TECHNOLOGY FACTSHEET SERIES

Solar Geoengineering

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The Technology Factsheet Series was designed to provide a brief overview of each technology and related policy considerations. These papers are not meant to be exhaustive.

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Design and layout by Andrew Facini

Executive Summary

Solar geoengineering refers to a set of emerging technologies that could alter the Earth's radiative balance—perhaps through injecting aerosols into the stratosphere, where they would reflect a small fraction of sunlight back into space—reducing the amount of climate change caused by greenhouse gases. It could not replace reducing emissions (mitigation), coping with a changing climate (adaptation), or carbon dioxide removal (CDR). Yet it does have the potential to supplement these efforts, and it might provide reductions in climate risk that are unachievable by other means.

What is Solar Geoengineering?

Solar geoengineering has the potential to reduce climate impacts around the globe, but it also carries its own risks and uncertainties. The science and the governance are very challenging. The question at issue now is not about deployment. It is about whether there should be a serious research effort on solar geoengineering to advance understanding on the efficacy, benefits, and risks, and to identify strategies that might make it safer.

Proposed solar geoengineering technologies include:

- marine cloud brightening
- cirrus cloud thinning
- space-based techniques
- stratospheric aerosol scattering

With the exception of **cirrus cloud thinning**, which would attempt to reduce the thin, high-altitude cirrus clouds to allow more long-wave radiation from the Earth to space, all solar geoengineering proposals would aim to reflect away a very small fraction of sunlight back to space to partially offset the energy imbalance caused by accumulating greenhouse gases. For example, **marine cloud brightening** would attempt to brighten marine clouds to reflect more sunlight back into space. **Space-based technologies** would attempt to reflect a small fraction of sunlight away from the Earth by positioning sun shields in space. And **stratospheric aerosol scattering** would introduce tiny reflective particles, such as sulfate aerosols or perhaps calcium carbonate, into the upper atmosphere, where they could scatter a small fraction of sunlight back into space. Other methods include tropospheric aerosols and increasing the reflectivity of crops or other land cover.

Each method introduces its own set of benefits and risks. This brief will focus most closely on stratospheric aerosol scattering, given its potential to bring the largest global benefits with the fewest risks, and its ability to do so at a cost and technical scenario that is within society's reach. But much more research needs to be done into all methods, particularly in the event that one day, a combination of technologies is considered the safest and most effective approach.

Furthermore, it is worth noting that several solar geoengineering proposals mirror human actions or natural processes that reflect sunlight back into space and cool temperatures.[1] For example, coal- fired power plants release aerosols into the troposphere that scatter light and increase the reflectivity of clouds, leading to cooling that offsets a significant fraction of the warming from greenhouse gases. Some major volcanic eruptions (e.g., Pinatubo, Tambora, Krakatoa) released substantial amounts of aerosols into the upper atmosphere, the stratosphere, producing a large transient cooling that provides a valuable natural analog to stratospheric aerosol geoengineering.

Why could solar geoengineering not replace efforts to reduce emissions?

As noted above, solar geoengineering could not eliminate all of the damages caused by green-house gas (GHG)-driven warming, even if it tried to restore global average temperatures to pre-industrial levels.[2] Put simply: solar geoengineering could not be anti-CO_2. This is because climate variables, such as temperature and precipitation, would respond differently to any cooling caused by solar geoengineering (by reflecting short wave radiation) compared to the warming caused by GHGs (by trapping long wave radiation). For example, if temperatures were restored to pre-industrial levels via solar geoengineering, the water cycle would be weaker than it was in the 1700s.

Still, strong evidence shows that if solar geoengineering were applied evenly—as might be produced by stratospheric aerosol geoengineering—and adjusted to offset roughly half of the warming from GHGs, then the change in important climate variables would be reduced in most locations and increased in only a small percentage of the land surface.[3] Relatedly, non-uniform or strongly patchy cooling—as might be produced by marine cloud brightening—will generally produce more unevenness in the climate response.

Marine Cloud Brightening, Cirrus Cloud Thinning, and Cooling Effects

There is much lower confidence that a substantial cooling (~2 Wm^{-2}) could be achieved with marine cloud brightening or cirrus thinning compared to stratospheric aerosols.[4] The magnitude, and even sign, of the effect is uncertain in both cases, and both are applicable over a limited domain of susceptible clouds, so may not be scalable to achieve a substantial cooling.

For example, marine cloud brightening is most effective in a specific kind of marine boundary layer cloud that covers ~10 percent of the Earth's surface, so the cooling produced is inherently non-uniform. Cirrus cloud thinning acts primarily by increasing outgoing thermal radiation, so the nature of its cooling is more similar to GHGs than most other solar geoengineering methods. However, unlike GHGs, its cooling would be patchy.

Furthermore, for both marine cloud brightening and cirrus thinning, the spatial pattern of cooling could be adjusted on a timescale of hours to days, a capability that would likely allow some form of weather control.[5] Stratospheric aerosols could only be adjusted over years, so they could not be used for weather control.

