# 25 The alternatives to unconstrained climate change: Emission reductions versus carbon and solar geoengineering

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*Having failed to limit emissions, negotiators began discussing adaptation about ten years ago. With the 2°C target likely to be crossed later this century, this chapter argues that it is now time to consider solar and carbon geoengineering as well. Carbon geoengineering offers the option of a true backstop and provides a ceiling to the costs of managing climate change. Solar geoengineering is a clear fall back, though it is unable to prevent all climate change impacts, and may have impacts of its own that cannot be foreseen. Both technologies are large engineering projects. Unlike emissions reductions, their use does not require large behavioral changes. However, solar geoengineering in particular poses problems for governance.*

For centuries, humans have been extracting carbon from below the ground and ultimately dumping it into the atmosphere. The fraction of carbon emissions that is not captured by the terrestrial biosphere and the oceans accumulates in the atmosphere, some of it staying there for thousands of years. The fraction absorbed by the seas creates ocean acidification, causing corals to die. The amount absorbed by the terrestrial biosphere increases net primary productivity and changes the chemical composition of soils. The fraction accumulated in the atmosphere increases global temperatures and alters precipitation patterns, causing droughts and a rise in the sea level.

There are four ways in which the world can limit the negative impacts of climate change. First, we can *reduce the flow of emissions* – that is, we can reduce the amount of $CO_2$ we add to the atmosphere (relative to 'business as usual'). Second, we can reduce the consequences of climate change through *adaptation*. Third, we can reduce concentrations, or the stock of $CO_2$ in the atmosphere, by removing $CO_2$ directly from the atmosphere, a process we call *carbon geoengineering*. Finally, we can reduce temperatures by blocking some incoming solar radiation, a process we call *solar geoengineering*.

The primary focus of climate negotiations has always been on the first approach – reducing emissions. But because these efforts to limit emissions have failed, increasing attention has been given to the second approach – adaptation. Both approaches are on the agenda for COP 21 in Paris.

We believe that the continued failure to reduce emissions and the eventual ineffectiveness of some adaptation interventions will inevitably cause countries to consider the other two approaches. Indeed, both geoengineering approaches have already been taken up by the IPCC (2012) and have been the subject of numerous scientific inquiries, including investigations by the National Academies in the US (McNutt *et al*. 2015a, 2015b) and the Royal Society in the UK (Shepherd *et al*. 2009). As both approaches will also have profound effects worldwide, we believe that they will ultimately have to be considered by climate negotiators.

According to the latest IPCC assessment report (IPCC 2014), it will be very difficult to meet the agreed goal of limiting mean global temperature change to 2°C relative to pre-industrial levels in the long term without exceeding the concentration level likely to limit temperature change to this level for some period of time (a situation the IPCC describes as “overshooting”). Countries may come to tolerate an increase in temperature above this target level, but if efforts to limit emissions continue to falter, or the temperature change associated with these concentration levels turns out to be higher than expected, their attention may turn to using solar geoengineering to prevent the temperature from continuing to rise. The same IPCC report says that to meet the 2°C goal in the long term, with or without overshooting, $CO_2$ may need to be removed from the atmosphere. The report emphasises the option of ‘bioenergy with carbon capture and storage’, but the scale of this approach is limited.[1] As concentrations continue to increase, it may become necessary for countries also to contemplate deploying industrial techniques for removing $CO_2$ directly from the atmosphere.

In this chapter we focus on carbon and solar geoengineering and how they compare and interact with the mainstream option of reducing emissions so as to limit climate change. Since efforts to reduce emissions may continue to fall short, we also compare the two geoengineering approaches with the option of *unconstrained* climate change.

## Comparison of the options

Emission reductions are the most conservative intervention to limit climate change. They simply involve not putting something into the atmosphere that isn't currently there.

