# Geo-Wedges:
# A Portfolio Approach to Geoengineering the Climate

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**Abstract**

A host of methods to combat climate change through geoengineering could be available soon. These methods can reduce the concentrations of carbon in the atmosphere, limit the amount of incoming solar radiation or perturb the Earth's radiation balance in other ways. They may be implemented to slow down the rate of temperature change and limit the impacts of climate change. Any one technology could be too risky or costly to do the job by itself, but a coordinated intervention that employs different methods with diverse attributes could achieve climate impact reduction goals while limiting risk.

## 1. Introduction

There have been a number of recent reviews on carbon and solar geoengineering, including two exhaustive reports issued by the US National Research Council in 2015 (National Research Council 2015a, 2015b). These reviews have developed frameworks for comparing technologies (Vaughan and Lenton 2011) and placed them in context with other conventional approaches to combating climate impacts (Caldeira *et al* 2013). They have emphasized physical modeling studies (Irvine *et al* 2016), impacts assessment (Irvine *et al* 2017) and economics (Heutel *et al* 2016). Some have taken the form of consensus reports aimed at interfacing with policy makers and identifying research priorities (Shepherd 2009).

Technologies classified as geoengineering could be used to meet a wide range of different objectives, beyond just reducing global mean temperature. In addition, a broad range of criteria could be used to select the technologies best suited for achieving these objectives. The purpose of this review is to provide a new framework for understanding the role of geoengineering in mitigating risks posed by climate change. In doing so, we cover some of the material already introduced and analyzed in previous reviews but with a specific purpose in mind: shifting the paradigm away from single-technology-planetary solutions to a portfolio approach where the combination of several technologies can reduce the overall risk of using geoengineering to manage impacts of climate change. One of the primary concerns about potential future use of geoengineering technologies is the multi-faceted risks that they may present relative to conventional climate change risk mitigation approaches. Like a portfolio of investments may be used to constrain financial risk, we argue that so too may a portfolio of geoengineering approaches be used to constrain the multi-attribute risk of climate intervention.

## 2. Geo-Wedges

The current literature defines geoengineering as, “the deliberate large-scale manipulation of an environmental process that affects the earth’s climate, in an attempt to counteract the effects of global warming”. (Stevenson 2010) This definition of geoengineering captures the main concepts that frame geoengineering research, but scale and effect are not sufficient defining features of the technologies. There are many other attributes and most geoengineering technologies have disparate effects, costs and co-benefits which may complement and interact with each other in complex ways. As a result, climate risk mitigation via climate engineering becomes a multi-attribute optimization problem; hence, it is no longer adequate to evaluate individual geoengineering methods in isolation.

Previous reviews of the geoengineering literature have generally emphasized a comparative framework, whereby various proposals are quantitatively or qualitatively ranked against each other according to their diverse properties. At the same time, hundreds of publications about geoengineering emphasize the non-ideal nature of any given technology, stating that no “silver bullet” solution exists.

This sentiment is prominent in the climate change mitigation literature as well. In 2004, Pacala and Socolow published their “stabilization wedges” paper which emphasized the need for the development of a robust portfolio of scalable technologies in order to realistically tackle global emissions reductions in the near future.(Pacala and Socolow 2004) With thousands of citations and a number of prominent follow-up and refining analyses, the salience of the wedges framework is self-evident. Thus, rather than following a traditional approach to this review of geoengineering technologies, we propose that geoengineering assessment can benefit from its own “geo-wedges” framework whereby technologies are applied as a portfolio to meet certain objectives under specified constraints.

However, unlike mitigation technologies, which are uniform in their effect on the climate system relative to their emissions reduction level, geoengineering technologies have diverse outcomes. Some substantially reduce the atmospheric carbon dioxide concentrations that harm ocean ecosystems, while others do not. Some have transient forcing effect, while others are essentially permanent. Some have the potential to counteract a large amount of warming, while others can only contribute a few tenths of a degree of cooling. Thus, while mitigation wedges can be sensibly normalized in terms of an emissions reduction effect that is tightly coupled with forcing, temperature and impacts; geoengineering wedges require a multi-attribute framing. Geo-wedge portfolios that are cobbled together to achieve one objective, for example, temperature stabilization, may look quite different presented in terms of another objective, for example, biodiversity preservation. Yet this is not a disadvantage of a geo-wedges framework. Rather, a portfolio approach to geoengineering can help address some of the commonly cited drawbacks of individual methods – for example, issues of heterogeneity, transience and scalability –and optimizing to constrain risk. That is, the strength of the portfolio approach relies precisely on the different properties and expected outcomes of the geoengineering methods considered.

## 3. Attributes of Geoengineering Methods

We aim not for an exhaustive comparative assessment of geoengineering methods, but rather consider a group of methods that represent a diversity of properties that are served well by a portfolio approach. The proposed methods include all of the technologies covered in at least three of four previous major review papers or reports on geoengineering (Shepherd 2009, National Research Council 2015a, 2015b, Caldeira *et al* 2013, Vaughan and Lenton 2011). They also generally comprise the methods most frequently included in a wide range of previous comparative analyses (Bellamy *et al* 2012). We also include two proposed geoengineering methods that do not fall neatly into the conventional CDR and SRM categorizations but still meet the definition of what would be considered geoengineering: cirrus cloud thinning (Storelvmo *et al* 2014) and ocean pumping (Kwiatkowski *et al* 2015b, Oschlies *et al* 2010).

Among the eleven geoengineering methods included are one that represents a hybrid between conventional mitigation and carbon reduction:

- Bioenergy with carbon capture and storage (BECCS): biomass is grown and combusted to produce carbon-neutral energy, the $CO_2$ emissions produced during combustion are sequestered to result in net-negative emissions;

Four methods that qualify as carbon reduction:

- Afforestation (AF): Forests are grown which sequester atmospheric $CO_2$;
- Direct air capture (DAC): Atmospheric $CO_2$ is captured directly from the atmosphere and sequestered;
- Ocean alkalinity enhancement (OAE): Alkalinity of ocean surface waters is induced with liming or other chemical interventions, which in turn induces enhanced uptake of atmospheric $CO_2$;
- Ocean Iron fertilization (OIF): Iron is applied directly to nutrient-limited areas of the surface ocean to stimulate growth of phytoplankton, which consequently take up atmospheric CO2;

One technology that represents a hybrid between carbon reduction and radiation management:

- Ocean pumping (OP): pumping cold, nutrient-rich deep ocean waters to the surface, could similarly enhance primary production while surface air temperatures are also directly cooled;

And, finally, five methods that are categorized as radiation management:

- Cirrus cloud thinning (CCT): high cirrus clouds are seeded to enhance ice crystallization and allow more long-wave radiation from the Earth's surface to escape to space (i.e., reducing the greenhouse effect);

- Surface albedo (SA): modifications to the albedo (or reflectivity) of the Earth's surface, whether by whitening of roofs or brightening of crops, reflect more solar radiation back to space before it can be absorbed by the surface of the Earth;
- Marine cloud brightening (MCB): seeding of low marine clouds enhances their albedo, thus reflecting more solar radiation back to space;
- Stratospheric albedo management (SAM): injecting aerosols or aerosol precursors into the stratosphere would reflect sunlight into space; and
- Space Mirrors (SM): constructing and launching a system of reflective satellites redirect solar radiation before it enters the earth's atmosphere.

