Though initially focused on ways to mitigate emissions—through subsidies, regulatory mandates, carbon pricing, etc.—and more recently advancing ways to enhance resilience to the impacts of a changing climate, future policy portfolios could be broadened to include SG.

Consideration of SG alongside mitigation and adaptation raises important economic, political economy, and decision science questions. Recent analyses have examined scenarios that optimize the mix of strategies—emission mitigation, carbon dioxide removal (CDR), adaptation, and SG—that minimize the costs of achieving a specific temperature goal (*8*, *11–13*). Such an optimized framework illustrates the potentially large benefits of coupling SG with mitigation and adaptation. This work, however, does not address the strategic and behavioral responses that SG projects may entail. Decades of experience with suboptimal and inadequate emission mitigation policies suggest that a more realistic treatment of the factors influencing SG decision-making—and the possibility of suboptimal SG policy—could advance this literature (*14*). For example, how feasible are peak-shaving scenarios—which rely on carefully coordinated timing of emission mitigation, SG, and CDR to limit temperature increases and damages until mitigation efforts realize global net-zero (or lower) emissions—given real-world decision-making processes among multiple actors facing heterogeneous impacts? Moreover, SG research may influence the strategic incentives for investing in other climate change risk reduction technologies.

Exploration of SG options by decision-makers could make climate change more salient for the public and galvanize support for more ambitious emission mitigation (*4*, *15*). Rigorous theoretical analysis, coupled with well-designed surveys and laboratory experiments, could better inform our understanding of how SG deployment would influence emission mitigation. This could be integrated with behavioral decision-making scholarship to explore how political leaders would interpret and act on information about the efficacy of a mitigation+adaptation+SG approach to climate change. The public perception of and engagement in SG research and policy serves as another key element of an SG research agenda (*1*).

Given the uncertainties about climate change and SG, a decision-making under uncertainty framework could guide research on the interactions among climate change strategies. For example, decision-makers may respond to new information that shows climate change is worse than expected by implementing SG and investing in more climate-resilient infrastructure. Constructing models of decision-making that can generate such policy response functions for SG and adaptation has implications for the optimal mitigation strategy, as well as for the estimation of the social cost of carbon. Anticipating SG as an active policy response to knowledge of more severe climate change could preclude the most extreme climate change damages, but could also raise tail risks from SG ancillary impacts. Advancing social science research to characterize these potential risk-risk trade-offs would better inform decision-makers.

Social science approaches to solar geoengineering

- Interdisciplinary work among social and natural scientists to address the gaps in our SG understanding most relevant for decision-making
- Convening experts on SG and international relations, along with the use of game theory and behavioral experiments and simulations, to better understand the possible evolution of SG strategies and countermoves
- Numerical modeling to integrate the climate and social systems and to understand how multiple interactions "add up" in a consistent framework
- Assessments by sociologists and cultural anthropologists, as well as science and technology studies scholars, to understand how norms and culture evolve as new technologies enter the policy space
- Applications of behavioral science to explore the mental models of relevant decision-makers in government and throughout society with respect to SG and other climate risk reduction strategies

Given the persistence of climate change risks even with SG, additional research could explore how learning about the benefits—and shortcomings—of SG could guide future adaptation efforts. For example, ocean acidification will worsen with continued CO_2 emissions even if SG interventions effectively halt the increase in temperatures. Or SG implementation may occur too late to prevent substantial sea level rise, locking in the need to manage coastal retreat worldwide over the coming centuries.

THE WAY FORWARD

In addressing these research themes, we envision contributions from an array of social science disciplines through a mix of approaches (see the box). Effective communication and engagement among the scientific community, decision-makers, and the public on this research could also lead to SG's integration into a broader range of climate change research assessment and synthesis activities (e.g., the Intergovernmental Panel on Climate Change). The governance of social science SG research should also evolve in tandem with broader governance considerations for SG scientific and engineering research.

The evolution of SG social science research should also engage scholars from around the world. The consideration of the justice implications of climate policy can be richer and more credible through a more inclusive approach in undertaking research and the production of evidence. Considering the potential for climate change and SG to have substantial impacts on developing countries, the next generation of SG research should integrate existing scholars and contribute to the training of new scholars in developing countries.

Given the mounting evidence of the economic and social impacts of climate change, the development of new emission mitigation policies and the notable public spending on resilience and adaptation illustrate decision-makers' interest in exploring new ways to combat climate change. Advancing SG social science scholarship—and integrating such research with that undertaken in the physical sciences—can help inform what role SG might or might not play in reducing the risks of climate change. ■

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Social science research to inform solar geoengineering

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