Lastly, engineering estimates of the cost and technical feasibility of delivery are much less certain for marine cloud brightening than stratospheric aerosols,[6] and no technical feasibility assessment of cirrus cloud thinning has yet been made.

Stratospheric Aerosols and Cooling Effects

There is high confidence that stratospheric aerosols could achieve sufficient cooling to offset half the warming from a doubling of CO_2 concentrations (~2 Wm^{-2})[7] This is largely due to the way in which the stratosphere circulates. By choosing where to release aerosols, a fairly uniform global aerosol layer could be created, or the aerosol layer could be thicker at high latitudes or in one hemisphere or the other to achieve a certain outcome.[8] That said, the circulation in the stratosphere strongly limits what can be achieved. For example, it is not possible to limit cooling to one country. Additionally, the roughly one- to two-year lifetime of stratospheric aerosols constrain how rapidly this pattern of cooling could be adjusted.

Public Purpose Considerations

When used in moderation and combined with emissions cuts, stratospheric solar geoengineering has the potential to reduce climate changes around the globe. For example, climate models have consistently shown that it could reduce local average temperatures, extreme temperatures, changes in water availability, and the intensity of tropical storms.[9] It could also reduce the rate of sea-level rise,[10] as well as the coral bleaching events that are caused by rising sea surface temperatures (the damage to coral reefs is largely caused by rising sea surface temperatures, followed by intensifying ocean acidification).[11] Solar geoengineering could also reduce poleward shifts in species ranges,[12] which has been posing serious risks to tropical fisheries. And it could lessen the amount of sea-ice loss, which could reduce the impacts on high-latitude ecosystems and climate, and help to limit changes in ocean circulation and glacier melt.[13] Furthermore, it could reduce some carbon cycle feedbacks, such as the release of carbon dioxide and methane from melting permafrost, which accelerate warming.[14]

In sum, solar geoengineering has the potential to significantly benefit society and the environment. In economic terms, the potential long-term benefits likely exceed $1 trillion. This is quite large, particularly when compared to the direct costs of deploying stratospheric solar geoengineering, which are about $2 to $10 billion per year.[15]

Yet, any benefits come with novel risks and significant uncertainty.

This is partly because solar geoengineering could not perfectly offset the warming caused by greenhouse gases. It would have different effects on different climate variables, as mentioned above. For example, by affecting temperatures differently than precipitation, solar geoengineering raises concerns and uncertainties surrounding the regional distribution of impacts, despite potential global benefits. Recent evidence suggests that solar geoengineering that would aim to halve warming (rather than fully offset it) could moderate several important climate change impacts in almost all regions (including extreme storms).[16] But much more research needs to be done to advance understanding.

Another challenge is that solar geoengineering (largely) does not address ocean acidification.[17] Every year, the ocean absorbs about one-quarter of the carbon dioxide humans emit into the atmosphere, changing the chemistry of the oceans and harming marine ecosystems. Given that solar geoengineering would not remove carbon dioxide from the atmosphere directly, but rather would reflect sunlight back into space, it could do little to address this serious problem except via carbon cycle feedbacks mentioned above, the process through which additional carbon is emitted into the atmosphere upon additional warming.[18]

Solar geoengineering could have further impacts on air quality, the ozone layer, and stratospheric dynamics, which would vary depending on the type of material used. Sulfate aerosol, for instance, the most frequently analyzed proposal for solar geoengineering, may reduce some climate risks, but it would also reduce the ozone layer and heat the lower tropical stratosphere. Early studies suggest that calcium carbonate might actually increase the ozone layer and reduce the amount of stratospheric heating compared to sulfate aerosol,[19] but much more research needs to be done to better understand if it holds true under real stratospheric conditions.

So how can one understand several of these risks in the context of climate change? The risks that would arise from stratospheric heating are not yet well understood and need to be studied. But we have started to learn more about the direct health risks arising from increased particulate matter and decreased stratospheric ozone from stratospheric aerosols. These latter risks are small—one or two orders of magnitude less than climate impacts.

For example, if stratospheric sulfate aerosol injection were adjusted to produce the same cooling as is produced by tropospheric sulfate aerosol pollution, the mortality from the stratospheric sulfates would be roughly 1,000-fold smaller.[20] This is because current polluting activities release sulfate near the surface, exposing populations to harm before it is rained out, whereas stratospheric geoengineering would release sulfates in the upper atmosphere, which would rain out as they make their way down to the surface, limiting the exposure of populations to this harm. Stratospheric sulfates would also be deposited broadly at the surface rather than concentrated near to population centers, which is the current case with polluting activities.[21]

The risks that could arise from altered precipitation patterns and other climate variables could be larger than these non-climatic effects. However, strong evidence shows that if solar geoengineering is spatially uniform—as might be produced by stratospheric aerosol geoengineering—and adjusted to offset roughly half the warming from GHGs, then the change in important climate variables would be reduced in most locations and increased in only a small percentage of the land surface.