From a decision framework perspective, these methods constitute the choice set. Any technology in this set, or any combination thereof, constitute a possible policy, resulting in different geo-wedges. We choose among actions that belong in the choice set to accomplish any particular objective. Changing the objective leaves the set of possible actions untouched, but the preferred choice, the geo-wedge portfolio, changes. Changing the criteria changes the feasibility set, a subset of the choice set. Importantly, neither the objective nor the criteria are characteristics of the technology. Examples of objectives include temperature stabilization, welfare maximization and biodiversity preservation. Examples of evaluation criteria include cost effectiveness, reliability, reversibility, aesthetics, impacts, equity, scale, and governability. Different objectives, criteria and choices alter the risk profile of any resulting geo-wedge portfolio.

Below we review a number of proposed geoengineering methods based on important attributes for potential consideration in the assembly of an optimal geoengineering portfolio. A qualitative comparison of methods according to these attributes are presented in Table 1 along with supporting references.

## 3.1. Technological Properties

Geoengineering technologies are generally categorized into two types: carbon geoengineering and solar geoengineering. Carbon geoengineering technologies aim to engineer the carbon cycle in order to increase the uptake of carbon by the natural environment or by extracting carbon directly from the atmosphere. Solar geoengineering technologies aim to reduce the incoming solar radiation that reaches the planet by increasing the albedo of the planet. While categorizing geoengineering methods mechanistically between carbon and solar approaches is intuitively sensible, there are a number of technological attributes for which the two categories do not result in clear delineation. We highlight two of these– scalability and cost– and qualitatively compare our geoengineering methods accordingly.

**Scalability**

One of the main reasons to consider geo-wedges, as with mitigation wedges, is scalability. No single mitigation technology can easily replace all greenhouse gas generating elements of the economy, so a portfolio of technologies, each scaling up over time, can aggregate to produce the desired reduction in emissions. Likewise, geoengineering methods vary in the maximum amount of carbon they can capture, sunlight they can block and ultimately what their maximum radiative forcing and global temperature outcomes are. They will also vary in the rates at which they can be deployed to achieve those outcomes. While some geoengineering methods, such as stratospheric albedo modification, may be able to counteract all anthropogenic warming, others may only be able to counteract some of it even at their maximum scale of deployment.

We understand scalability in two ways: *maximum potential* and *rate of deployment*. Stratospheric solar geoengineering is the example of a high scalability technology in both ways. It could theoretically be used to counteract the entirety of anthropogenic warming (or even more) and could be deployed to that maximum amount very quickly, on the time scale of a year or two (National Research Council 2015b). A technology like direct air capture of $CO_2$ has high scalability in terms of maximum deployment but technological, economic, and thermodynamic constraints will limit the rate at which it can be deployed to maximum effect(National Research Council 2015a). Technologies like urban surface albedo modification occupy the opposite side of the spectrum(Irvine *et al* 2011). They may be deployable to maximum effect relatively quickly, but are limited in their maximum potential to reduce global temperature. Finally, there are some methods such as afforestation that are limited in both their maximum forcing or temperature effect and also their rate of deployment(National Research Council 2015a, Vaughan and Lenton 2011). Low scalability methods, we argue here, still play an important role in a portfolio approach because they can help minimize the overall risk of a geo-wedge portfolio.

**Cost**

Even if a technology is scalable, it might not be affordable. Low relative cost is one of the primary reasons geoengineering approaches have been seriously considered as a stop-gap option in addressing climate risks, but many proposed methods are not necessarily inexpensive. Another reason to construct wedges, rather than focusing on a single option, would be to meet budget constraints. One technology may be more desirable than others in terms of their overall effect on the climate system (e.g., many forms of CDR), but may be prohibitively expensive in the short term. Solar geoengineering is generally considered to have low direct costs, while carbon reduction has high costs. Nonetheless, the literature to-date shows a broad range of cost-effectiveness estimates even within these categories. For example, it has been estimated that the entire warming effect of anthropogenic greenhouse gases could be counteracted by SAM efforts costing on the order of $10 billion per year (McClellan *et al* 2012), but space mirrors would likely cost several orders of magnitude more (Angel 2006). Likewise, carbon geoengineering methods have a large range of estimated costs. Smith et al (2016) found that afforestation would be a relatively low cost approach to capturing $CO_2$, large-scale BECCS deployment to stabilize temperatures would cost on the order of $100 billion, and DAC would cost much more (National Research Council 2015a, Smith *et al* 2016). Another important aspect to consider is the rate at which the costs decline over time. To date, there is little research on the expected rates of learning that would eventually reduce the costs of implementation. Even expensive methods today can play an important role in the future. This uncertainty about future economic performance is another good reason to consider a geo-wedge approach that minimizes financial risks.

## 3.2. Effects

**Transience**

One of the primary ways in which geo-wedges differ from mitigation wedges is in their more complex transient properties. Geoengineering methods have various levels of *latency*, that is, delays between implementation and realization of their climate effects. They also have varied *persistence*; while the effects of some methods are essentially permanent after implementation, others will fade away or even rapidly terminate if they are not continuously maintained.

Probably the most consistent distinguishing characteristic of solar geoengineering methods are low latency and low persistence. More than their low cost, these methods are particularly attractive because they complement traditional emission reduction strategies in these two dimensions. Carbon geoengineering methods are universally limited by the same fundamental thermodynamic constraints as the natural carbon cycle: $CO_2$, once well-mixed in the atmosphere, inevitably takes significant work to remove (House *et al* 2011). These methods therefore always have comparatively higher latency than solar methods.

In comparison to conventional mitigation methods, all climate geoengineering methods have lower latency. Carbon geoengineering methods reduce atmospheric $CO_2$ concentrations more rapidly than the Earth's carbon cycle can do naturally. While some mitigation approaches could contribute to temperature stabilization by avoiding emissions that would otherwise have occurred, once emissions have been reduced enough to stabilize concentrations, an excess of $CO_2$ will still remain in the atmosphere for centuries. Carbon geoengineering reduces the latency in the post-zero-emissions carbon cycle.