To reduce emissions, countries must either prevent the $CO_2$ associated with fossil fuel combustion from entering the atmosphere – a process known as carbon capture and storage (CSS) – or they must reduce their consumption of fossil fuels. CSS is expected to be costly and may encounter local political resistance, due to concerns about the safety of $CO_2$ storage (Tavoni 2015). Fossil fuel consumption can be reduced at relatively little marginal cost initially, either by increasing the efficiency of energy use (conservation) or by switching to alternative energy sources like solar, wind, and nuclear power. However, to limit global mean temperature change, atmospheric concentrations must eventually be stabilised, meaning that fossil fuel consumption will have to cease entirely. Achievement of this goal will require a radical change in the global energy system. It will also be beset by free-riding problems, since it is very difficult to enforce an agreement to limit emissions. Finally, as the effort would affect production costs and

1 To be precise, the IPCC says, "[m]itigation scenarios reaching about 450 ppm $CO_2$eq in 2100 typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm to about 550 ppm $CO_2$eq in 2100. Depending on the level of overshoot, overshoot scenarios typically rely on the availability and widespread deployment of BECCS and afforestation in the second half of the century" (IPCC 2014: 12). A concentration level of 450 ppm $CO_2$eq will only have a 'likely' chance of limiting temperature change to 2°C, whereas a concentration level of 500 ppm $CO_2$eq with a temporary overshoot of 530 ppm $CO_2$eq before 2100 is 'about as likely as not' to keep temperature change below 2°C (IPCC 2014: 10).

fossil fuel prices in global markets, efforts to stabilise concentrations will be vulnerable to 'trade leakage' (Fischer 2015).

Carbon geoengineering methods aim to capture and remove $CO_2$ from ambient air. This approach reduces the concentration of $CO_2$ in the atmosphere *directly*. Like emissions reductions, carbon geoengineering affects the temperature very slowly; it is not a 'quick fix'. Compared to reducing emissions, carbon geoengineering will likely be very expensive. However, in contrast to emission reductions, carbon geoengineering technologies can be scaled up to limit atmospheric concentrations to virtually any level, making this approach the only true backstop technology for addressing climate change. Also unlike emission reductions, carbon geoengineering allows a single country or small 'coalition of the willing' to stabilise atmospheric concentrations unilaterally. Using this technology, achievement of a stabilisation target does not require large-scale international cooperation, and is less vulnerable to free riding than efforts to reduce emissions.[2] As it operates outside the international trade system, it is also protected from trade leakage.

Solar geoengineering methods aim to reflect a small fraction of incoming solar radiation back out into space, counteracting the effect on temperature of rising concentrations of greenhouse gases. Solar geoengineering can lower the global mean temperature quickly and at relatively little cost, but its effects on radiative forcing are different from those of the approaches that limit greenhouse gas concentrations. Solar geoengineering would also do nothing to limit ocean acidification. Solar geoengineering *is* a 'quick fix' for global mean temperature change, but is not a true fix for 'climate change' (Barrett et al. 2014). It might also have potentially damaging side effects. Like carbon geoengineering, solar geoengineering can be done unilaterally or by a coalition of the willing, and is not hampered by trade effects. Unlike carbon geoengineering, however, solar geoengineering is expected to be cheap to deploy.

2 The marginal cost of air capture will be approximately constant. So long as the global social cost of carbon exceeds the marginal cost of air capture, it will pay a subset of countries to fund air capture as a joint venture. This funding arrangement will be self-enforcing since, once enough countries drop out of the joint venture, the remaining countries will no longer have a collective incentive to fund air capture on their own, creating an incentive for countries not to drop out. In other words, countries need only *coordinate* financing of air capture.

Together, both of these geoengineering technologies provide a powerful frame for how we should think about climate policy and governance. Reducing emissions requires changing behaviour worldwide – a goal that, despite receiving unprecedented diplomatic attention, has so far seemed beyond our grasp. Unconstrained climate change is usually assumed to be the 'default' option, but as Table 1 shows, there are other options. The main thing that distinguishes solar and carbon geoengineering from emission reductions is that both approaches can be implemented as projects. In both cases, a decision has to be made to deploy them, and to pay for them, but no effort is needed to change behaviour or the global energy system.

The options shown in Table 1 are not mutually exclusive. The more we succeed in reducing emissions, the less carbon geoengineering will be required. The more we succeed in doing both of these things, the less tempting it will be to use solar geoengineering. At a fundamental level, all of these options are substitutes. They are, however, imperfect substitutes, as they operate on different stages of the carbon/climate cycle. From the perspective of reducing climate change risk, there is a case for deploying all of these technologies as part of a portfolio of options (Keith 2013, Moreno-Cruz and Keith 2013). For example, solar geoengineering could be used to limit temperature increases while some combination of emission reductions and carbon engineering is used to limit concentrations to a 'safe' level. Under this arrangement, solar geoengineering would be used to limit the risk from climate change, and the other interventions used to limit the risk from solar geoengineering.

