Geoengineering

The Gamble

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Introduction
Start here – But don’t start with geoengineering

The first time I heard about solar geoengineering, I considered the idea nuts. It is. Two decades later – after having worked on the topic at Environmental Defense Fund, helping launch Harvard’s Solar Geoengineering Research Program, and doing quite a bit of research and writing on the topic myself – I still think it is a rather healthy attitude to have toward the topic. The entire enterprise seems like a gamble, and a planetary one at that.

Of course, anyone who’s been paying attention to what’s happening with the rapidly changing climate will recognize that the world is currently playing a different kind of gamble with the planet, and arguably an even larger one.

Geoengineering – in particular, *solar* geoengineering, attempting to cool the planet by sending a small fraction of sunlight back into space, or by increasing the amount of solar radiation that escapes back into space – is no solution to climate change. That much is clear. It does not address the root cause of too much carbon dioxide (CO_2) in the atmosphere, nor the continuing inflow of CO_2 emissions. Geoengineering is a technofix, and a highly imperfect one at that.

Of course, sanitation, too, is a technofix. Without it, cities would not be possible. Modern life is replete with such technofixes. It’s often a fine balance between decrying something as a technofix that simply serves to cement the status quo and celebrating an invention as a clear step

forward. It is this constant back-and-forth, this constant internal debate, which characterizes many a geoengineering conversation. There is simply no easy answer, no clear line. Even the very idea of working on the topic comes with a number of judgment calls.

A long history of healthy skepticism

All of us having worked on solar geoengineering have stories on how we got to work on the topic. Most came to it hesitantly – some after a lifetime of work on cutting CO_2 emissions.

Geochemist Wally Broecker left an indelible imprint on the climate science community. In 1975, he introduced the term “global warming” into the literature, after the phenomenon had previously been known by the slightly cumbersome moniker “inadvertent climate modification.”[1] In a video message, recorded from his hospital bed, for a 2018 “Planetary Management Symposium” at Arizona State University, Broecker said: “If we are going to prevent the planet from warming up another couple of degrees, we’re going to have to go to geoengineering.” Broecker did not arrive at this conclusion lightly, in what would turn out to be his final address to his scientific colleagues before his passing.

Broecker was, in fact, highly skeptical of solar geoengineering as a possible climate intervention. I remember him having a number of probing questions, when, in 2013, David Keith came to give a talk on the importance of solar geoengineering research at a climate policy seminar at Columbia University’s Faculty House. Broecker’s main worry, like that of most others, was that mere talk of geoengineering – especially, once again, the

"solar" variety – might detract from the need to cut CO_2 in the first place, a concept often called "moral hazard."

It was precisely this worry that had led to a long-standing, self-imposed, unspoken near-moratorium on solar geoengineering research within the scientific community. Broecker had been a key member of the high-powered group that authored a section on CO_2 as part of a 1965 report by President Lyndon B. Johnson's Science Advisory Committee on "Restoring the Quality of Our Environment."[2] The report did not mention cutting CO_2 emissions as a possible option for addressing climate change. Doing so apparently seemed inconceivable at the time. Instead, it mentioned one possible method of addressing the problem: brightening ocean surfaces in an attempt to reflect more sunlight back into space and cool the planet.

In hindsight, this singular focus on solar geoengineering in the 1965 report was a clear mistake, and one the scientific community has overcorrected for over the course of the coming decades. In 1974, Russian scientist Mikhail Budyko first proposed what has since become the most prominent solar geoengineering method: stratospheric aerosols – introducing tiny reflective particles into the upper atmosphere.[3] Budyko's proposal was translated into English in 1977. It was briefly known as "Budyko's blanket," but mentions of it in the scientific literature and especially public climate discourse soon disappeared.

A 1992 National Academies report picks up on the possibility,[4] but it was not until the 2000s that the technology reemerged in broader scientific and climate conversations. After hearing vague mentions of solar geoengineering in the early 2000s, followed by quick dismissals, I first encountered solar geoengineering in earnest shortly after the late Nobel laureate Paul Crutzen

wrote his now famous essay presenting stratospheric sulfur injections as a possible way “to resolve a policy dilemma.”[5]

The dilemma: Air pollution in the form of sulfur dioxide (SO_2) kills millions each year; it also helps cool the planet. For example, Europe having begun to clean up its air pollution in the 1980s was clearly beneficial. Medieval cathedrals were no longer melting under acid rain. Forests – and people – are healthier. However, the Arctic is now around 0.5°C warmer as a direct result of decreased SO_2 emissions.[6] These are clear tradeoffs.