We note here, that latency is not a strictly physical property, but also depends on engineering and economics. Because latency of carbon geoengineering is tied to the scale of implementation, it partially depends on the rate at which it is deployed, which in turn depends on prices and the rate of technological development. For instance, in Table 1 we categorize DAC as high latency and BECCS as moderate latency based not on theoretical considerations, but on a combination of theoretical scalability and present day deployability.

Persistence is also generally considered to be a fundamentally distinct characteristic between solar and carbon geoengineering approaches, with solar geoengineering methods exhibiting low persistence and carbon geoengineering, high. This is because solar geoengineering methods mask the effects of greenhouse gases, while carbon geoengineering removes them, meaning that even when active geoengineering ceases, the effects of carbon reduction methods persist. Solar geoengineering is associated with termination risks due to the rapid deterioration of its temperature effects after cessation (Matthews and Caldeira 2008). However, this is not a hard and fast rule. For example, some solar geoengineering methods, such as certain surface albedo technologies, may persist even if active maintenance of geoengineering ceases, while some carbon geoengineering methods, such as ocean iron fertilization or afforestation, may not persist if the carbon sequestration method is fallible or temporary. These risks associated with termination and fallibility of effects are another reason to consider a portfolio approach that hedges against risk of failure of any one technology.

**Regionality**

One area of frequent concern about implementation is regional inequality, especially for solar geoengineering. Geoengineering methods exhibit geographic heterogeneity in both *implementation* and *effect*. Not all methods, carbon or radiation-based, can be implemented everywhere in the world. For example, only certain areas of the globe have land available and appropriate for large scale afforestation (Zomer *et al* 2008). And only certain regions of the ocean are suitable candidates for effective marine cloud brightening (Oreopoulos and Platnick 2008).

Some methods have disparate regional climate impacts. Stratospheric albedo modification, even when applied in a globally uniform way to stabilize global scale temperature or precipitation, results in regional climate states that continue to change (Ricke *et al* 2010). Regionally implemented solar geoengineering methods have even more extreme geographic heterogeneity in their effects (Robock *et al* 2008), with some simulated surface albedo modifications potentially drastically transforming local climate states when implemented at scale (Irvine *et al* 2011). But even in the case of carbon geoengineering regional effects will not necessarily be uniform: due to feedbacks associated with the regionality of implementation or a method of carbon sequestration which may cause changes to, for example, ocean surface chemistry.

Regionality of geoengineering has raised concerns that geoengineering could cause international conflict or be difficult to govern equitably (Ricke *et al* 2013, Virgoe 2009, Moreno-Cruz 2015). A portfolio approach provides additional degrees of freedom in mitigating regional effects of any one method (MacMartin *et al* 2013) and could mitigate conflicts that may mire binary decisions about single technologies.

## 3.3. Impacts

**Efficacy**

Geoengineering methods often decouple climate variables that are correlated under standard projections of anthropogenic warming (Oschlies *et al* 2017, MacMartin *et al* 2018). Even absent consideration of geoengineering, temperature targets are imperfect tools for constraining climate change impacts (Knutti *et al* 2015). For example, consider solar geoengineering methods that can theoretically be applied with a relatively uniform forcing over the entire planet, such as stratospheric aerosols or space mirrors. Applied in this way, these methods could be implemented to stabilize global mean temperature while $CO_2$ concentrations continue to rise. Nonetheless, other impact-relevant variables would continue to change with atmospheric composition. Because $CO_2$ has a direct dampening effect on the global hydrological cycle, absent warming rising $CO_2$ will reduce global precipitation (Bala *et al* 2008). Ocean surface chemistry tracks closely with atmospheric $CO_2$, so ocean acidification would continue apace, or even be slightly exacerbated, with solar geoengineering and no emissions reductions (Kwiatkowski *et al* 2015a).

With the possible exception of DAC with perfect sequestration, all geoengineering methods have such efficacy deficits relative to mitigation and a pre-industrial or present-day baseline. While these "imperfections" are generally more pronounced for solar geoengineering, carbon geoengineering methods can result in residual environmental changes as well due to, e.g., regionality of implementation, or sequestration of $CO_2$ that impacts ocean chemistry. A portfolio approach to geoengineering can be used to diminish efficacy shortcomings of single technologies, for example by simultaneously implementing precipitation-enhancing cirrus cloud thinning to cancel out stratospheric albedo modification's precipitation-reducing effects (Cao *et al* 2017).

**Side effects and co-benefits**

In addition to impact reduction, geoengineering methods would have various side effects, some likely to be negative, others maybe positive (i.e., co-benefits). Geoengineering research over the past decade has, perhaps quite reasonably, focused more on potential negative side effects: stratospheric ozone destruction (Tilmes *et al* 2008) or increased acid rain (Kravitz *et al* 2009) for SAM, negative ecosystem disruptions for OIF (Strong *et al* 2009). However, the implications of projected outcomes may be complex. BECCS provides a source of decarbonized energy in addition to capturing previously emitted $CO_2$, but implemented at large scale, the required land use could have damaging effects on ecosystems (Smith *et al* 2016). Ocean alkalinity enhancement could have positive or negative effects on ocean ecosystems depending on the scale and region of implementation (Albright *et al* 2016, Keller *et al* 2014, Taylor *et al* 2016).

## 3.4. Multi-attribute Risk and Portfolio Diversification

Geoengineering technologies are often purported to be relatively risky methods for dealing with climate change compared to mitigation and adaptation, but the magnitude and character of these risks varies greatly by the technology and how it is implemented. All of the attributes discussed above contribute to the risk associated with a given technology, imbuing each method with its own unique risk characteristics.

In finance, assets with different risk profiles are usually combined in a portfolio in order to minimize the exposure to overall risk (Mas-Colell *et al* 1995). Using the variance of the returns on an asset as a measure of its riskiness, it can be shown that increasing the number of assets in a given portfolio can reduce the risk of the overall investment to a lower level of risk than if investing on a single asset, and it can even be lower than the lowest risk in the basket of assets. For example, when investing in two assets with the same variance and same return, as long as they are uncorrelated, the variance in the return of the portfolio is half the variance of the individual assets (Samuelson 1967). This example of the proverbial "don't put all your eggs in one basket" can also be applied to the way we think about climate policy in general and geoengineering interventions in particular. The goal is then to find enough alternatives so that the policy, or portfolio, is not overexposed to any one particular intervention.

By constructing a portfolio of geo-wedges, it would be possible to constrain the risks associated with various adverse side effects. For example, it could be specified that all geo-wedges combined could not introduce more than a 5% chance that stratospheric ozone recovery would be reversed. Risks posed by exacerbated ocean acidification under cooler surface temperatures could be balanced with select ocean alkalinity enhancements around sensitive ecosystems. Just like a portfolio of investments, a portfolio approach to climate geoengineering can be used to manage risks associated with failure, termination, or various environmental side effects. Ultimately these complex and varied risk characteristics are the most compelling reason for diversifying the geoengineering portfolio – i.e., the driving force behind geo-wedges.