**Table 1** Comparison of the options for limiting climate change

| Options | Objective | Costs | Risks | Unknowns | Collective action |
|---|---|---|---|---|---|
| Unconstrained climate change | Not an intended outcome, but a consequence of failure to limit emissions | Low | High | Many | Not achieved |
| Substantial emission reductions | Reduce the flow of $CO_2$ into the atmosphere. | High | Low | None | Difficult |
| Carbon geoengineering | Reduce the concentration of $CO_2$ in the atmosphere | Very high | Moderate | Few | Coalition of the willing |
| Solar geoengineering | Limit solar radiation reaching the lower atmosphere | Low | High | Many | Easy, apart from governance |

## The simple economics of carbon and solar geoengineering

Various methods have been proposed for removing $CO_2$ from the atmosphere. The one emphasised in the latest IPCC "Summary for Policymakers" report is land-based biomass capture and storage. This works like ordinary CSS at the power plant level, with the difference being that biomass is a renewable resource, and biomass growth takes $CO_2$ out of the atmosphere. If the $CO_2$ associated with burning the biomass is not captured, the $CO_2$ is essentially recycled from the trees into the air and back again. However, if the $CO_2$ emitted by burning the biomass is captured and stored, $CO_2$ will be removed from the atmosphere. This approach may prove useful, but it will inevitably be limited in scale. Other technologies have been considered, including ocean fertilization and increases in ocean alkalinity. However, these approaches are speculative, pose risks to the environment, or can only operate on a limited scale.

The most important carbon geoengineering technology is industrial air capture – a process by which a chemical sorbent such as an alkaline liquid is exposed to the air, removing $CO_2$. The process involves not only trapping the $CO_2$, but recycling the sorbent, and storing the captured $CO_2$. To be effective, the energy required to operate such 'machines' would need to be carbon-free, and this is one reason why the approach may prove expensive. Estimates of the cost vary from \$30/t$CO_2$ (Lackner and Sachs 2005) to over \$600/t$CO_2$ (Socolow *et al*. 2011).

Given current and future estimates for the social cost of carbon (calculated without regard to either form of geoengineering), if the costs of industrial air capture turn out to be as high as \$600/t$CO_2$, then the approach is unlikely to be used on any meaningful scale. If the cost turns out to be below \$200/t$CO_2$, then it might be deployed at scale this century. If air capture turns out to be as cheap as \$30/t$CO_2$, then this technology would be a 'game changer'. This is because the global social cost of carbon is almost certainly already above this value. As the social cost of carbon for individual countries is currently well below \$30/t$CO_2$, no country is likely to deploy air capture machines unilaterally on a large scale any time soon. However, a coalition of countries would have an incentive to deploy this technology on a large scale. Of course, it would also be desirable for emissions to be reduced at a marginal cost below the marginal cost of air capture, but even if these emission reductions were not forthcoming, it would still pay to deploy air capture. Moreover, as the scale at which air capture can be deployed is independent of the emissions of the countries doing it, air capture by a 'coalition of the willing' could suffice to stabilise concentrations. Unfortunately, we don't know the true value of the marginal cost of air capture; almost no research has gone into development of this technology. In our view, it is imperative that this situation be corrected. It is very important for the world to know the marginal cost of the only backstop technology for limiting climate change, as this value establishes a ceiling on the price of carbon.

Some solar geoengineering options, like the placement of reflective disks in space, are so technically challenging and expensive that they are almost certain never to be deployed. Other options, especially the injection of sulfate aerosols into the stratosphere, are so cheap that cost is likely to play almost no role in the decision to deploy them. A recent paper estimates that it would cost less than \$8 billion per year 'to alter radiative forcing by an amount roughly equivalent to the growth of anticipated greenhouse forcing over the next half century' (McClellan *et al.* 2012). This cost is so low that the economics of solar geoengineering appear truly 'incredible' (Barrett 2008). Indeed, it could easily pay a large number of countries to deploy solar geoengineering unilaterally.