Current State of Research

Research could reduce uncertainty about the technology's potential benefits and risks, but for decades, research into solar geoengineering has been limited. This has been in part because of a fear that it could lesson efforts to cut emissions. There have also been concerns pertaining to its ethics, governance, and potential impacts on the climate system.

Consequently, funding for solar geoengineering research around the world has been scarce. China, Germany, Australia, and the U.K. have funded research, but the U.S. government has funded very little. In fact, there is currently less than $10 million USD spent globally toward solar geoengineering-related work.[22] Recently, a larger set of climate scientists have begun to work on this topic using existing funds for climate research, but formal funding remains miniscule.

Yet, calls for research are growing. Major environmental groups such as the Environmental Defense Fund, the Natural Resources Defense Council, and the Union of Concerned Scientists have begun to support careful research. The U.S. National Academy also supports research and has launched a study to develop a research agenda and recommend research governance approaches for solar geoengineering (to be completed in early 2020). The U.S. also published the Climate Science Special Report, which discussed geoengineering and called for further research. The report was a key part of the Fourth National Climate Assessment, which the U.S. Global Change Research Program (USGCRP) oversaw.

Research Issues for Consideration

There are several linked challenges that solar geoengineering research could address:

- ***The forcing challenge (Can it be done?)*:** To develop practical solar geoengineering proposals that could achieve a substantial cooling would require iteration between science and engineering to ensure the assumptions made in scientific studies align with the performance criteria of the engineering studies:
    - **Scientific aspects**: Research would evaluate whether the proposed intervention would result in a substantial cooling, e.g., demonstrating that sea-salt aerosols with certain properties reaching the base of stratocumulus clouds under certain conditions would result in a substantial increase in cloud albedo.
    - **Engineering aspects**: Research would evaluate whether the proposed intervention could be achieved through practical means, e.g., with a device designed to produce the required sea-salt aerosols and loft them to the required altitude.
- ***The climate prediction challenge (How would it change the climate?)***: The problem of predicting the climate's response to a specific deployment of solar geoengineering is closely related to the problem of predicting response to other anthropogenic influences, such as aerosol pollution and GHGs. Useful predictions require well-specified interventions. This is a challenge for climate science.
- ***The objective challenge (What is the climate goal?)***: The deployment of solar geoengineering could be tailored to meet specific objectives, within the constraints identified by the forcing and prediction challenges. Research will not be effective without some specification of the goal. Defining the climate goal is a challenge for public policy, albeit one that ought to be coupled to advances in the science and engineering of solar geoengineering, and to growing understanding of climate impacts.
- ***The management challenge (How to deploy solar geoengineering to meet its goal?)***: To pursue a specific objective through solar geoengineering deployment, it will be necessary to make short-term deployment decisions, despite substantial uncertainties. These decisions will require observations that likely include new climate observing systems, along with development of forecast tools and feedback controls.

Policy Issues for Consideration

Important governance issues include:

- **Moral hazard:** There is serious concern that talking about, researching, and/or deploying solar geoengineering will reduce incentives to cut emissions—this problem is often referred to as "moral hazard." It is highly likely that some fossil fuel interests will seek to exploit solar geoengineering to block mitigation.
- **Slippery slope:** There is also concern that research on solar geoengineering could create powerful constituencies in favor of eventual deployment. Such a potential for socio-technical lock-in is sometimes called a "slippery slope."
- **Balancing efforts:** Small-scale research may have negligible environmental impacts but entail special socio-political risks (such as moral hazard or socio-technical lock-in). This creates a need to balance investigation and knowledge production, on the one hand, against precaution and risk mitigation on the other. Existing research governance frameworks may not strike an appropriate balance.
- **Unilateralism:** The apparently low direct costs of solar geoengineering mean that one or a few states could in theory impose deployment on the rest of the world. This potential for unilateralism raises concerns about global stability, justice, and fairness.
- **Winners and Losers:** The variable distributional effects of any solar geoengineering deployment may create "winners and losers" compared to a world without solar geoengineering. This could foster disagreements in the context of negotiating or implementing solar geoengineering.
- **Termination Shock:** Solar geoengineering may need to be maintained for a long time. If deployment ends before atmospheric concentrations of carbon dioxide have been sufficiently reduced, "termination shock" may occur—the rate of change resulting from unmasked climate change would be much higher and more damaging than would have occurred without solar geoengineering.
- **Threat multiplier:** While it is unlikely that solar geoengineering could be "weaponized" due to its inherently low controllability and predictability, it could function as a "threat multiplier," just like climate change.

No comprehensive national or international governance frameworks exist for solar geoengineering. The nongovernmental Carnegie Climate Geoengineering Governance Initiative, however, is actively working to promote awareness and discussion of solar geoengineering within and among governments.

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