# 4. Geo-wedges Applied

One could imagine any number of hypothetical objectives and constraints formulating a portfolio of geo-wedges: a cost-constrained initiative to preserve global biodiversity, a Pareto-improving regional climate stabilization scheme, or a risk-constrained strategy for rapid sea-level stabilization. Here we present an imagined geo-wedge portfolio based on a commonly discussed framing – the 1.5 degree temperature target – and a suite of constraints based on the technological attributes discussed above. The portfolio we present here is based in large part on our own subjective judgement about the attributes we discussed and how they apply to the set of methods considered. The result is a more distributed technological risk profile that should translate in an overall reduction on the overall risk of any geoengineered intervention.

## 4.1. An Illustrative Example

Under the Paris climate agreement, countries agreed to endeavor to limit global temperature to 1.5 degrees Celsius above pre-industrial (UNFCCC 2015). This ambitious target has provided a new context for climate geoengineering methods, as its widely acknowledged that such a target cannot be met without carbon removal, and even under optimistic deployments of CDR is not guaranteed to be met without solar geoengineering (Geden and Löschel 2017). In the spirit of Pacala and Socolow, and only as an illustration, we present here a concrete geo-wedge portfolio based on meeting a 1.5$^{o}$C target under the multi-attribute constraints and considerations we have discussed above. The objective, a lower-risk climate policy.

We begin with the understanding that geoengineering options can only be successfully deployed in concert with significant decarbonization efforts. Our wedges case study builds upon previous work proposing (Wigley 2006, Long and Shepherd 2014, Heutel *et al* 2016, 2018) and quantifying the effects of (MacMartin *et al* 2018) such a combined approach. As illustrated in Figure 2, we start from a business-as-usual emissions scenario that corresponds with RCP8.5 and stabilize global temperatures at 3 $^{o}$C above pre-industrial through mitigation alone (similar to emissions scenario RCP4.5) using approaches that fill the areas shaded in yellow. The temperature pathways indicated in black that delineate mitigation, carbon geoengineering and radiation management are identical to those presented in Figure 3 of MacMartin et al (2018), but further partitioned into geo-wedges of particular methods, and highlighting some methods for which these broad categorizations are not entirely straightforward. Table 1 summarizes the implementation and attributes of the methods considered in this portfolio example.

**Carbon Geoengineering Wedges**

**Geo-wedge 1:** BECCS, is both a mitigation and a carbon removal method, providing a decarbonized form of energy and reducing atmospheric carbon dioxide concentrations. BECCS is the primary mechanism for negative emissions as manifested in the RCPs and simulated by integrated assessment models in the IPCC Working Group 3 database (Fuss *et al* 2014). Despite the fact most constrained temperature stabilization scenarios deploy BECCS aggressively, in reality BECCS has yet to be scaled up beyond pilot-scale initiatives. Its land use requirements also limit its scalability (Smith *et al* 2016), in particular if protection of terrestrial ecosystems is a constraint. In our wedge, BECCS deployment is steadily scaled up over the next century to a point of removing approximately ten gigatons of carbon dioxide per year from the atmosphere. By 2300, its negative emissions component accounts for approximately three quarters of a degree Celsius' worth of temperature stabilization, though its decarbonization and negative emissions combined temperature effect is approximately twice as large.

**Geo-wedge 2:** afforestation, is a low-tech carbon geoengineering method. In our 1.5$^{o}$C portfolio, as in many of the WG3 database scenarios, we deploy it aggressively in the near term to capture atmospheric carbon, but its maximum potential effect is limited (Zomer *et al* 2008). Scaling up afforestation to counteract a significant amount of the warming would require massive land and water commitments (Smith *et al* 2016). Nonetheless, it is the only carbon removal method that can be scaled with certainty in the near term. In our portfolio, it accounts for less than two tenths of a degree of temperature stabilization in 2300, most of which is realized this century.

**Geo-wedge 3:** direct air capture (DAC), is a highly scalable but currently immature technology that directly captures and sequesters carbon dioxide from the air using industrial processes(National Research Council 2015a). Currently DAC is very expensive compared to other carbon reducing approaches (Mazzotti *et al* 2013, House *et al* 2011), but research and development is underway by both public and private entities to develop cost-effective methods. In our portfolio, DAC is developed, but not deployed this century. It is aggressively scaled during the next century and by 2300 it accounts for approximately three quarters of a degree worth of temperature stabilization; just as much as BECCS.

## Hybrid Geoengineering Wedges

**Geo-wedge 4:** ocean alkalinization (OA), is a technology that captures atmospheric carbon dioxide by chemically altering surface ocean waters. The feasibility of this proposed geoengineering method is highly uncertain according to research to date. Some work suggests that it could be deployed at a much larger scale than we propose here (Feng *et al* 2017), while other work suggests it will be prohibitively expensive even at a modest deployment level. One of the drawbacks of solar geoengineering approaches is that they will do nothing to mitigate the negative impacts of ocean acidification, but it is possible that ocean alkalinity enhancement could ameliorate some of these impacts, even if deployed at a regional scale (Feng *et al* 2016, Albright *et al* 2016). Its contribution to temperature stabilization in our portfolio is of a similar magnitude as afforestation in 2300, about two tenths of a degree, having been selectively deployed primarily to mitigate effects of ocean acidification in areas with a high density of sensitive marine ecosystem.

**Geo-wedge 5:** ocean pumping (OP), is a technology that straddles the carbon reduction and radiation management divide. The general principle of the variants of this method involve bringing cool, nutrient-rich deep ocean water to the ocean surface and/or transporting warm surface water down to the deep ocean. While originally proposed as a carbon management approach for accelerating ocean uptake of $CO_2$, its implementation can also have a radiation management effect by essentially forcing energy accumulated in the surface ocean down to deeper waters where it has no direct or immediate impact on atmospheric temperatures(Keller *et al* 2014, Kwiatkowski *et al* 2015b).

## Radiation-Management Geoengineering Wedges

**Geo-wedge 6:** surface albedo modification (SA) which is a suite of regional approaches to increasing the reflectivity of the natural and built environment at the surface of the Earth, accounts for a trivial amount of global scale cooling in our portfolio. Research to-date has indicated limited scalability for this technology (Vaughan and Lenton 2011). Only very extreme, and likely expensive, interventions would have large regional climate side effects (Irvine *et al* 2011). However, some evidence indicates modest and targeted deployment of SA, such as urban roof-whitening or crop brightening, could mitigate regional climate extremes for relatively low cost. Because even 1.5ºC warming will increase heat extremes considerably relative to the past, we deploy SA to this effect.