Crutzen, in his essay, presented this moral quandary. His essay was published jointly with one written by the late Ralph Cicerone, himself a famed atmospheric scientist and then the President of the U.S. National Academies of Sciences, who wrote in support of Crutzen’s controversial essay and of further research.[7] While Crutzen and Cicerone’s essays did much to lift the self-imposed research moratorium, skepticism throughout the research and policy communities has remained to this day. I would hasten to add that much of that skepticism is, in fact, still healthy. Solar geoengineering is not a topic one should “embrace,” in any sense of the term. That goes for policymakers as much as for researchers “merely” trying to answer lingering scientific questions. To this day, much of the skepticism, in turn, can be explained by “moral hazard” worries, a topic we will discuss in depth in Chapter 7.

Narrowing down “geoengineering”

A quick definitional detour is in order here, as “geoengineering” means different things to different people. In fact, the term is so vague and all-encompassing as to have lost much meaning, despite still being in frequent use. The term “geoengineering” itself is largely an

artefact and a result of the term's frequent use in popular discourse. Experts are typically more precise, and for good reason.

Except for the book's cover – *mea culpa!* – I do not use the term "geoengineering" in this book without further explanation, apart from in direct quotations. I instead use either "solar geoengineering" or "carbon removal." The two are sometimes subsumed under the broad heading of "geoengineering," but the two are, in fact, very different. Neither, in turn, is the only term used for either category of interventions.

Solar geoengineering is sometimes also called "solar radiation management" (SRM), "solar radiation modification" (conveniently, also abbreviated as SRM), or traditionally also "albedo modification." It is a largescale, deliberate intervention to cool the planet by sending a small fraction of sunlight back into space, or by increasing the amount of solar radiation that escapes back into space. The plethora of terms here already indicates the problem. While those working on the topic would immediately recognize the abbreviation "SRM," and I have used it myself in peer-reviewed papers and op-eds alike, I will eschew its use here in favor of "solar geoengineering." The reason for this nomenclature is simple: the "solar" modifies the all-too-popular broader term. That doesn't make "SRM" any less accurate. It's just another term for the same idea.

Here it's also useful to dissect the definition a bit further. One operative term is "largescale." Wearing white in the summer does not count, nor does painting roofs or streets white in an attempt to cool cities – though they are all good illustrations of the broader point. Black absorbs heat, white reflects it.[8] Even all of us in any one hemisphere wearing black winter coats or white summer shirts at once, however, does not alter the global climate. Aerosols in the

stratosphere do. “Budyko’s blanket” – stratospheric aerosols – thus, is the most commonly discussed method, though by far not the only one. (See Part I for more in-depth discussions of different solar geoengineering methods.) More precisely then, I will often refer to stratospheric aerosols as the specific solar geoengineering method.

Sometimes I will also explicitly discuss another set of technologies that are often subsumed under the broader “geoengineering” heading but that are entirely different: a set of techniques typically called carbon removal, carbon dioxide removal (CDR), carbon geoengineering, or direct air capture. All of these technologies remove CO_2 from the atmosphere directly. Their big advantage: they address the root cause of climate change – excess atmospheric CO_2. Solar geoengineering does not. That makes carbon removal an important part of the world’s collective climate response, especially given where things stand today. Carbon removal also comes with its own set of important caveats. Many are entirely different from concerns about solar geoengineering. The one area where they do clearly overlap is vis-à-vis moral hazard considerations, their interaction with efforts to cut CO_2 emissions in the first place (see Chapter 7).

One carbon removal technology is planting trees, in turn sometimes subsumed under a broader umbrella of “natural climate solutions.” That is surely part of the overall solution, but it can indeed only be one part of it. Planting trees might sound more innocuous than building large industrial facilities to take CO_2 out of the atmosphere; however, it also comes with significant limitations. One of these is the time and space needed to plant the billions of trees needed to make a dent in atmospheric CO_2 concentrations. Another is permanence. Trees decay,

releasing CO_2 in the process. In technical terms, trees help take CO_2 out of the atmosphere, but they keep the carbon in the biosphere instead of returning it to the geosphere. Other carbon removal techniques do, in fact, remove CO_2 from the biosphere entirely.

Meanwhile, even planting trees has now been used as a delaying tactic to avoid doing what's necessary. U.S. Republicans under President Donald Trump, for example, have used their "One Trillion Trees" initiative as a way to detract from the need to cut CO_2 – moral hazard in action, or perhaps better: moral hazard *inaction*. None of this, of course, means that we should not be planting more trees. We should. However, we must not use it as an excuse to delay CO_2 emissions cuts.

A possible role for carbon removal and solar geoengineering

Most importantly, we must stop burning fossil fuels and putting CO_2 into the atmosphere. Nothing else will do. There are indeed other, even more potent, and thus important greenhouse gases. Methane (CH_4), for example, might be more important than CO_2 for the *rate* of global warming – something solar geoengineering, too, has a direct role in affecting (see Chapter 2).[9] Nitrous oxide (N_2O) is similarly more potent than CO_2, around 300 times so on a 100-year timescale. And yes, technically water (H_2O) is the most important greenhouse gas of them all. However, human CO_2 emissions stand alone in their long-term influence on the changing climate.