The 'cost' that is likely to matter more concerns the risk of using this technology. Some risks, such as the possibility of added ozone depletion, are known (Crutzen 2006). Others are unknown. Research into this technology is sure to reveal more information about its effectiveness and the processes governing its functioning (Keith *et al.* 2010, Keith 2013). However, we won't know the full effect of deploying this technology at scale until we do it.

## Geoengineering governance

Because the economics of solar geoengineering are so attractive, there has been concern that countries will be only too inclined to use this technology. In simple game theory terms, if anyone can use it, everyone can use it, and the country most likely to use it will be the one who desires the biggest change in the global mean temperature (Moreno-Cruz 2015, Weitzman 2015). That is, solar geoengineering introduces the possibility of 'free driving', a situation virtually opposite that of reducing emissions, which entails free riding. With free driving, policies are needed to rein in those who want to pursue climate engineering without consideration of the interests of the broader global community.

However, this assumes that countries have a *right* to use solar geoengineering as they please, and international law generally requires countries to take due regard of the effects of their actions on other countries. Moreover, other countries may be able to react to an attempt to deploy geoengineering unilaterally. They could deploy 'counter-solar-geoengineering', throwing particles into the stratosphere intended to warm rather than cool Earth, or releasing short-lived and powerful greenhouse gases like difluoromethane that would have a similar effect. More likely, they could use other measures such as trade sanctions or, possibly, the threat of military action. It is probably more realistic to assume that countries will need to negotiate the use of geoengineering. As matters now stand, however, there are no rules for whether, how, and when geoengineering can be deployed – or for which countries get to decide. The risk of not negotiating these issues, let alone settling them, is that countries may feel that they are free to act more or less without restraint.[3]

Carbon geoengineering can also be done unilaterally, but because of its likely high cost, this approach is unlikely to be attempted at scale by anything less than a substantial

3 Analyses of the governance of solar geoengineering are still fairly primitive; examples include Schelling (1996), Barrett (2008, 2014), Victor (2008), Ricke et al. (2013), Lloyd and Oppenheimer (2014) and Weitzman (2015).

coalition of countries. Moreover, this approach addresses the root cause of climate change, and so poses fewer risks than solar geoengineering. For both reasons, the governance of carbon geoengineering has not been a major concern. If this technology were deployed on a large scale, a decision would need to be made as to the desired level of atmospheric concentrations, but this is little different from the decision countries have already made to reduce their emissions so as to limit global mean temperature change. Countries would also need to agree how to share the substantial costs of carbon geoengineering. However, this is a relatively simple matter – countries frequently agree on cost-sharing arrangements for costly enterprises. For example, every three years, over 190 countries agree on how to fund the United Nations (Barrett 2007).

## Conclusions

Just as the failure to limit emissions has brought adaptation onto the agenda of climate negotiations, so we believe the time has come for negotiators to consider the roles that solar and carbon geoengineering can play in addressing climate change.

If the 2°C goal were truly sacrosanct, then it seems unreasonable to ignore approaches that are capable of limiting temperature change directly or of limiting concentrations directly, especially as the IPCC's analysis suggests that even with a turnaround in the success of emission reduction efforts, overshooting of the 2°C goal is very likely. Should efforts to reduce emissions continue to fall short, the case for considering these alternative approaches will only increase over time.

The decision to use, or not to use, carbon and solar geoengineering will have consequences, and our view is that these consequences should be evaluated and the results of such analyses used to justify these decisions.

First, there should be collective funding of R&D into the costs and risks of carbon geoengineering. If the true cost of this approach is as high as \$600/t$CO_2$, then the approach can be disregarded this century. If the true cost turns out to be closer to \$30/t$CO_2$, however, then this technology will be a game changer.

Second, there should also be collective funding of R&D into the feasibility, effectiveness, and risks of solar geoengineering. At least as important, countries should begin to discuss governance of such research and of the possible future deployment of this technology (the distinction between research and deployment may not always be obvious). The risk of not doing this is that countries will feel that they are free to act more or less without restraint. A key focus should be on obtaining a consensus about these things, as excessively restrictive rules are likely to cause the countries that are most enthusiastic about geoengineering not to accept the rules but to strike out on their own.

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