**Geo-wedge 7:** cirrus cloud thinning (CCT), is a recent addition to geoengineering proposals that alter radiation balance rather than atmospheric composition (Storelvmo *et al* 2013). At its maximum deployment CCT offsets about two tenths of a degree of warming, however due to its amplifying effect on the hydrological cycle, it offsets more than 90% of the drying effects (Cao *et al* 2017) of solar geoengineering methods. This is a very important characteristic when implemented in combination with wedges 8 and 9 below.

**Geo-wedge 8:** stratospheric albedo modification (SAM), is the solar radiation management method that currently appears most feasible and scalable (National Research Council 2015b). Because it operates similarly to its natural analog – volcanic eruptions – its impacts and efficacy have been easier to quantify than other more theoretical approaches. One well-understood risk associated with SAM is the termination effect (Matthews and Caldeira 2008, Trisos *et al* 2018). The risk-limiting deployment to 1 $W/m^2$ in this portfolio counteracts, at its peak between mid-century and mid- next century, about three quarters of a degree of anthropogenic warming that would otherwise occur.

**Geo-wedge 9:** marine cloud brightening (MCB), also reflects more sunlight back into space before it is absorbed by the Earth. Its efficacy is less certain than that of SAM, due to uncertainties about cloud processes. Because only certain regions of the ocean are amenable to significant brightening, MCB would require much larger radiative perturbations over a much smaller fraction of the planet. However, its deployment in conjunction with SAM allows termination and technological failure risks to be low. At its peak at the end of this century, MCB contributes just over a quarter of a degree of temperature stabilization.

Not all methods should or need to take part of all portfolio. As climate geoengineering methods are incorporated into the suite of climate risk management tools applied to reduce the harm of anthropogenic emissions, certain methods will be closely considered, but never implemented. For example, and in addition to these nine deployed geo-wedges, we include two hypothetical wedges in Table 1: ocean iron fertilization and space mirrors.

**Geo-wedge 10:** Ocean Iron Fertilization is a technology where iron is applied in certain areas of the ocean to increase the rate of absorption of atmospheric CO2 into phytoplankton. It is expensive, (Harrison 2013) and of limited overall scalability (Aumont and Bopp 2006) and latency (National Research Council 2015a). Ocean iron fertilization is never implemented at scale due to poor efficacy in field trials (Denman 2008) as well as concerns about impacts on ocean ecosystems (Strong *et al* 2009).

**Geo-wedge 11:** Space mirrors prove to be prohibitively expensive (Angel 2006), and so this proposed method is abandoned in favor of more cost-effective methods of solar radiation management.

Thus, we have constructed a hypothetical portfolio in which geoengineering methods supplement conventional mitigation approaches to meet the 1.5 ºC temperature target while considering scalability and cost limitations associated with any one technology. The portfolio spreads across a larger set of methods, each supplementing a small fraction of the overall intervention; the result is a risk profile that is more manageable than an alternative version of single-technology-planetary interventions, or one where no geoengineering interventions are allowed.

## 5. Discussion

**How geo-wedges differ from a single-technology planetary framework**

The role of a portfolio is to allow for the possibility of satisfying particular objectives with a large number of limited interventions while minimizing risks. The advantages of the approach can be best understood by comparing our illustrative geo-wedge above with two alternative hypothetical climate geoengineering deployment scenarios:

(a) A BECCS-only intervention to reduce concentrations back to current or historical levels: Relative to the BECCS-only scenario, the portfolio approach is cheaper, as multiple instruments result in low marginal implementation costs and lower overall costs. The portfolio approach breaks with the idea of carbon reduction as a generic category. There are enough methods being discussed today that could supplement BECCS making the overall carbon reduction approach less costly and risky. We present four options that can be implemented alongside BECCS to reduce concentrations in the atmosphere with fewer environmental side effects. While all carbon reduction methods have large latency and transiency, there are differences in the technological risks associated with their implementation, political risks associated with the regionality of their implementation, and physical and ecological risks associated with the heterogeneity of their impacts. The ability to spread risks across multiple intervention is a substantial improvement over the BECCS-only intervention.

(b) A SAM-only intervention to limit the temperature change associated with increased greenhouse gases accumulation in the atmosphere: Relative to the SAM-only scenario, the portfolio approach is relatively more expensive, but it has a lower termination risk and also has lower overall side effects and efficacy deficiencies compared to large deployment of SAM. Just like with the carbon reduction methods, radiation management methods are not a single generic and uniform form of intervention. There are several alternatives within this framework that can be used to minimize the costs and risks associated with a single-technology planetary intervention.

The strength of the portfolio approach becomes apparent when we combine both types of methods. The patchwork shading in Table 1 reveals that neither carbon reduction, nor radiation management, methods are homogenous in their properties. There are limitations to each technology that can be partially compensated for by either reducing or complementing the use of a technology with another with similar characteristics, but different risk profile.

**How geo-wedges differ from mitigation wedges**

By their own admission, Pacala and Socolow's sole consideration in the construction of mitigation wedges was scalability. The construction of a geo-wedge portfolio is a multi-attribute risk minimization problem. While, like mitigation wedges, geo-wedges can be used to split the burden of meeting climate-related targets, their primary purpose is to manage risks associated with climate intervention. As such, it is their risk profiles, rather than their scalability, that determines their role in a geoengineered climate. The large variation in the characteristics of these methods represent different risk profiles that can contribute to minimize the overall risk of a given portfolio.

Another important difference is that the order and timing in which each geo-wedge is implemented affects the outcome. There are no notable interactions between mitigation wedges other than through markets and access to capital goods. The impact of geo-wedges, on the other hand, is not only a function of the scale of implementation, but also of the latency, persistence and other properties of all methods being implemented. This raises important research questions that have been little explored until recently. In certain contexts, such as first-order efficacy quantifications and explorations of physical mechanisms, research focused on single technologies continue to make sense. However, especially in social scientific research, when characterizing attributes such as cost or risk, ignoring contingencies and interactions between geoengineering technologies may render research essentially useless. But social scientists can only assess those interactions when supported by strong scientific evidence. To date, only a few studies have simulated portfolio approaches to geoengineering to assess additivity or interactions (Vaughan and Lenton 2012, Keller *et al* 2014, Cao *et al* 2017, MacMartin *et al* 2018). The research community needs to expand their horizons and begin to research the interactions between different geoengineering options.