Cutting CO_2, even to zero, will only stop the further increase in climate impacts. It won't stop them altogether.

That immediately leads to another important step: coping with what's already in store. Not unlike both carbon removal and especially solar geoengineering today, mentioning climate adaptation was once considered taboo among many committed environmentalists, and for similar reasons. "Let's stop climate change first," the refrain went in the 1990s, "only then can we start talking about adapting to warming already in store." Even Vice President Al Gore believed as much at the time, considering adaptation a mere distraction. He has long since publicly changed his mind on the topic.[10]

Adaptation, of course, can only go so far. For one, there are the usual endemic inequalities. It's the rich who adapt. The poor suffer. Then there are limits to adaptation. Building a seawall to protect against extreme storm surges is one thing; adapting to one or two meters of sea-level rise by century's end by moving entire cities to higher land within decades is quite another. Parts of Miami are flooding today, on sunny days.[11]

Enter carbon removal, taking excess CO_2 out of the atmosphere and, ideally, putting it back underground, into the geosphere. Carbon removal, meanwhile, comes with important caveats of its own, not least the same kind of moral hazard that beset earlier adaptation conversations. Equally important, much like cutting CO_2 emissions in the first place, removing it from the atmosphere is both slow and, for the most part, relatively expensive.

Solar geoengineering, by contrast, is *fast*, *cheap*, and *imperfect*.[12] These three characteristics make solar geoengineering unique among possible climate policy interventions. They also go to the heart of the solar geoengineering gamble. Little is fully known and, thus, certain. Lots depends on details yet to be worked out, and some may never be known for sure. Governance is key.

Each of the three core characteristics figures in this assessment.

Fast, cheap, and imperfect

Fast means that solar geoengineering, fully deployed, could help lower global average temperatures within weeks and months – rather than the years and decades that it would take for CO_2 reductions. For example, Mt. Pinatubo's eruption in June 1992 in the Philippines lowered global average temperatures by around 0.5°C within a year. A year later, temperatures were back to normal and have been rising ever since (see Chapter 2).

Cheap is relative, but most estimates put the direct engineering costs for deploying stratospheric aerosols at a scale somewhere in the single-digit billions of dollars per year. Think of several dozen newly designed planes with large fuselages and enormous wingspans flying missions into the stratosphere around the clock.[13] That's not exactly free, but it might as well be. The direct deployment costs are in the single-digit billions of dollars, compared to cutting CO_2 emissions or removing carbon *ex post*, both typically measured in trillions of dollars. It is cheap enough to ensure that the direct costs do not matter meaningfully in a deployment decision made by the world's governments.

Imperfect is just that: solar geoengineering does not address the root cause of excess CO_2 in the atmosphere. It comes with plenty of potential risks. It might be a really bad idea to contemplate, and worse to actually go through with. Equally important, none of that might matter in light of the first two characteristics, all but pushing the world toward deploying solar geoengineering sooner than most of us might deem possible – or desirable – today.

The combination of *fast* and *cheap* puts solar geoengineering at the exact opposite end of the spectrum from cutting CO_2 emissions in the first place. Whereas cutting CO_2 is all about motivating more people, companies, and countries to do more, solar geoengineering governance is largely about stopping premature deployment – doing it too fast, too much, stupidly.

A gamble worth exploring

One does not need to like solar geoengineering to take the idea seriously. I don't like it. The mere thought of it is scary, as I believe it should be. Somebody somewhere will surely find a way to abuse it. Conceptually, as a foil for ambitious CO_2 cuts, people already have. In 2008, at the height of the most significant U.S. federal climate policy push to that date, Newt Gingrich wrote an op-ed saying how solar geoengineering shows that we don't need to cut CO_2 emissions.[14] If only.

I remember shaking hands with David Keith on Saturday, December 12, 2015 in my living room in Cambridge, MA, agreeing to work on what would turn into Harvard's Solar Geoengineering Research Program. The day is significant for indeed a much more significant reason. It was the same day that the Paris Climate Agreement was gaveled into place across the Atlantic. The irony of the moment was not lost on either of us.

The Paris Agreement has been widely hailed for breathing new life into sluggish global climate negotiations. Nobody thought it would solve climate change. Nothing can, by itself. But the Agreement clearly did show some momentum in the right direction and, after a four-year hiatus here in the United States, the pendulum is once again swinging hard in the right direction, hopefully without avoiding the

swing back. All of that momentum toward more ambitious emissions cuts is clearly good, and nothing should take away from it!

While somewhat ironic then, it is precisely against this backdrop of increased global ambition to cut CO_2 emissions in the first place, and a broader understanding of the importance of serious climate action, that solar geoengineering should be discussed.