## 6. Conclusions

The purpose of this review was to reconsider the role of different geoengineering methods as part of a portfolio approach, rather than single-planetary intervention objectives. To do this, we presented a framework that shows how different objectives can be satisfied under different constraints using flexible combinations of geoengineering technologies. We described how to group methods under different criteria that move beyond costs and are more suitable for comparative analysis. We then presented an illustrative example to showcase how the framework operates and to help emphasize some aspects of geoengineering implementation that need further attention. Using this framework, we propose that relatively small interventions from a large number of methods can reduce the costs and the risks of failure of each independent geo-wedge. We also suggest that while the cost objective favors large amount of solar radiation methods, alternative objectives will push towards a more balance use of carbon reduction and radiation management geoengineering methods. Regional heterogeneity adds a dimension to the optimization problem, but can also be dealt with using suitable combinations of methods. Finally, and unlike mitigation wedges, geo-wedges are time dependent as they transition from temporary interventions like SAM to permanent interventions like DAC. Increasing the scientific understanding of how these methods would interact in a portfolio context, is paramount to inform policy and decision makers about the risks and benefits of geoengineering interventions.

Just like choosing financial portfolio investments, picking methods with very different, uncorrelated risks, can minimize overall risk. Geoengineering methods come in very different forms and embody different characteristics that make them more or less suitable to fulfill any particular objective. These differences, however, are important when designing climate policy and can help alleviate some of damages from climate change at minimum risk. While zero-risk assets are hard to find, there is an option that comes close in the climate policy environment: mitigation. But in the absence of investment in this, relatively riskless asset, the next best alternative is a portfolio that minimizes the overall risk. Just like any other type of investment, there will always be risk involved when using geoengineering technologies. But there are many possible arrangements in between no-geoengineering implementation and a full-blown single-technology planetary intervention; geo-wedges provide a framework to analyze these interventions.

## 7. References

Albright R, Caldeira L, Hosfelt J, Kwiatkowski L, Maclaren J K, Mason B M, Nebuchina Y, Ninokawa A, Pongratz J, Ricke K L, Rivlin T, Schneider K, Sesboüé M, Shamberger K, Silverman J, Wolfe K, Zhu K and Caldeira K 2016 Reversal of ocean acidification enhances net coral reef calcification *Nature* **531** 362–5

Angel R 2006 Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1) *Proc. Natl. Acad. Sci.* **103** 17184–9

Aumont O and Bopp L 2006 Globalizing results from ocean in situ iron fertilization studies *Glob. Biogeochem. Cycles* **20**

Bala G, Duffy P B and Taylor K E 2008 Impact of geoengineering schemes on the global hydrological cycle *Proc. Natl. Acad. Sci.* **105** 7664–9

Bellamy R, Chilvers J, Vaughan N E and Lenton T M 2012 A review of climate geoengineering appraisals *Wiley Interdiscip. Rev. Clim. Change* **3** 597–615

Caldeira K, Bala G and Cao L 2013 The Science of Geoengineering *Annu. Rev. Earth Planet. Sci.* **41** 231–56

Cao L, Duan L, Bala G and Caldeira K 2017 Simultaneous stabilization of global temperature and precipitation through cocktail geoengineering *Geophys. Res. Lett.* **44** 2017GL074281

Denman K L 2008 Climate change, ocean processes and ocean iron fertilization *Mar. Ecol. Prog. Ser.* **364** 219–25

Feng E Y, Keller D P, Koeve W and Oschlies A 2016 Could artificial ocean alkalinization protect tropical coral ecosystems from ocean acidification? *Environ. Res. Lett.* **11** 074008

Feng E Y, Koeve W, Keller D P and Oschlies A 2017 Model-Based Assessment of the CO2 Sequestration Potential of Coastal Ocean Alkalinization *Earths Future* **5** 1252–66

Fuss S, Canadell J G, Peters G P, Tavoni M, Andrew R M, Ciais P, Jackson R B, Jones C D, Kraxner F, Nakicenovic N, Le Quéré C, Raupach M R, Sharifi A, Smith P and Yamagata Y 2014 Betting on negative emissions *Nat. Clim. Change* **4** 850–3

Geden O and Löschel A 2017 Define limits for temperature overshoot targets *Nat. Geosci.* **10** 881

Harrison D P 2013 A method for estimating the cost to sequester carbon dioxide by delivering iron to the ocean *Int. J. Glob. Warm.* **5** 231–54

Heutel G, Moreno-Cruz J and Ricke K 2016 Climate Engineering Economics *Annu. Rev. Resour. Econ.* **8** 99–118

Heutel G, Moreno-Cruz J and Shayegh S 2018 Solar geoengineering, uncertainty, and the price of carbon *J. Environ. Econ. Manag.* **87** 24–41

House K Z, Baclig A C, Ranjan M, Nierop E A van, Wilcox J and Herzog H J 2011 Economic and energetic analysis of capturing CO2 from ambient air *Proc. Natl. Acad. Sci.* **108** 20428–33

Irvine P J, Kravitz B, Lawrence M G, Gerten D, Caminade C, Gosling S N, Hendy E J, Kassie B T, Kissling W D, Muri H, Oschlies A and Smith S J 2017 Towards a comprehensive climate impacts assessment of solar geoengineering *Earths Future* **5** 2016EF000389

Irvine P J, Kravitz B, Lawrence M G and Muri H 2016 An overview of the Earth system science of solar geoengineering *Wiley Interdiscip. Rev. Clim. Change* **7** 815–33

Irvine P J, Ridgwell A and Lunt D J 2011 Climatic effects of surface albedo geoengineering *J. Geophys. Res. Atmospheres* **116** Online: http://onlinelibrary.wiley.com/doi/10.1029/2011JD016281/full

Keller D P, Feng E Y and Oschlies A 2014 Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario *Nat. Commun.* **5** ncomms4304

Knutti R, Rogelj J, Sedláček J and Fischer E M 2015 A scientific critique of the two-degree climate change target *Nat. Geosci.* **9** ngeo2595

Kravitz B, Robock A, Oman L, Stenchikov G and Marquardt A B 2009 Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols *J. Geophys. Res. Atmospheres* **114** D14109

Kwiatkowski L, Cox P, Halloran P R, Mumby P J and Wiltshire A J 2015a Coral bleaching under unconventional scenarios of climate warming and ocean acidification *Nat. Clim. Change* **5**

777–81

Kwiatkowski L, Ricke K L and Caldeira K 2015b Atmospheric consequences of disruption of the ocean thermocline *Environ. Res. Lett.* **10** 034016

Long J C S and Shepherd J G 2014 The Strategic Value of Geoengineering Research *Global Environmental Change* Handbook of Global Environmental Pollution ed B Freedman (Springer Netherlands) pp 757–70 Online: http://link.springer.com/referenceworkentry/10.1007/978-94-007-5784-4_24

MacMartin D G, Keith D W, Kravitz B and Caldeira K 2013 Management of trade-offs in geoengineering through optimal choice of non-uniform radiative forcing *Nat. Clim. Change* **3** 365–8

MacMartin D G, Ricke K L and Keith D W 2018 Solar Geoengineering as part of an overall strategy for meeting the 1.5◦C Paris target *Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci.*

Mas-Colell A, Whinston M D and Green J R 1995 *Microeconomic theory* vol 1 (Oxford university press New York)

Matthews H D and Caldeira K 2008 Stabilizing climate requires near-zero emissions *Geophys. Res. Lett.* **35** L04705

Mazzotti M, Baciocchi R, Desmond M J and Socolow R H 2013 Direct air capture of CO2 with chemicals: optimization of a two-loop hydroxide carbonate system using a countercurrent air-liquid contactor *Clim. Change* **118** 119–35

McClellan J, Keith D W and Apt J 2012 Cost analysis of stratospheric albedo modification delivery systems *Environ. Res. Lett.* **7** 034019

Moreno-Cruz J B 2015 Mitigation and the geoengineering threat *Resour. Energy Econ.* **41** 248–63

National Research Council 2015a *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration* (National Academies Press) Online: https://books.google.com/books?hl=en&lr=&id=_hE9CgAAQBAJ&oi=fnd&pg=PT17&dq=nrc+climate+intervention&ots=IKM8XAhGd9&sig=A5aBZoP-RL7LS4TNVMpauFxCOfU

National Research Council 2015b *Climate Intervention: Reflecting Sunlight to Cool Earth* (National Academies Press) Online: https://books.google.com/books?hl=en&lr=&id=RErgCgAAQBAJ&oi=fnd&pg=PT22&dq=%22climate+intervention%22+national+research+council&ots=_0oYhKAYKe&sig=Sqb0TLK6c9oXMohoiDPwY9hIpuk

Oreopoulos L and Platnick S 2008 Radiative susceptibility of cloudy atmospheres to droplet number perturbations: 2. Global analysis from MODIS *J. Geophys. Res. Atmospheres* **113** Online: http://onlinelibrary.wiley.com/doi/10.1029/2007JD009655/full

Oschlies A, Held H, Keller D, Keller K, Mengis N, Quaas M, Rickels W and Schmidt H 2017 Indicators and metrics for the assessment of climate engineering *Earths Future* **5** 49–58

Oschlies A, Pahlow M, Yool A and Matear R J 2010 Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice *Geophys. Res. Lett.* **37** Online: http://onlinelibrary.wiley.com/doi/10.1029/2009GL041961/full

Pacala S and Socolow R 2004 Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies *Science* **305** 968–72

Ricke K L, Moreno-Cruz J B and Caldeira K 2013 Strategic incentives for climate geoengineering coalitions to exclude broad participation *Environ. Res. Lett.* **8** 014021

Ricke K L, Morgan M G and Allen M R 2010 Regional climate response to solar-radiation management *Nat. Geosci.* **3** 537–41

Robock A, Oman L and Stenchikov G L 2008 Regional climate responses to geoengineering with tropical and Arctic SO2 injections *J. Geophys. Res. Atmospheres* **113** D16101

Samuelson P A 1967 General Proof that Diversification Pays<a href="#fn01">**</a> *J. Financ. Quant. Anal.* **2** 1–13

Shepherd J G 2009 Geoengineering the climate: science, governance and uncertainty Online: http://eprints.soton.ac.uk/156647/

Smith P, Davis S J, Creutzig F, Fuss S, Minx J, Gabrielle B, Kato E, Jackson R B, Cowie A, Kriegler E, van Vuuren D P, Rogelj J, Ciais P, Milne J, Canadell J G, McCollum D, Peters G, Andrew R, Krey V, Shrestha G, Friedlingstein P, Gasser T, Grübler A, Heidug W K, Jonas M, Jones C D, Kraxner F, Littleton E, Lowe J, Moreira J R, Nakicenovic N, Obersteiner M, Patwardhan A, Rogner M, Rubin E, Sharifi A, Torvanger A, Yamagata Y, Edmonds J and Yongsung C 2016 Biophysical and economic limits to negative CO2 emissions *Nat. Clim. Change* **6** 42–50

Stevenson A 2010 *Oxford Dictionary of English* (OUP Oxford)

Storelvmo T, Boos W R and Herger N 2014 Cirrus cloud seeding: a climate engineering mechanism with reduced side effects? *Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci.* **372** 20140116

Storelvmo T, Kristjansson J E, Muri H, Pfeffer M, Barahona D and Nenes A 2013 Cirrus cloud seeding has potential to cool climate *Geophys. Res. Lett.* **40** 178–82

Strong A, Chisholm S, Miller C and Cullen J 2009 Ocean fertilization: time to move on *Nature* Online: https://www.nature.com/articles/461347a

Taylor L L, Quirk J, Thorley R M S, Kharecha P A, Hansen J, Ridgwell A, Lomas M R, Banwart S A and Beerling D J 2016 Enhanced weathering strategies for stabilizing climate and averting ocean acidification *Nat. Clim. Change* **6** 402

Tilmes S, Müller R and Salawitch R 2008 The Sensitivity of Polar Ozone Depletion to Proposed Geoengineering Schemes *Science* **320** 1201–4

Trisos C H, Amatulli G, Gurevitch J, Robock A, Xia L and Zambri B 2018 Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination *Nat. Ecol. Evol.* 1

UNFCCC 2015 Paris Agreement

Vaughan N E and Lenton T M 2011 A review of climate geoengineering proposals *Clim. Change* **109** 745–90

Vaughan N E and Lenton T M 2012 Interactions between reducing CO2 emissions, CO2 removal and solar radiation management *Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci.* **370** 4343–64

Virgoe J 2009 International governance of a possible geoengineering intervention to combat climate change *Clim. Change* **95** 103–19

Wigley T M L 2006 A Combined Mitigation/Geoengineering Approach to Climate Stabilization *Science* **314** 452–4

Zomer R J, Trabucco A, Bossio D A and Verchot L V 2008 Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation *Agric. Ecosyst. Environ.* **126** 67–80