It must not be either–or. The best approach is a balanced portfolio, where solar geoengineering might have some, at most temporary, role in *mitigating* the worst effects of climate change, while the world cuts CO_2 emissions rapidly – to zero, and then some.[15]

Such a balanced approach may well be wishful thinking. If history – and not just climate history – is any guide, it almost surely is. Fundamental forces hold the world back from doing enough to cut CO_2 emissions. Those same forces push the world to do too much when it comes to solar geoengineering.

Notes

1 See Broecker (1975).

2 See Revelle et al. (1965). This report is often billed as the first ever report to a president on climate change. In fact, John F. Kennedy, too, received a (brief) climate change warning, and so has every president since (Hulac, 2018).

3 Budyko's proposal first appeared in Russian (Budyko, 1974), subsequently translated into English (Budyko, 1977). See Caldeira and Bala (2017) for a brief history of the idea. Morton (2015) reviews the history in depth.

4 See National Research Council (1992).

5 See Crutzen (2006).

6 See Navarro et al. (2016).

7 See Cicerone (2006).

8 The clothing example is imperfect for another reason. The additional heat absorbed by black outerwear is typically lost before it reaches the skin. See Shkolnik et al.'s (1980) aptly named *Nature* study: "Why do Bedouins wear black robes in hot deserts?"

9 See e.g. Ocko et al. (2017).

10 See *The Economist* (2008).

11 See e.g. Goodell (2017).

12 Keith (2000) first mentions the three core characteristics. Keith, Parson, and Morgan (2010) first mentions the exact phrase: "fast, cheap, and imperfect." Parson and Ernst (2013) explores its governance implications, Moreno-Cruz, Wagner, and Keith (2018) its formal economic implications, and Mahajan, Tingley, and Wagner (2019) U.S. public opinion of these characteristics.

13 See table 2 in Smith and Wagner (2018). Also see Smith (2020) as well as Lockley, MacMartin, and Hunt (2020).

14 See Gingrich (2008).

15 See Baker and Wagner (2016), and Moreno-Cruz, Wagner, and Keith (2018) for a formal exploration.

Part I
Incentives

1
Not *if*, but *when*

Solar geoengineering turns everything we think we know about climate change and climate policy on its head. For one, there is the link between CO_2 concentrations in the atmosphere and eventual global average temperatures, which itself is highly uncertain. The technical term for this link between concentrations and temperatures is "climate sensitivity." A recent, comprehensive review has advanced our thinking there quite a bit and indeed narrowed the band of uncertainties; alas plenty of uncertainties remain.[1] More on that topic, much more, in my prior book, *Climate Shock*, joint with the late, great Marty Weitzman.[2]

Most importantly for our purposes here, solar geoengineering breaks this link between concentrations of CO_2 in the atmosphere and global average temperatures. It is the only potential climate policy intervention to do so. It also does so highly imperfectly. Solar geoengineering does not tackle the root cause of climate change directly. It does, however, tackle global average temperatures – quickly and cheaply.[3]

That, in a nutshell, is why solar geoengineering is not a question of *if* but *when*. There are few ifs and buts about it.

From "Free Rider" to "Free Driver"

Economics 101 is clear about the cause of excess CO_2 emissions in the atmosphere: the benefits of emitting CO_2 are privatized, while the costs of one's pollution are largely socialized. The solution is self-evident: price CO_2 at the

difference between the marginal private and social cost. Arthur Pigou suggested as much in 1920, in his case for rabbits overrunning a communal meadow.[4] The diagnosis is the same.

The term for this Economics 101 principle: the *free-rider* effect. It is in nobody's immediate self-interest to go first and bear the costs of mitigating CO_2. That goes for individuals and companies as much as it does for countries. Why commit to something if others won't?

Economists arguably make too much of a deal out of this one element of the analysis. Political Economics 101 immediately points to vast vested interests as the true hurdle for action. Even if politicians in one country are citing other countries' lackadaisical climate policies as a reason for their own inaction, it typically comes down to domestic politics. In short, the *free-rider* effect may be overplayed. It clearly isn't the full explanation of what is preventing steeper CO_2 cuts.[5] But it surely is one part of the fuller picture.

Much as the *free-rider* effect implies too much CO_2 pollution, solar geoengineering is governed by the opposite fundamental forces. It's not about motivating to act, it's about stopping too much action. Call it the "*free-driver*" effect. Marty Weitzman and I coined the term in a *Foreign Policy* essay memorably titled "Playing God." Weitzman later formalized the idea in a peer-reviewed economic paper.[6] We were by far the first to recognize this fundamental property and to consider it important. As is so often the case with game-theoretic ideas, the first mention goes back to Nobel laureate Tom Schelling.[7] Whatever its name, the fact that solar geoengineering is such a potentially powerful tool relative to its costs makes it a force to be reckoned with.