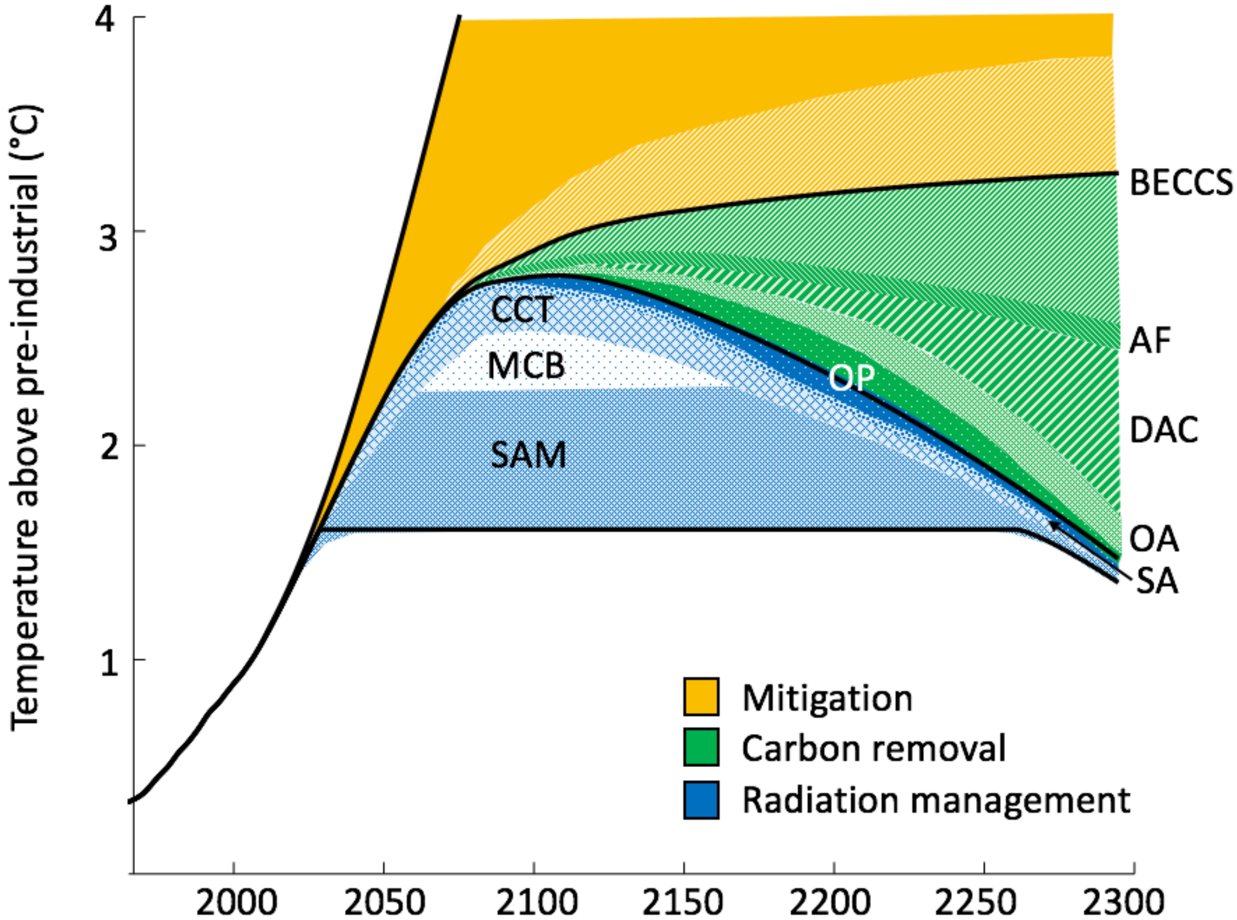


Figure 2. A transient portfolio of geoengineering methods to meet a 1.5ºC temperature target. A combination of mitigation (yellow), carbon removal (green) and radiation management (blue) methods fill the temperature gap between a business-as-usual scenario (RCP8.5) and long-term temperature stabilization at or below 1.5 ºC above pre-industrial. This illustrative portfolio includes bioenergy with carbon capture and storage (BECCS), afforestation (AF), direct air capture (DAC), ocean alkalization (OA), ocean pumping (OP), surface albedo (SA) modification, cirrus cloud thinning (CCT), marine cloud brightening (MCB) and stratospheric albedo modification (SAM). See Table 1 for details.

| | Technology | | Transience | | Regionality | | | |
|---|---|---|---|---|---|---|---|---|
| **Method** | **Scalability** | **Cost** | **Latency** | **Persistence** | **Implement** | **Effect** | **Side effects & co-benefits** | **Illustrative geo-wedge implementation** |
| **Mitigation and carbon reduction** | | | | | | | | |
| Bioenergy with carbon capture and storage (BECCS) | high | mod | mod | high | high | low | Provides decarbonized energy, land use competes with natural ecosystems | Ramp up to max potential deployment over 100 years |
| **Carbon reduction** | | | | | | | | |
| Afforestation (AF) | low | low | high | high | high | low | Positive or negative land use and ecosystem impacts | Near-term deployment reaching maximum potential CDR this century |
| Direct air capture (DAC) | high | high | high | high | low | low | Competing for materials in a global economy. Driving up prices of scarce resources. | Ramp up mid- to late century, capacity increasing indefinitely |
| Ocean alkalinity enhancement (OAE) | mod | mod | high | high | mod | mod | Could positively or negatively impact ecosystems | Limited deployment focused on areas with co-benefits |
| Ocean Iron fertilization (OIF) | mod | high | high | mod | mod | mod | Could upset natural balance of marine ecosystems | Excluded due to low efficacy and high ecological risks |
| **Carbon reduction and radiation management** | | | | | | | | |
| Ocean pumping (OP) | mod | high | low | low | mod | mod | Tunability could enable optimization of regional climate impacts, could interfere significantly with marine ecosystems | Limited deployment in areas with regional co-benefits |
| **Radiation management** | | | | | | | | |
| Cirrus cloud thinning (CCT) | mod | mod | low | low | mod | mod | Amplification of hydrological cycle could have negative impact or complement solar approaches | Use to balance global hydrological impact of SAM & MCB |
| Surface albedo (SA) | mod | mod | low | mod | high | high | Reduction of urban heat islands, regional tunability | Deployed at a limited scale where cost-effective and/or beneficial for regional climate moderation |
| Marine cloud brightening (MCB) | mod | low | low | low | mod | mod | Regionality could have negative or positive side effects | Used to supplement SAM during peak solar geoengineering deployment |
| Stratospheric albedo management (SAM) | high | low | low | low | low | mod | Reduction of stratospheric ozone and other environmental impacts | Deployed to a risk-limiting level of 0.75 W/m2 |
| Space Mirrors (SM) | high | high | low | high | low | low | | Excluded due to prohibitively high cost and high deployment-driven latency |

Table 1. Eleven geoengineering methods evaluated for a geo-wedge portfolio. Shadings indicate the authors' qualitative assessment of high (orange), moderate (green) or low (purple) potential. Hatching indicates high uncertainty. Colors are not intended to have positive or negative connotations, but rather to illustrate the diversity of attributes among various proposed climate interventions. The final column synthesizes each technology's implementation in our illustrative transient portfolio shown in Figure 1.